Cranfield University

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The Development of an Integrated Routing and Carbon Dioxide Emissions Model for Goods Vehicles

School of Management

PhD Thesis

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ABSTRACT

The issues of global warming and climate change are a worldwide concern and the UK government has committed itself to major reductions in CO_2 emissions, the most significant of the six greenhouse gases. Road transport currently accounts for about 22% of total UK emissions of CO_2, and has been steadily rising. Therefore, initiatives are required to try and reduce the gas emissions in this sector.

The aim of this research has been to develop a computer based vehicle routing model that calculates the overall amount of CO_2 emitted from road journeys, as well as time and distance. The model has been used to examine a number of delivery strategies to assess how CO_2 emissions vary. The aim has not been to produce new mathematical theories, but to produce an innovative basis for routing which will provide new information and knowledge about how CO_2 emissions vary for different minimisation and congestion criteria.

The approach used in this research brings together elements from transportation planning and environmental modelling combined with logistics based vehicle routing techniques. The model uses a digitised road network containing predicted traffic volumes, to which speed flow formulae are applied so that a good representation of speed can be generated on each of the roads. This means that the model is uniquely able to address the issue of congestion in the context of freight vehicle routing. It uses driving cycle data to apply variability to the generated speeds to reflect acceleration and deceleration so that fuel consumption, and therefore CO_2, can be estimated. Integrated within the model are vehicle routing heuristics to enable routes to be produced which minimise the specified criterion of time, distance or CO_2.

The results produced by the model show that there is a potential to reduce CO_2 emissions by about 5%. However, when other transport externalities are considered overall benefits are dependent on road traffic volumes.

Keywords:
vehicle routing and scheduling, speed-flow, driving cycles, transportation planning, fuel consumption and emissions, social cost of carbon, externalities, heuristics

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In cases where there are many factors which have a notable bearing on a problem, we find that for research to be tolerable at all we have to restrict our investigation to the observation of relatively few of the factors. We shut our eyes to the rest, either deliberately because we just cannot cope with everything, or unconsciously because we just cannot name all the factors anyway. But the fact that we shut our eyes to factors does not mean that they cease to exist and to exert an influence. When we can name a factor which we are going deliberately to ignore, we can often do something to minimise the disturbing effect of its existence on our results by experimental design before the experiment is put under way. We can arrange for the factor to be held constant during the course of the experiment, or failing this, we take steps to ensure that such a factor shall not introduce bias into our data which would lead to misleading conclusions. When we are ignorant of the nature of disturbing factors we just have to let them do their worst and hope that they will not introduce such confusion into our data that we can never find anything significant in them.

(Moroney, 1951 quoted in Akcelik, 1982)

1 Introduction

1.1 Background

Issues and concerns about climate change and the need to reduce greenhouse gas emissions are continually discussed by the media and, periodically, major reports are issued such as those from the UN supported Intergovernmental Panel on Climate Change (IPCC), and the Stern Review on the economics of climate change, for the UK government.

The most widely quoted prediction of how the world's climate might change this century was made by the IPCC in their 2nd Assessment (1995) and used as the basis for the Kyoto negotiations of 1997. This report showed that the average temperature of the world's climate had increased by 0.6 degrees centigrade during the 20th century and, based on computer modelling, made predictions of a global temperature rise of between 1.4 and 5.8 degrees centigrade by 2100 for a range of scenarios which assumed that there would be no changes in current human activity. Additional Assessment reports were produced in 2002 and 2007 which refine, but reiterate, these conclusions. The IPCC receives input from more than 2500 scientists in 130 countries, and

although a number of scientists argue against the conclusions, there is a general consensus among this group that the global warming arising out of climate change is "very likely" attributable to human activities. According to Stern (2006), there is compelling scientific evidence that rising levels of carbon dioxide (CO_2) are implicated as the primary cause of global warming.

In 1997, the Kyoto Agreement legally bound the world's developed nations to an overall reduction of a basket of six greenhouse gases by an average of 5.2% below 1990 levels by 2012 at the latest, with the UK committed to a reduction of 12.5%. However, the UK government set its own domestic goal to cut CO_2 emissions to 20% below 1990 levels by 2010 (DEFRA, 2007) with a long term target to reduce greenhouse gas emissions by 60% by 2050.

The six greenhouse gases are CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), HFC's (hydrofluorocarbons), PFC's (perfluorocarbons) and SF_6 (sulphur hexafluoride). Of these, CO_2 is estimated to account for two thirds of global warming (DETR, 2000). It is present in the atmosphere in significant quantities, representing 99.4% of the six greenhouse gases, by tonnage.

CO_2 is released from a wide range of sources including industrial processes, waste and agriculture as well as transport. In the UK, the net release of CO_2 into the atmosphere in 1990, from all sources, was 589 million tonnes. By 2005 this had reduced by 5.6% to 556 million tonnes, but in this time road transport had increased by 10% to 120 million tonnes (DEFRA, 2007), which represents 22% of all CO_2 emissions in the UK, and this has happened despite improvements in engine design and lower emission fuels.

Pollutants from vehicle engines are mainly CO (carbon monoxide), NOx (oxides of nitrogen), fine particles and HC (hydrocarbons). These four pollutants are known as 'local pollutants' in that when emitted, they remain in the vicinity in which the vehicle has driven. They are also subject to controls by European legislation that places limitations on vehicle emission levels. Consequently, motor manufacturers and oil companies have been required to

take steps to improve engine design and fuel quality to satisfy these controls, and have consequently succeeded in reducing the levels of these local pollutants (Vehicle Certification Agency, 2002).

CO_2, however, is a 'global pollutant', i.e. it impacts the air not only in the close vicinity of the vehicle, but can affect a much wider area and so represents a greater threat to the global environment. Also, the levels of CO_2 emissions, as opposed to the other pollutants mentioned previously, do not have any legal limitations. In November 2001, the UK government did introduce legislation requiring motor manufacturers to state carbon dioxide emissions for all new cars, which is linked to taxation levels, in an effort to reduce the level of this pollutant, but no firm maximum levels are specified and the legislation does not apply to goods vehicles.

Estimating the amount of CO_2 emitted from road freight transport is complex. Two methods can be used. One is to use the amount of fuel purchased by companies in different industry sectors, but this only applies to UK companies, some of whom may operate abroad, and doesn't cover foreign freight vehicles operating in the UK. The other method estimates CO_2 from the distance travelled by vehicles and the quantity of goods carried, and is obtained from surveys such as the Department for Transport Continuing Survey of Road Goods Transport. Emissions are estimated using average grams of CO_2 per kilometre, but will vary according to the mass of the vehicle, therefore the load carried is an important parameter (McKinnon, 2006). From these approaches, CO_2 emissions from road freight transport have been shown to be approximately 6% of all UK emissions of CO_2.

The externalities associated with transport include accidents, noise, air quality, infrastructure and congestion as well as CO_2. In urban areas these are more acute than rural areas. By definition, the urban area has more traffic and with that comes environmental impacts such as congestion and pollution. With local authorities in the UK having a statutory duty to meet national air quality objectives (DEFRA, 2007b), and the Highways Agency who are responsible for major roads and roads in rural areas having an objective "to take practical

steps to minimise emissions" (Highways Agency, 2001), the need to understand the environmental issues and reduce vehicle movements is paramount.

Several EU and UK government initiatives have been introduced to try and reduce the levels of CO_2 emissions such as carbon emissions trading, the climate change levy and the carbon disclosure project. In order to achieve the required reduction in CO_2, additional carbon related policy and regulation change is possible. All this will have fundamental consequences for future business performance and company valuation. Some companies have taken actions to reduce their CO_2 emissions. Marks & Spencer are aiming to become carbon neutral by 2012 (Marks and Spencer, 2007) and many of the major supermarket retailers are making efforts to reduce their emissions including adding carbon labeling to their products. A recent study undertaken for DEFRA to reduce the external costs of food distribution in the UK by 20% was supported by many of the major food companies and logistics service providers (DEFRA, 2007a).

Various reports have been produced estimating the global damage cost of carbon emissions (Clarkson et al, 2002; AEA Technology Environment, 2005; SEI, 1999; Stern, 2006). These reports have been evaluated by DEFRA and indicate a range from £35 to £140 per tonne of carbon with a central case figure of £70 per tonne of carbon at 2000 prices (DEFRA, 2007c). This is a wide range due to the uncertainty associated with climate change and the unpredictability of future effects. However, with inflation based on a Bank of England figure of 2% a year and an additional £1 per tonne of carbon per year to reflect cumulative damage effects, DEFRA's current guidance is to use a central case figure for 2005 of £82.59 per tonne of carbon (DEFRA, 2007a). If these external costs are internalised through taxation, or other forms of legislation, then companies will have to accommodate extra vehicle costs.

The necessity to find ways to reduce CO_2 in road freight transport is therefore clearly important. An operational issue facing the transport sector will be decisions relating to the routing and scheduling of vehicles, and the choice of

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vehicle type for given deliveries, particularly in relation to the potential added cost of CO_2 emissions. Thus, there is a need for models which produce forecasts of CO_2 emissions as well as calculating routes and schedules in terms of time and distance. One possible approach is the technique used in this research which has been to develop an enhanced computer based vehicle routing model to assess CO_2 emissions from freight vehicles. It has not been the intention of this research to create a new heuristic for vehicle routing, but to adapt the method of representing road speeds which are an input to the heuristic, to allow for the calculation and minimisation of CO_2 emissions.

High level approaches based upon an average value of CO_2 emissions per kilometre could be used but studies have shown differences by as much as 40% from more detailed methods which measure CO_2 emissions per second (Van Woensel et al, 2001; Palmer, 2005), the assumption being that more detailed methods equate to higher levels of accuracy.

Unlike other vehicle emissions, CO_2 is directly proportional to fuel consumption (Kirby et al, 2000; Vehicle Certification Agency, 2002; Australian Greenhouse Office, 2003). Vehicle fuel consumption and emissions require complex calculations due to the many different variables which affect the calculated values, such as vehicle and travel characteristics. Even the more detailed calculation methods can only represent an approximation because some of the variables are impossible to reflect realistically, such as driving style, weather conditions and an engines state of repair. The complexity also means that the calculations become computationally prohibitive in that it can take a long time for a computer to produce the required results. Some balance must be found between model accuracy and computational efficiency. For a journey by a specific vehicle on a defined route, the characteristics of the vehicle and roads used will be known and fixed. Assumptions can be made about the unknown travel factors of weather and driving style but, specifically, an objective of this research is to find a realistic representation of speed for each of the roads by, in the first instance, identifying average speed and then to apply a perturbation to that average speed to reflect a speed variability, or

driving cycle, so that a vehicle's fuel consumption can be estimated more accurately, and hence CO_2 emissions.

Many companies use vehicle routing and scheduling (VRS) software in an attempt to optimise the use of their vehicles. Inherently, this is a better approach than manual allocation of deliveries to routes because the software can handle so many more variables. However, problems occur if these models are to be used as a basis for estimating CO_2 emissions because of the inability to reflect road speeds in a realistic manner. These software packages apply an average speed to a limited number of road categories in order to generate a travel time. Speed and levels of acceleration are also a function of vehicle and travel characteristics, but also the category of road being used, its topography, and the volume of traffic on the road.

Current VRS systems consist of algorithms that attempt to optimise the routing of vehicles so that deliveries (or collections) are made in the most efficient sequence minimising either the time taken, distance travelled or cost, and also schedule vehicles so that a defined fleet is utilised in the most effective way. The former technique is usually referred to as the vehicle routing problem (VRP), and the latter as the vehicle scheduling problem (VSP). The VRP is solved using various types of heuristic which calculate delivery routes based on a matrix of times and/or distances between all delivery locations and depots. This matrix will have been derived from a digitised road network containing a series of nodes (points on a map) and links (roads connecting those points). The nodes would correspond to some location on the road network such as a motorway exit, junction, roundabout, traffic lights, or a change in road category. The links would contain information about the road between the nodes. Typically this would be a distance and a road category against which a constant average speed would be applied in order to calculate the time to drive that distance. The times and distances for each link would be applied to a shortest path algorithm, to produce a matrix of the quickest or shortest routes between locations. Most VRS packages allow for a speed reduction, as a percentage of the standard speeds, at certain times of the day thereby allowing for rush hour congestion. Speed reductions

can also be applied by area, such as town centres. Despite this, the use of road categories means that all links in a road network having the same road category and distance will produce the same time to travel that distance. In reality, those same links will each have different combinations of congestion levels, and delays associated with road furniture such as traffic lights and roundabouts, and road topography and geometry such as inclines and bends. This will cause speed variations and therefore produce different times over links with the same road category and distance. In addition these speed variations resulting from acceleration and deceleration would cause fuel consumption to vary and therefore CO_2 emissions.

Once the matrix has been generated, the software would then apply one or more heuristic based techniques to this data, to sequence the deliveries, and route them in such a way as to minimise journey times or distances. A great deal of effort has been spent by academics and commercial enterprises on developing better heuristic techniques, but all the solutions produced are totally dependent on the accuracy of the initial matrix of times or distances. If this is inaccurate, then the final solution of routes and drop sequences could well be inaccurate.

With environmental issues assuming greater importance, it is desirable that VRP software consider methods that improve the accuracy of road speeds and incorporate speed variability as a factor, which will enable matrices to be produced to permit the construction of better routes in both time and fuel efficiency, so that these packages can be used to evaluate the environmental impact.

1.2   Aims of the Research

Currently VRP software produce routes based on minimisation criteria of time, distance or cost, but increasing worldwide concern about global warming from governments, and from customers, are forcing companies to consider the externalities of running a vehicle fleet. One of the main environmental aims of the UK government is to significantly reduce the level of CO_2. There is therefore a need to produce VRP software which takes into account these

emissions, as well as time, distance and cost, to help guide government policy and assist that aim.

The approach used in this research brings together elements from transportation planning and environmental modelling combined with logistics based VRP techniques. The aim has been to develop a computer based model that uses a digitised road network to allocate deliveries to routes and calculates the overall amount of CO_2 emitted from the road journeys, as well as time and distance, for minimisation criteria of time, distance and CO_2. Thus the model will estimate CO_2 emissions whether the routes are calculated based on minimum time or distance, or the CO_2 emission itself.

The CO_2 emissions can only be estimated because establishing this pollutant from individual vehicles is complex. It relies on an estimation of a vehicle's fuel consumption which is a function of many parameters, including speed and acceleration. Speed, again, is a function of many parameters, including the volume of traffic on the road. Once a realistic speed has been established, it would then be possible to reflect the acceleration and deceleration of vehicles by applying a level of variability to the speed. This enables a vehicle's fuel consumption to be estimated more accurately, and hence CO_2 emissions.

It has not been the intention of this research to create a new heuristic for vehicle routing, but to understand and incorporate the relationships between speed and fuel consumption, and to adapt the heuristic, to allow for the calculation and minimisation of CO_2 emissions. A requirement of the model is to produce a more appropriate representation of speed so that a more realistic estimate of fuel consumption, and therefore CO_2 emissions can be calculated.

In order to develop this model it is necessary to have a digitised road network. Commercial VRS suppliers typically purchase this data from companies such as Navtech or AND Data. The network used for this research has been obtained from Surrey County Council who use this data in the Surrey area as part of their transportation planning process. Although it only covers a limited area, it contains the key parameters necessary for the fulfilment of this

research. Each of the links in the data contain characteristics which will allow the calculation of speed. Since CO_2 is directly related to the fuel consumed, and will vary according to a vehicles speed, a method must be used that links fuel consumption with speed, acceleration and deceleration, so that an estimate of CO_2 can be produced for each link in the road network. To ensure the chosen minimisation criterion is fulfilled, a shortest path algorithm must then be used on the road network data to produce the necessary matrices, so that a VRP heuristic could allocate deliveries in the most appropriate way.

The context of this thesis involves the use of a set of delivery data for a home delivery operation in Surrey, but the overall findings will be generalisable to any form of vehicle routing.

The model could be used to examine a number of strategies such as comparing the CO_2 emission results produced when routes are created based on minimised time and by minimised CO_2 emissions, and to establish whether there is any environmental benefit. Further strategies could then consider the impact of increasing congestion, and to examine how different parametric settings affect the choice of roads used, when calculating the routes.

The overall aim of this research is therefore to develop a model for measuring the emissions of CO_2 and to use the model to examine a number of delivery strategies to assess how CO_2 emissions vary. The aim is not to produce new mathematical theories, but to produce an innovative basis for routing which will provide new information and knowledge about how emissions vary for different minimisation and congestion criteria.

1.3   Objectives and Contribution

The objective of this research is to identify what methods should be used to estimate CO_2 emissions when planning vehicle routes and to incorporate these methods into a computer based model, so that it can be used to assess how routes and emission values change when different minimisation criteria are applied.

The model will be run to establish a base case against which alternative strategies can be compared. A series of model runs will then be undertaken varying the minimisation criteria and the results observed and compared with the base case.

With the DfT expecting a 30% increase in traffic levels over a 2000 base by 2015 (DfT, 2004a), a series of runs will identify the impact of congestion on the various strategies. A further objective is therefore to assess how increasing levels of traffic volume impact on the results obtained from the base year strategies.

This thesis provides an academic contribution because a model is created which combines elements from transportation planning in the form of speed flow methodology, and elements from vehicle emission models in the form of driving cycles and fuel consumption formulae, with a VRP model which is grounded in the field of logistics. A further academic contribution is an improvement in the way speed is represented within the VRP model. A practical contribution is also provided in that the model techniques can be used by operators and government in the ongoing policy debate on CO_2 emissions. Indeed, the model was recently used as part of a project which examined the opportunities for reducing the external costs of food distribution in the UK (DEFRA, 2007a).

There is a vast amount of research investigating the various types of algorithm to solve the VRP, but relatively little research examining the issues of the road network which is an input to these algorithms. In this research the issue of which algorithm to use for the VRP is of minor importance since the significant academic contribution is the method of adapting and presenting the road network into the VRP.

The techniques used in this research adopts a more detailed approach than other research and is therefore an academic contribution in terms of the novel methodological process of combining aspects of the three hitherto discrete

areas of logistics and transportation planning with an emissions model, to produce a greater accuracy in estimating speed and CO_2 emissions.

Papers addressing the specific topic of freight transport routing and the consequent environmental implications have been quantitatively based but have tended to be on a micro scale focussing only on local operations, and using VRP software to assess mileage differences for various strategies which are then converted into an approximate environmental impact (Cairns, 1999), (Punakivi & Holmstrom, 2000). They do not use the VRP software for creating routes which minimise CO_2 emissions. Measuring CO_2 emissions is complex and simplistic methods such as these are inaccurate (van Woensel et al, 2001; Palmer, 2005). The technique proposed in this thesis improves the method of estimating CO_2 and therefore provides a contribution to commercial operations particularly, as seems likely, CO_2 will become a taxable commodity and the cost of CO_2 emissions will be internalised.

The method proposed is also uniquely able to assess the impact of traffic congestion by increasing traffic volumes on each of the links in the road network, and using speed flow formula for the appropriate road categories, in order to predict a reduced speed. This will have a direct impact on fuel consumption and therefore CO_2 emissions.

It is also a contribution to practitioners and government in that the use of the model will help companies achieve a more sustainable logistics operation and also assist government targets for a reduction in CO_2 emissions, as well as practical benefits by being able to use the model for public body policy-making purposes.

The desire by the government, and research bodies such as Engineering and Physical Sciences Research Council (EPSRC), to evaluate and reduce CO_2 is evident by the numerous research studies being commissioned into sustainable distribution (EPSRC, 2006; DEFRA, 2007a). The relevant governmental environment departments, at national and regional level, would be able to make use of this model to provide an alternative source of

information about the impact of freight vehicles on CO_2, and so be better able to gauge compliance with their targets.

It could be argued that companies are not altruistic and would therefore not adopt the methodology proposed in this research. However, many companies are using their environmental credentials to competitive advantage with a number aiming to be carbon neutral, in that they have identified and offset their carbon emissions through the purchase of equipment and activities, for use in the third world, or the purchase of carbon credits. (Carbon Neutral Co., 2006). Also, although carbon trading is currently limited to companies who are high emitters of CO_2 and does not cover transport, CO_2 emissions from vehicles may well be included in the future, and the approach detailed in this research would be suitable for minimising these emissions. CO_2 from road based freight transport has already been costed at €43 billion per year in 17 EU countries (INFRAS, 2004) and legislation may be introduced in the future requiring companies to value emissions in their accounts.

CO_2 emissions are therefore of concern to the operator of the trucks, but the method used in this research can also be used as a policy instrument for decision makers in the government who might be concerned about estimating CO_2 in relation to highway design and use.

The integrity of the modelling process is as important as the results themselves. The modelling methodology in this research will use a static, deterministic, heuristic based approach which can be replicated and applied by future researchers to further explore the issue and have the opportunity to update the results based on alternative, and potentially improved, data.

1.4   Philosophical Basis

The approach being adopted for this research is based on a positivist epistemology. The various relevant studies undertaken in the area of this research, as discussed in the literature section, are all quantitatively based and follow a similar epistemology.

This research is based on the ontological premise that "the world is real and knowable" (MacMillan, 1989). Given a 'real-life' research problem, further knowledge can only be obtained by taking a pragmatic, empirical approach. There is the assumption of an objective truth in the positivist paradigm which can be established through an empirical scientific approach, The mathematical logician, Harry Scheffer, argued that only in strictly deductive fields like logic, was progress of a scientific sort possible, and that this could only be derived from a logical positivist approach (Ignatieff, 1998)

A computer based model to route deliveries, whilst minimising CO_2 emissions, has been developed as part of this research. A model can be explained as being a simplified representation of a complex real world situation. By more simply representing reality, a complex issue can be more easily understood. Quantitative models seek to reproduce the real world situation and its behaviour by means of mathematical equations, based on certain assumptions. The robustness of conclusions derived from the model depends on the relationships built into the model and the way they react with each other. The quote at the beginning of this thesis is relevant in that it is important to identify the essential factors that should be incorporated into the model but, since it is an abstraction of reality, some balance must be made between the degree of model development and the complexity of representation required. Inevitably, some factors will be retained as constants within the model and some inappropriate factors will be ignored. Every effort will be made to ensure all factors considered do not introduce bias into the solutions. A model is always based on a series of assumptions and relies on the fact that there is a logical system of causes and effects, within the real world activity being examined, and that this can be identified, measured and represented in the model, taking into account constraints that may be imposed on these effects.

The aim of developing the model is not to produce new mathematical theories, but to combine existing theories from VRP algorithms with environmental and transportation planning elements in a unique way, to produce new information and knowledge about how emissions vary for different minimisation criteria.

Following an extensive literature review of similar studies and the methods employed, a deterministic, heuristic based vehicle routing model has been adapted to meet the aims and objectives of this research, and a set of delivery data used to answer the research questions.

1.5   Summary

This thesis is set out in six chapters. This chapter has introduced a range of related subject matter and highlighted the issues associated with CO_2 emissions, and problems and deficiencies in the methods used to examine this. The aim of this research is to develop a model capable of evaluating CO_2 emissions in a comprehensive way and a set of objectives has been specified in the way the model is to be developed and used. The next section examines some of the literature related to this research, including an assessment of modelling techniques that could be used, and a review of research from the areas of vehicle routing, transportation and vehicle emissions.

A key determinant in the type of model to be developed has been the level of granularity and a preliminary investigation of this is discussed in Chapter 3. This chapter also discusses the rationale behind the way the model has been designed, and the developmental concepts. The model functionality is described in Chapter 4. The detailed analysis undertaken using the model and the results, is discussed in Chapter 5, and conclusions are drawn in the final Chapter 6.

2 Literature Review

The aim of the research which underpins this thesis is to develop a computer based vehicle routing model which not only calculates time and distance, as in conventional VRP software, but also estimates the amount of CO_2 produced for the calculated routes. These values will be generated for three minimisation criteria of time, distance and CO_2. In order to estimate CO_2, the relationships between fuel consumption, vehicle and topological road characteristics, volume of traffic, speed and acceleration must be understood. This literature review examines the extensive research that has been undertaken in the three areas of vehicle routing and scheduling heuristics, transportation planning in terms of modelling traffic flows, and vehicle emissions, and considers the methodologies and outcomes that could be used in the model development and strategy analysis. This chapter starts with an assessment of what is meant by modelling, how it is used, and what techniques are available for possible use in the development of the model required for this research. An assessment is made of various techniques used in vehicle routing and scheduling software, and the related areas of transportation and vehicle emissions modelling. Research relating to possible methods for assessing fuel consumption and measuring speed are also considered.

2.1 Modelling

The complexity of the calculations required for this research means that some form of modelling is the only feasible option. A computer based model can be defined as "an attempt to replicate a simplified representation of a part of the real world – the system of interest – and its behaviour, by means of mathematical equations based on certain theoretical statements about it" (Ortuzar and Willumsen, 1998). These mathematical equations are in the form of algorithms which emulate a real world situation, such as that of operating delivery networks, reflecting the movement of vehicles along a road, or estimating vehicle emissions.

Vehicle routing and scheduling software generally use heuristic techniques but the purpose of this section is to consider whether alternative modelling methods may be more appropriate for this research. Many different modelling techniques exist and it can be difficult to compare the various model outputs as they tend to be developed from differing starting perspectives, goals and assumptions. According to Waller, quoted in Guedes (1994), "the selection of a modelling technique (simulation, optimisation, heuristics) for decision support in logistics strategy planning requires an analysis of the trade offs between the degree of model optimisation (as in model development) and the complexity of representation required". The suitability of modelling as a tool and of simulation, optimisation and heuristic modelling methods in the context of this research is examined in the next section. This is followed by an assessment of the way modelling has been used in the fields related to this research.

2.1.1 Modelling as a Management Tool

Models have been used extensively in the physical, life and social sciences, with considerable success (Maki and Thompson, 1973). They originated from the scientific and mathematical disciplines and have principally been used for prediction, proof and discovery. This research is primarily focussed on discovering new relationships and principles associated with carbon dioxide emissions from the movement of freight delivery vehicles.

The modelling of complex interactions has become an established method in many areas of management such as manufacturing, logistics and finance, and has been extended into areas involving social interactions using techniques such as multi agent modelling and cellular automata. A model is used to simplify complex situations and to analyse that real life phenomena in order to instigate change or to investigate specific issues. This method is useful in that it often saves implementing an action which may subsequently be found to be inappropriate, and hence, costly. Modelling an activity is very beneficial as an aid to decision making. From the authors experience, results from a model, as well as the development of the model itself, often stimulate discussion across

management functions. This may generate new ways of thinking and generate innovative opportunities which would not otherwise have been considered.

Modelling is both an art and a science. A model involves converting reality into a mathematical abstraction using a series of logical constructs, or algorithms. A set of input data is processed by the model to produce a resulting output. The construction of the model represents the science because of the quantitative tools being used, but it is also an art because of the qualitative experience and preferences used by the modeller in the construction process, and in the interpretation of the results. Modelling has therefore both quantitative and qualitative elements. Modelling is an art because it is important to have experience and intuition in the research area, so that the idealisations and approximations that have to be made can produce the desired outcome. Model results should not be automatically accepted without some form of validation. It is important that a modeller's knowledge of the real world operation is used to check that the answers produced by the model appear sensible (in other words it fits well in a qualitative way). Then it can be tuned by varying some of the parameter values to improve the quantitative fit of the model results to the data (Cross and Moscardini, 1985).

For model building to be successful there needs to be a clear understanding of the real world situation. According to Rivett (1994), that reality must be observable, measurable and systemic. In other words, the modeller must be able to understand the characteristics of the issues and to model this behaviour. Those characteristics will involve a series of causes and effects which interact with each other in a complex way and often simultaneously. In this research an example of this might be a vehicle travelling along a road. The characteristics of that road, together with the characteristics of the vehicle, will determine the speed of the vehicle, and this consumes fuel which causes an emission of CO_2.

In a decision making situation there will be variables which have to be estimated or manipulated. It is the task of the modeller to understand the real world issue and to form those variables into logical patterns of causes and

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effects. According to Drew (1968), when abstracting from reality it is essential that:

- No assumptions should be made before their effects are clearly defined
- No variables should be used in a model until each one is properly explained and its relationships to the other variables are set and understood

In the case of this research, inevitably, assumptions may have to be made because either:

- Certain data is not available, or
- The data is not in the form required and difficult to assess, or
- Only high level aggregate data is available

By comparing the same assumptions with different values, it is hoped that the effects can be understood. There are going to be some variables that have a direct impact on the system being modelled and others that have a peripheral impact. Producing a model specification may help define the boundaries of the system, and indicate the important flows and interactions between the variables. This method may also minimise any errors and deficiencies in the model.

There are imperfections when abstracting a real life activity. Crucially, the level of simplification and granularity is key to the model development process and its outcome. Drew (1968) stated that "simplification is desirable, but over simplification is fatal". This research has undergone an assessment of the level of granularity to be used in the model and this is discussed in chapter 3.

2.1.2 An Assessment of Modelling Techniques

This section examines the various modelling techniques that could be used in this research.

According to Rivett (1994), "There can be no such thing as an optimal model for any management situation. Since the problems as seen in each of our minds will be different, it follows that we have a significant freedom in the way in which we select the models which will represent the decision making situations".

This is echoed by Maki and Thompson (1973) who state that "the decision of which modelling approach to use is often down to the intuition of the model builder, and consists of the intuitive feelings about the assumptions and consequences of the model".

Rivett believes that there is also a tendency for proponents of a specific technique to expound the virtues of that technique without consideration of the problem to be examined.

There are several different modelling approaches that may be suitable for this research, and each method could contribute to the understanding of the issue in different ways.

The use of multi agent modelling, for example, relies on interaction between the agents over a simulated time period. An agent can be defined as a self contained computer program of mathematical instructions, or set of rules, which, when the model runs, causes actions and reactions in the agent depending on the simulated time or the activity of the other agents in the vicinity (Gilbert et al, 1999). According to Gilbert et al there isn't a formal definition of an agent but it is a term normally used to describe an entity that can control its own actions depending on the operating environment. In the context of this research an agent could be considered as a customer delivery with attributes such as the quantity to be delivered and a delivery time window. There is a form of communication between agents in multi agent

modelling so the location of the delivery, or agent, in relation to other agents in the area could be used to assess when a delivery vehicle arrives. However, this interaction element is not required in this research. In any case, social scientists have not been successful in accurately simulating social interaction, though important relationships and principles have been established from fairly simple models (Axelrod, 1997)

It would be possible to use simulation techniques for this research but because the main data are known, the complexity and variability associated with running a simulation model is unnecessary. Simulation techniques normally require dynamic sampling from a probability profile and simulating the outcome stochastically. If this research were to use simulation, then, for example, a probability profile of customer demand would need to be created. As detailed customer delivery data is available for use in this research a stochastic approach is unnecessary, though this method might be appropriate for sampling from a speed flow profile or generic driving cycle.

The use of dynamic simulation techniques would be appropriate for this research if there were a lack of detailed information about customer deliveries. Assumptions would need to be formulated in the absence of data or observations. These assumptions would be based on less evidence than deterministic modelling which depends on a clear understanding of the causes and effects. Simulations only produce approximate answers because of the stochastic elements within this type of model which are used to derive estimated characteristics. Statistics must then be used to interpret the output. Simulation techniques generally use random variables because cause and effect relationships are less clear and it requires a range of input values to assess potential outcomes. In this situation stochastic or random events would generate values to populate the appropriate variables. A simulation would use these transition values to move from one state to another in a manner depending on whether the model is a discrete events or continuous simulation. In the case of discrete events simulation, time moves forward when transition events occur. In the case of continuous simulation, time is advanced at constant intervals and at each advancement checks are made to

see if transition events should be activated (Taniguchi et al, 2001). For the purposes of this research, simulation would be inappropriate because much of the data is known. For instance, customer orders and delivery vehicle operating parameters are known, as are the delivery timings. What is unknown are the delivery sequences in the form of routes, and from this the driving speeds along the various road categories used on the routes.

Simulation is useful to replicate the dynamics of a network rather than producing a feasible solution (Moynihan et al, 1995). According to Guedes (1994), "simulation must be treated as a statistical experiment. The results obtained from running a simulation model are observations that are subject to statistical error". In addition, the very nature of a simulation model means that it is difficult to replicate a specific scenario to produce the same results. The same strategy would have to be run repeatedly and then all the results statistically analysed to assess an overall outcome for that scenario. As there will be a large number of different results possible for the same scenario, the usefulness of simulation to resolve this research problem is limited. Simulation is therefore more a method that aids understanding of a problem, rather than a technique for determining an optimal solution.

The alternative to simulation is to create a model using static techniques such as optimisation or heuristics, as discussed in the following section.

2.2   Vehicle Routing and Scheduling Techniques

Within logistics, vehicle routing and scheduling (VRS) packages are used extensively to optimise fleets in terms of time utilisation, distance travelled, cost or vehicle fill, and these models use a detailed road network to perform this optimisation. VRS software consists of two elements, one to allocate deliveries to routes referred to as VRP and the other to allocate vehicles to those routes referred to as VSP.

The VRP (vehicle routing problem) is a complex mathematical problem and it is solved using a technique called the Travelling Salesman Problem. This is

defined as identifying a route starting at a point, visiting a number of other defined and separate nodes once only, in a sequence which minimises some criteria such as time or distance, before returning to the starting point. There is the added complexity to the VRP used in this research, in that the locations visited (i.e. customers) have delivery time windows which must be met. A range of exact, heuristic and metaheuristic algorithms can be used to solve the VRP. Exact methods which are based on linear programming techniques can produce an optimum solution but for a limited number of deliveries. If a computer with a processing power of 10^9 operations/second were used on 10, 15, 18 and 20 customers, then the computer would take less than 1 second, 21 seconds, 74 days and 77 years respectively, to solve the problem optimally (Gold et al, 2005; Taniguchi et al, 2001). Thus the time required to solve the problem increases exponentially with the number of locations, and there are no procedures that can determine the optimum solution in a reasonable time. The VRP is therefore classified as NP-hard and heuristic techniques are typically used, but this means that the routes produced are not necessarily optimal.

There is a vast amount of academic literature covering VRP, and nearly all of them focus on trying to improve the type of heuristic used to produce an optimum result. Solomon et al (1988) set the standard with six test problems applied to a heuristic that produced a set of routes for 100 customers with identical Euclidian times and distances. Subsequent academic research has tended to use these same Solomon test problems and to benchmark the results produced against Solomon's results.

A number of variants to the VRP heuristics have been developed to cope with operational requirements such as limitations on the capacity of a vehicle (CVRP), ability to handle backhauls (VRPB), pickup and delivery (VRPPD), delivery time windows (VRPTW), etc. (Desrochers et al, 1990).

The classical heuristics which were developed 20 or 30 years ago such as the Clarke & Wright savings algorithm, the sweep algorithm, or the sequential insertion technique, are flexible enough such that they can be adapted to

include the various real life constraints such as pickup and delivery, time windows, etc. which means they are often used in commercial software packages. The main drawback with these classical techniques is that they often find suboptimal solutions by getting trapped in local minima. To overcome this problem, academic approaches have focussed on metaheuristic techniques such as tabu search, simulated annealing and genetic algorithms, and some of these have started to appear in commercial packages (Slater, 2006). These metaheuristic techniques use high level algorithmic approaches to search for feasible solutions.

Part of the model developed for this research uses a VRP variant in which deliveries have specified time windows, with the notation VRPTW, using heuristics provided by Braysy et al (2004). This VRPTW software was originally developed with the premise of creating vehicle routes which minimise the distance travelled. It uses a range of heuristic methods to create the routes, starting with a construction heuristic based on a variation of the Clarke and Wright Savings algorithm (Lui and Shen, 1999). Improvements to this initial construction are attempted using the cross exchange heuristic developed by Taillard (1997) which tries to improve the solution by swapping individual deliveries between neighbouring routes, and the I-opt technique developed by Or (1997) which also tries to improve the solution by swapping consecutive groups of deliveries between neighbouring routes, and the number of deliveries in the group is reflected by the value of I. Thus a group of two deliveries would mean 2-opt, a group of 3 deliveries would mean 3-opt, etc.

CO_2 can be calculated from this software, and also any of the other VRP variants, by applying an average emission value per kilometre or mile, but these have been shown to be inaccurate (Van Woensel et al, 2001). However, there is a need to calculate vehicle routes which minimise CO_2, not just the ability to calculate the emission for routes minimised by time or distance.

It is the links between the nodes of a digitised road network that enable a VRP to produce routes with the specified minimisation criteria. With typical

parameters of distance and road category for each link, and an average speed for each road category, a shortest path algorithm is used to produce a matrix of distances and times between all delivery locations and the starting depot location (Slater, 2006). If an estimate of CO_2 emissions could be added to each link it would be possible to use a shortest path algorithm to produce a matrix of CO_2 which could be used to calculate routes. It is therefore necessary to understand the relationships between fuel consumption, speed, acceleration and traffic volume along a length of road (link) in order to obtain a good estimate of CO_2 emissions.

2.3   Fuel Consumption and Emissions Modelling

Fuel consumption and emissions models have been used extensively in general traffic management and traffic performance measurement, but they have not been used in conjunction with any logistics related applications such as vehicle routing.

There are many models that examine the broader environmental impacts of vehicle use. Some are grounded in the discipline of geography using geographic information systems (GIS) based techniques, involving spatial data analysis to display information such as roadside emissions. In MacMillan (1989) Goodchild is quoted as saying "GIS use probably characterises the majority of efforts in environmental simulation modelling", and MacMillan himself advocates using GIS to build models, which reflect Rivett's comment about proponents of a technique expounding its virtues (Rivett, 1994)

Sharma and Khare (2001) undertook a detailed review of many different types of models that have been developed to examine the pollutant levels from vehicle exhausts. They concluded that most used analytical modelling techniques such as deterministic mathematical models, numerical models and statistical models. In these studies, emissions tended to be predicted at the aggregate level for all traffic and were not generally broken down into different vehicle categories as is required for this research. In those studies which did categorise vehicles, further assumptions are made about the type of vehicle and fuel used based on national statistics.

Studies have been undertaken that rely on emission measurements within tunnels, sampling from roadside points or using across road remote sensing (Marsden et al, 2001). They have investigated the relationships between emissions and traffic flow variables, sometimes including meteorological conditions, at various roadside locations, for specific purposes such as the effects of new roads and bridges (Highways Agency, 2003). The methodology used in these studies cannot be used in this research because of the need for modelling the emissions of individual vehicles. Some studies have used instrumented vehicles (dynamometer testing) to measure individual vehicle emissions (Washburn et al, 2001). This method uses typical driving cycles along defined routes under fixed conditions. This does not reflect the reality in which vehicles are used since not only are new or well tuned vehicles used for the tests, but the tests themselves do not mimic driving styles, a factor which has been shown to produce significant differences in emissions for exactly the same routes and conditions (Holmen and Niemeier, 1998; Pelkmans and Debal, 2006).

To illustrate the problem of estimating individual vehicle emissions required for the model used in this research, emissions vary with many factors such as the age of a vehicle, the engine size, speed, type of fuel, and the weight of the vehicle. They are also dependent on the engines state of maintenance and the way in which it is driven (Taniguchi, 2001), and the type of roads on which the vehicle is driven. When setting off from a cold start, emissions of carbon dioxide are 10% higher than average, until the engine has reached a certain temperature at which point emissions tend to settle into a lower level. According to the Highways Agency (2003), the highest emissions of carbon dioxide occur in congested, slow moving traffic.

Although there is a current legal requirement for new cars to state their carbon dioxide emission levels as well as fuel consumption, this does not apply to freight vehicles. The Vehicle Certification Agency (2002) produce a table of CO_2 emissions for cars but these are typical average levels shown as grams per kilometre. However, use of average levels can be misleading because a vehicle's speed is constantly changing which produces varying levels of CO_2.

Because of the complexity associated with accurately producing definitive information about specific vehicle emissions, a study was undertaken to capture individual vehicle/driver performance and emissions data using in-vehicle sensors (VPEMS, 2004). Although this project was based on collecting real time data from two cars fitted with various sensors, rather than freight delivery vehicles, the outcome showed significant variations between on road reality and the values predicted by using artificial driving cycles such as test bed measurements. These driving cycles consist of various phases of urban, extra-urban and suburban driving and are often criticised for their unreliable estimates of fuel consumption, and hence emissions, with indications that CO_2 emissions could be 15-20% higher in real traffic conditions. (Pelkmans and Debal, 2006; Green et al, 2004; Hickman, 1999).

2.3.1 Estimation of Fuel Consumption and CO_2

Unlike other vehicle emissions, CO_2 is directly proportional to fuel consumption, (Hutton, 2002; Kent et al, 1979; Romilly, 1999; Schingh et al, 2000). Emissions from diesel engines vary according to the type and density of diesel used. Standard diesel emits 2.82kg CO_2 /litre (Freight Transport Association quoted in J. Sainsbury plc, 2002) and ultra low sulphur diesel emits 2.57kg CO_2 /litre (Greenergy quoted in J. Sainsbury plc, 2002). Generally, conversion factors from the DETR Environment Reporting Guidelines 1999 specify diesel (including ultra low sulphur) as emitting 2.68kg CO_2 /litre (J. Sainsbury plc, 2002). This value is very comparable with that specified by the Australian Greenhouse Office (2003) who state that approximately 2.7 kgs of CO_2 are emitted per litre of diesel fuel.

Studies of fuel consumption and emissions calculations have tended to focus on cars and used multiple regression techniques on test bed or real driving data to produce predicted values in the various models that have been created. The predictions are usually based on hot stabilised engine conditions and do not consider the effect of cold vehicle starts. The outcomes from these studies are valid, but are limited to the driving cycles undertaken and the type of vehicle used. Many of the studies have taken place in the USA and reflect the type of roads, driving conditions and vehicles that are commonplace in

that country (Ahn, 2002). In Australia, similar approaches have been adopted with studies examining the fuel consumption and emissions of vehicles in urban areas of Sydney and Melbourne (Kent et al, 1979; Bowyer et al, 1985; Biggs et al, 1986; Akcelik, 1982). In the UK various formulae have been derived from studies to calculate fuel consumption and CO_2 for a range of cars and goods vehicles (Everall, 1968; Department for Transport, 2004; Highways Agency, 2003).

Fuel consumption and emissions are complex to estimate and are a function of several variables. Those elements that influence fuel consumption are:

- Travel related factors such as speed, acceleration rates, driving style, gear changes
- Vehicle characteristics such as engine size, fuel type, payload and age
- Road geometry and furniture such as bends, gradients, roundabouts and traffic lights
- Meteorological conditions such as ambient temperature, wind speed and direction

Fuel consumption is also linked to the energy efficiency and drag forces required to overcome the aerodynamic and rolling resistance of a vehicle. One study developed formulae which incorporate aerodynamics, the rolling resistance of tyres, gear ratios, and power to weight ratios in the calculation of fuel consumption (Renouf, 1981). Other formulae derived by Everall, Department for Transport (DfT) and Akcelik, have analysed and incorporated these as constant values which vary according to the type of vehicle, with the ability to estimate fuel consumption and CO_2 for the average speed on a link. Average speed over a link distance is the primary variable in these calculations. The Highways Agency (2003) formula estimates CO_2 emissions directly from an average link speed, with factors for specific vehicle types as constants. It was developed by the Transport Research Laboratory (TRL) for the Highways Agency using a polynomial statistical model using average speeds and covering a representative range of driving cycles. The values

derived from this model are incorporated into the National Atmospheric Emissions Inventory.

According to Biggs et al (1986) there are four levels of detail that can be used when estimating fuel consumption:

- An instantaneous analysis which requires second by second data on speed, acceleration levels and the various forces on the vehicle
- An elemental analysis which requires data on cruise speed, number of stops and stop time, and initial and final speeds in each acceleration and deceleration, over a link distance.
- A running speed analysis which is suitable for estimating fuel consumption for an entire trip greater than 1km rather than short road sections, and requires data on travel time, distance and stopped time.
- An average travel speed analysis which can be used for an overall estimate of fuel consumption over a large urban area, since it is only accurate for average travel speeds less than 50 km/hr.

The last three options require an average speed over a distance, but the first option requires a speed profile of a journey, or driving cycle, to reflect transient changes in speed.

Ahn (1998) argues that the use of average link speeds alone cannot fully represent the transient changes of speed and acceleration, or systematically varying speed, along a link, for an accurate assessment of fuel consumption to be made. A preliminary investigation to establish the level of detail at which the model should be developed, as discussed in chapter 3, has shown that in the calculation of fuel consumption there is a difference of up to 40% depending on whether a constant speed or variable speed is used on a link. This is supported by Woensel et al (2001) when they assessed the differences in CO_2 emissions between using constant speeds and flow dependent speeds. Based on a survey of cars counted over a 3.5 km stretch of a motorway in Belgium, they showed that flow dependent emissions of CO_2 from a diesel engine are, on average, 11% higher than CO_2 emissions

calculated using a constant speed. This peaked at 40% higher during the congested rush hour period between 7.30am and 9.30am. In real driving conditions, it is impossible to maintain a constant speed, because of road, vehicle and travel factors, which means that fuel consumption is higher than constant speed models (Akcelik, 1982).

The use of driving cycles gives a better indication of fuel consumption because it reflects the changing power demand on the engine. The driving cycles can be created from test bed measurements using a chassis dynamometer, or by instrumenting vehicles which measure real life driving patterns over different routes. This latter option is expensive to perform because of the large number of vehicle tests required to obtain representative results, but better reflects the transient and much wider ranges of speeds and accelerations. Models that use these driving cycles to predict fuel consumption or emissions are referred to as instantaneous because they measure these parameters at a point in time.

There are a number of instantaneous models that have been developed. A European Union (EU) sponsored study called MEET (**M**ethodologies for **E**stimating air pollutant **E**missions from **T**ransport) identified data sources and used a model called COPERTII for estimating emissions from road transport (Hickman, 1999). This study subsequently spawned an updated version of the model referred to as COPERTIII. However, there was a paucity of data on large freight and light commercial vehicles in the MEET study, and it also used a limited range of vehicle classes. A second study, ARTEMIS (Sturm et al, 2005), was subsequently commissioned by the EU which pooled data from a wide range of emission related projects from different countries, and developed two models:

- PHEM (**P**assenger car and **H**eavy duty vehicle **E**mission **M**odel) which simulated emissions from individual vehicles, and
- NEMO (**N**etwork **E**mission **Mo**del) which was a meso-scale model for estimating emissions on road networks

Another instantaneous model VeTESS (**Ve**hicle **T**ransient **E**missions **S**imulation **S**oftware) was developed out of the EU funded project DECADE (2003).

All of these studies acquired and used real life transient driving cycle data and involved models which calculated dynamic emissions and fuel consumption for individual vehicles over a given driving cycle on a second by second basis, thereby achieving high levels of accuracy.

The speed and acceleration data from the driving cycles input to these models produced a scatter of fuel consumption and CO_2 emissions for a given speed. The reason for this is due to differences in the operation of the same vehicle, over different driving cycles, which can vary with driving style, weather conditions, particularly wind direction, gear changes and the road conditions. An example is shown in the graph below:
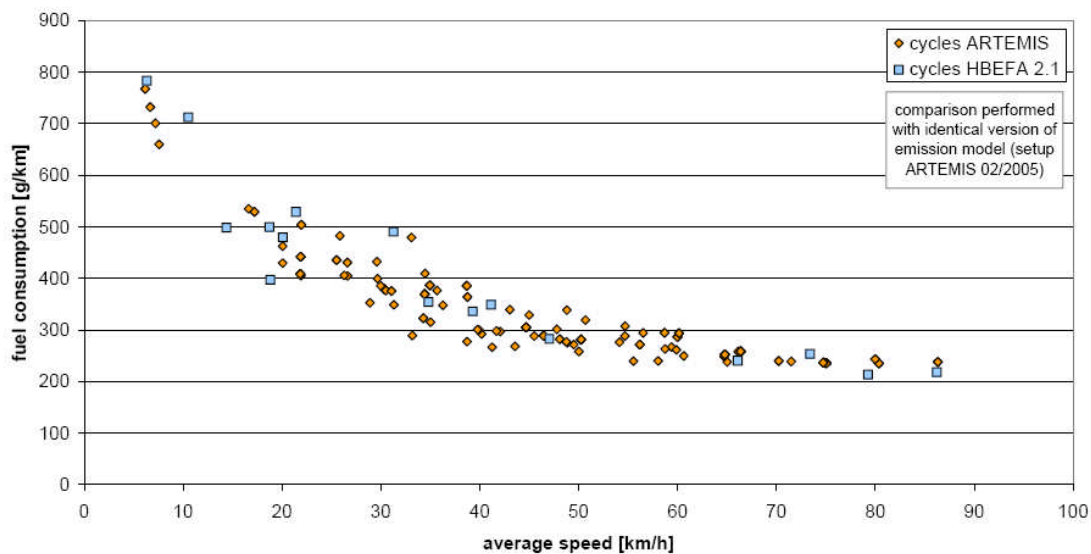
Figure 1: *Example of scatter effect for fuel consumption against speed (Sturm & Hausberger, 2005)*

From this scatter a regression analysis produces a statistical curve fit so that CO_2 emissions or fuel consumption can be obtained from an average speed which is calculated by combining measurements from different driving cycles. The shape of the speed-fuel consumption, or speed-CO_2, curve is well established (Hickman, 1999) and is shown in the graph below.
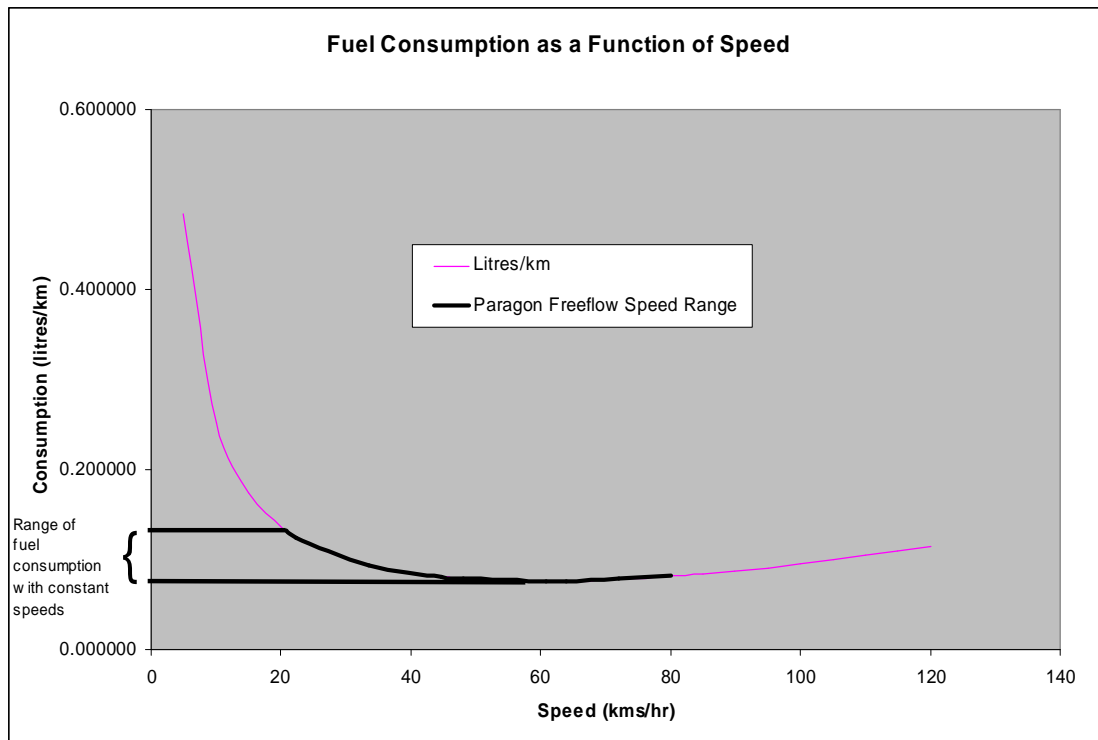
Figure 2: *Typical fuel consumption profile against speed showing range of values for constant speeds between 20 km/hr and 80 km/hr*

This curve has been derived from an elemental formula which approximates fuel consumption by averaging speeds over different driving cycles (Akcelik, 1982). The formula is referred to as elemental because it breaks down a driving cycle into the basic elements of idling, acceleration, deceleration and cruise speeds. The curve shows high fuel consumption at slow average speeds because of stops, starts and delays, higher fuel consumption at high speed levels due to the extra power demand on the engines, and lower fuel consumption in the middle range of speeds. The range of constant speeds used in vehicle routing and scheduling software is often user input, but would typically be in the range of 12 to 80 km/hr, depending on the road category, area and time of day. To illustrate how the use of an average speed to estimate fuel consumption from this curve can be erroneous, if a vehicle has an average speed of 20km/hr on a particular road, this curve would indicate a fuel consumption of approximately 0.1 litres per km and from this, given a road length, the total fuel consumed could be calculated. However, realistically, to achieve that average speed along the length of a road could mean the vehicle travels at a wide range of speeds, maybe between 0 and 40 km/hr, depending on the road topography and geometry. Thus an average

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speed could be achieved in many different ways because it can be made up of many seconds of different sets of fluctuating speeds which produce different values of fuel consumption, as shown in the graph below:
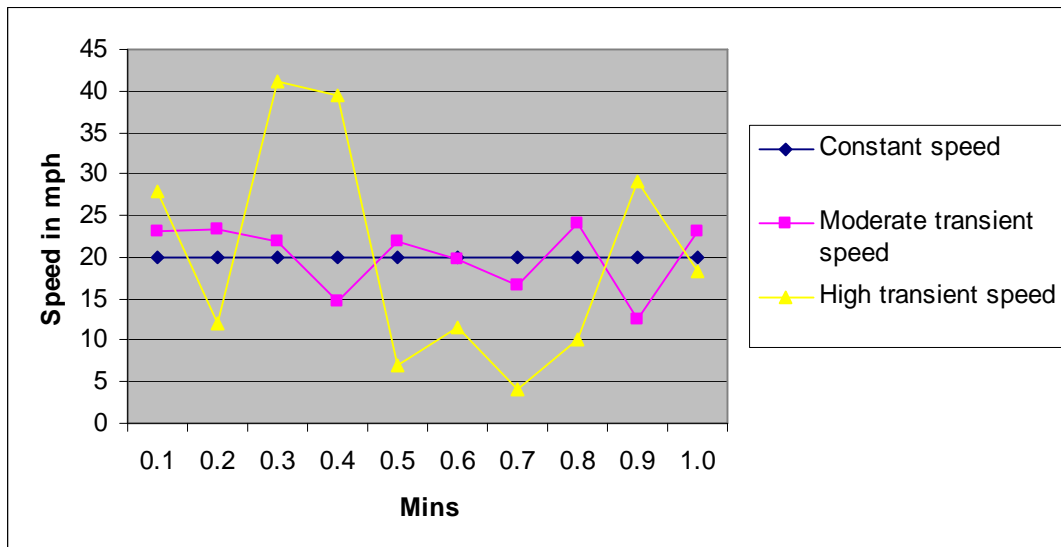
Figure 3: *An example of three speed variations each with an average speed of 20km/hr (Source: Author)*

The use of average speeds therefore has the potential to produce less accurate values than the use of an instantaneous model that uses second by second driving cycles to estimate fuel consumption and CO_2 emissions.

There are two fuel consumption formulae that have been selected for use in the model developed for this research. The formulae for each of these options include parameters that can be modified to reflect different vehicles in different countries. They are also applicable to freight delivery vehicles providing the energy efficiency, drag and mass parameters are adjusted to reflect the specific vehicle being analysed.

Akcelik's (1982) elemental formula enables calculations to be made over a cycle of changing speeds and has been used in a number of emissions research papers (Hutton, 2002; Affum et al, 2003; Mengguzzer, 1995; Haris et al, 1994). The formula, adapted by Kirby (2006), is based on three speed sensitive parameters and is as follows:

$$F = 3.6 \left(k_1 \left(1 + v3 / 2\, v_m^3 \right) + k_2 v \right) / v \qquad [1]$$

where: F is the fuel consumption at a chosen constant
speed v (litres /km)
v is the chosen constant speed (km / hour)
v_m is the speed at which fuel consumption is optimal
(km / hour)
$k1$ and $k2$ are constants defined as:

$$k_1 = v_m 3 \left(R_{90} - R_{120} \right) / (v_m^3 - 113400) \qquad [2]$$

$$k_2 = \left(14580\, R_{120} - 25920\, R_{90} + 4\, v_m^3\, R_{120} - 3\, v_m^3\, R_{90} \right) / \\ 36 \left(v_m^3 - 11340 \right) \qquad [3]$$

and where: $R90$ is the fuel consumption at a constant 90
km/hour (litres/100km)
$R120$ is the fuel consumption at a constant 120
km/hour (litres/100km)

The values expressed in constants k_1 and k_2 reflect the mass, drag and energy coefficients associated with a vehicles movement and were derived from regression analysis. Kirby adapted Akcelik's elemental model to estimate fuel used at a speed at a point in time.

Hutton (2002) examined different speed profiles in a built up area and a rural area, over a 100 second cycle and, using the elemental model, the results showed a variation of 400% between fuel consumption per km in the two environments. Typically, this is because obstructions to traffic flow occur more frequently in built up areas than in rural areas of the country. This reinforces the need to understand how fuel consumption varies with speed profiles on different types of road.

In contrast, the instantaneous model described in Bowyer el al (1985) has been derived to allow for a more exact analysis of fuel consumption by enabling vehicle characteristics to be included such as mass, energy efficiency parameters, drag force and fuel consumption components associated with aerodynamic and rolling resistances. It has been validated against measured data with a variability estimated to be less than 2% (Bowyer et al, 1985). This model is suitable for use in different countries and for different vehicles, and will provide greater accuracy than the elemental model

by having the ability to estimate fuel consumption on a second by second basis as a vehicle moves through different cruise and idle speeds, acceleration and deceleration levels, and taking into account gradients. The formula makes an assumption that acceleration increase and deceleration decrease levels change evenly within the one second time interval. The formula is expressed as follows:

$$F_t = \alpha + \beta_1 R_T v + [\ \beta_2 M a^2 v\ /\ 1000\ ] \qquad\qquad [4]$$

where F_t is the fuel consumption per unit time (mL/s)
α is the constant idle fuel rate (mL/s)
β_1 is the efficiency parameter which relates fuel consumed to the energy provided by the engine (mL/kJ)
β_2 is the efficiency parameter which relates fuel consumed during positive acceleration (mL/(kJ.m/s^2)
v is speed (m/s)
M is vehicle mass (kg)
a is instantaneous acceleration which has a negative value for slowing down (m/s^2)

and where R_T is the total tractive force and is defined as

$$R_T = b1 + b2\ v^2 + Ma\ /\ 1000 + 9.81M\ G\ /\ 100000 \qquad\qquad [5]$$

where $b1$ is the drag force value related to rolling resistance (Kn)
$b2$ is the drag force value related to aerodynamic resistance (Kn)
G is the percent grade which has a negative value for downhill

2.4   Transportation Models

Transportation models are used by traffic planners to assist them in making decisions about the flows of vehicles and to examine the impacts of changes in traffic volumes and road network characteristics. With a general increase in road traffic there are significant transport issues associated with congestion, accidents, noise and the environment. Transportation modelling provides traffic planners with a range of tools to examine these issues to ensure the correct remedial action is adopted. The key relevance of transportation models to this research is the way they handle speed within the models, and the literature review in this section contributes to the understanding of this aspect.

There are four distinct types of models that could be used by traffic planners which can be described as:-

- Static
- Junction
- Micro simulation
- Dynamic

Static assignment models such as Saturn, Vision, Omnitrans and Contram (Ortuzar and Willumsen,1998) describe a road network in a similar manner to a VRP with links and nodes, typically referred to as road junctions. The time taken to travel along a link depends on the type of road, the speed limit and the number of other vehicles on the road. The time taken to travel through a road junction depends on the type of junction, its layout, the number of vehicles using the junction and the turning movements of these vehicles. These models use an origin and destination trip matrix as the basis for examining flows of vehicles on the links of a road network. This is obtained by road surveys and statistical analysis to extrapolate the figures into a network wide matrix. Incorporated into these models are complex calculations involving the speed and flows along links, and delay stops, relative to capacity, at road junctions, roundabouts and traffic lights.

In the UK these calculations follow the guidelines specified in the Design Manual for Roads and Bridges (Highways Agency, 2003a). Vehicles are assigned to the road network using an equilibrium assignment technique such as the method of successive averages (Vliet and Hall, 2004). This means that every vehicle is taking the lowest "cost" route. The equilibrium assignment technique takes into account the time taken to travel along the links which rises as the number of vehicles using the road increases.

Junction models such as Arcady, Picady and Oscady (Ash and Hudson, 2004) simulate the flow of traffic through a specific junction, roundabout or set of traffic lights. The physical characteristics of the junction and turning movements are inputs to the model. Although speed is a parameter in these

models, they are used to show how queues build up and dissipate over a specified period of time.

Micro simulation models such as Paramics, Vissum and Aimsum (Barlow et al, 2007) are used to understand driver behaviour under changing situations. It is also used for traffic performance measurement where second by second modelling of vehicles is required which can help establish the reliability of journey times. The entire network is described by its physical characteristics and the software contains rules on driver behaviour. Individual vehicles are considered which interact with each other in terms of lane changing, acceleration and overtaking. Due to the complexity of these simulation models and the time taken to run, the area of examination is often limited to a region of a few square kilometres, or slightly longer corridor areas. These models also rely on a network of roads within the defined area, and the data applied to each road junction and link such as incline, speed limit, road width. The simulations often have a visual representation of the traffic flows on each of the roads in the network which is particularly useful for modelling traffic management where random or stochastic events are used to generate vehicle arrival, queuing and departure activities (Akcelik and Besley, 2001). The results can be used to evaluate the environmental and congestion implications of new or modified road junctions, bridges or roads. In these models road speeds are dependent on road conditions such as congestion, inclines, bends, roundabouts, traffic lights, and volume of traffic.

Dynamic modelling software such as Omnitrans, Dynamism and Dynaque (Ash and Hudson, 2004) are similar to static models but use smaller time slices. Route choices are still calculated using equilibrium assignment techniques but are recalculated more frequently than static models, say every five minutes rather in one hour intervals in static models. Instead of reporting average speeds and delays, dynamic models can show how traffic conditions vary within an hour.

2.4.1 Road Speeds and Speed Variability

Clearly road speeds are an important element of these transportation models and it is the use of speed flow formulae in the calculations that will form part of this research. A speed flow function estimates the speed of a vehicle depending on the volume of traffic on a road. The form of the speed flow relationship indicates that the speed of vehicles decreases as the flow, or volume of traffic, increases. There is a great deal of research covering this subject using various theoretical and empirical methods to obtain speeds from flow rates such as the Highways Agency (2003), Akcelik (2000), HCM, MTC, BPR and Davidson in Singh (1999). Davidson (1966, 1978) produced one of the first realistic formulas and set the standard against which improvements were attempted. Akcelik (2000) created a variation of Davidson's function which improved the intersection delay function and produced a better calibration. Singh argues that both theoretical and empirical calculations have drawbacks, so the main decision criteria as to which option to use in this research is the extent to which a particular formula has been used and the success in replicating actual speed from flows. All the formulae in these papers produce similar results at flows below a roads capacity. The main weakness of such formulae occurs in congested conditions where the flows exceed capacity. To this end, Singh (1999) analysed a wide range of speed curve formulae and concluded that "the Akcelik link congestion function has the added advantage of better simulating link travel times for oversaturated conditions". Also, "the Akcelik model appears to be theoretically more appealing … and the curve performs well" and it "provides more accurate speed estimates" under congested conditions. The Akcelik time dependent speed flow formula is as follows:

$$t = t_o + \{0.25T[(x-1) + \{(x-1)^2 + (8J_a x/QT)\}^{0.5}]\} \qquad [6]$$

where: t = average travel time per unit distance (hours/mile)
t_o = free-flow travel time per unit distance (hours/mile)
T = flow period, i.e., the time interval in hours, during which an average arrival (demand) flow rate, v, persists
Q = Capacity
x = the degree of saturation i.e., v/Q
J_a = the delay parameter

A comparison of the speed flow curves produced by four functions is shown in the graph below.
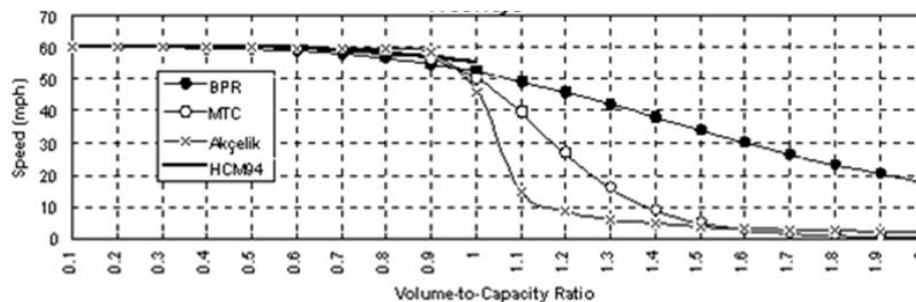
Figure 4: *Comparison of BPR, MTC, Akcelik and 1994 HCM speed flow functions for freeways in California (Source: Singh, 1999)*

Each of the formulae being analysed produces similar results until road capacity is reached but the results vary once the volume of traffic exceeds the capacity of the road. However, the basis for this comparison is an analysis of cars on roads in the USA. Clearly, this comparison may not be appropriate for use in a study requiring speed flow relationships for freight delivery vehicles on UK roads.

In the UK, nearly all transportation models, which have been designed for analysis of complex travel behaviour and the evaluation of traffic flow and control options, have the capability of using the COBA speed flow formulae (DfT, 2007). All the formulae have been derived from empirical measurement based on average journey speeds over a one hour period in fine conditions. As with the other speed flow methods, the COBA formulae are hypothetical in congested conditions. Using regression techniques the curves appear as a single line, but when plotted, the data from which the relationships are derived form 'clouds', even for free flowing motorways. This is because of the wide range of speeds and traffic conditions that change by the minute along a route (Gray, 2004). The speed prediction relationships in COBA are by road category, of which there are thirteen, and by two vehicle types, one classified as cars and light goods vehicles (LGV), the other as heavy goods vehicles (HGV). The various formulae for each category of road incorporate a wide range of parameters such as hilliness, bendiness, visibility, road width, side roads intersecting, percentage of route with frontage, as well as flows at

capacity and breakpoint (Highways Agency, 2003). These details far exceed any of the other non UK derived speed flow formulae.

The use of speed flow formulae will give an overall average speed for a road link but fuel consumption, and therefore CO_2 emissions, depends not just on speed, but also on acceleration and deceleration. Therefore it is important to understand the way speed varies as a vehicle travels along a road link.

As a vehicle moves along the length of a road, or link, speed varies systematically. The level of variability will depend on many factors such as volume of traffic, parked vehicles, road topography, the number of turnings off the link, etc. (Highways Agency, 2003a). The issue of speed variability on a link section of a digitised road network has highlighted potential deficiencies in the way VRS packages work. The outcome from a study (Palmer, 2005) showed that there are wide variances in the route times, fuel consumption and CO_2 emission results depending on the road categories and speed variability applied. It may be possible that by adding detailed speed related parameters to a typical digitised road network, a more accurate estimation of route times, fuel consumption and emissions can be calculated. Ratliff et al (1999) examined real time speed data from a number of delivery fleets operating in urban and suburban areas and concluded that constant speed, by class of road, as used by VRS software, is inaccurate over short distances.

Average fuel consumption of vehicles is provided by manufacturers from which it is possible to derive CO_2 emissions. However, for freight vehicles, this is based on engine test benches, or from a standard European test cycle using a chassis dynamometer, rather than real life driving cycles. These emission certification tests have been shown to differ significantly from real life driving conditions (Pelkmans and Debal, 2006).

A report produced by the Transport Research Laboratory (TRL) for the Department for Transport (DfT) examined vehicle emissions in six towns around the UK with the aim of identifying potential breaches in levels of air quality according to the Environment Act 1995 (Green et al, 2004). One of the

key objectives of this study was to produce generic driving cycles for use in emissions testing because of the problem with emission certification testing. The research paper states that using a test bench or chassis dynamometer is not representative of real urban driving conditions, and it argues that 'real world' driving cycles, or operational profiles, should be used. Using a data logger and GPS system, generic driving cycles classified as urban congested, urban non-congested and suburban, were developed for a range of vehicles including a LGV and a HGV, by travelling designated routes within the six towns. Forty driving cycles were measured in each area and graphs of second by second speeds were produced across these driving cycles with durations ranging from 900 to 1200 seconds. These show vehicles stopping and starting to varying degrees depending on the area and traffic conditions and are an ideal way of representing speed variability in a VRP model. The graph below illustrates the systematically varying speed that typically occurs in a non congested urban area.
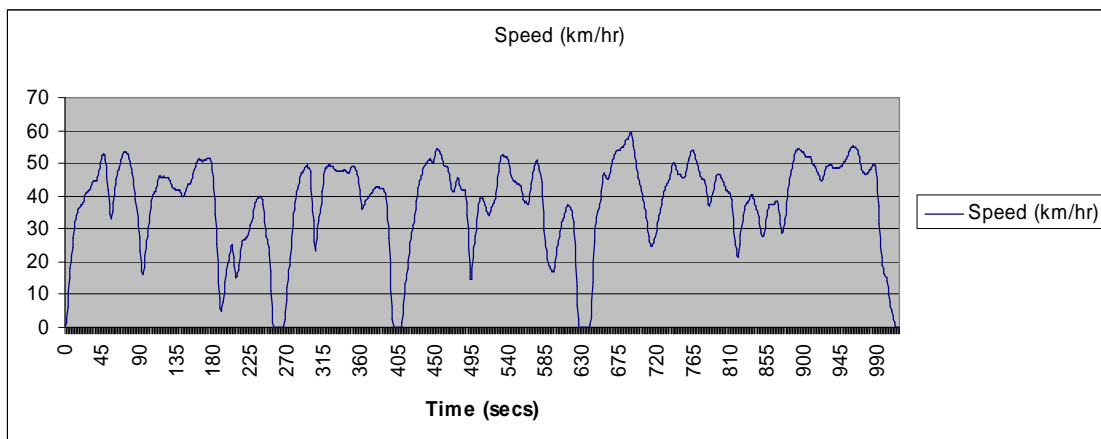
Figure 5: *Driving cycle for a non congested urban area (Source: Green et al, 2004)*

By way of an example, if a number of fuel consumption formulae were applied to the TRL data for non congested urban and suburban areas, the table below shows the differences in estimated fuel and CO_2 values that occur compared to the Bowyer instantaneous model

	Non congested urban area			Non congested suburban area		
Time (secs)	1016			881		
Average speed (km/hr)	37.726			36.019		
Kms Travelled	10.647			8.815		
	Litres fuel consumed	CO2 emitted (kgs)	% difference over inst model	Litres fuel consumed	CO2 emitted (kgs)	% difference over inst model
1). DfT TAG	1.2381	2.848	37%	1.0453	2.404	41%
2). Akcelik-elemental model	1.2521	2.880	38%	1.0959	2.521	48%
3). Everall	1.2710	2.923	41%	1.0706	2.462	45%
4). Akcelik-average travel speed model	1.2373	2.846	37%	1.0421	2.397	41%
5). Highways Agency		2.083	0%		1.767	4%
6). Bowyer-instantaneous	0.9045	2.080		0.7403	1.703	

Table 1: *Fuel consumption and CO2 emissions for various calculation methods (Source: Palmer, 2005)*

The first four methods all use the average speed of the driving cycle. Acceleration, stops and vehicle characteristics are all reflected by the use of various parameters within the formulae. The Highways Agency COBA option calculates the CO_2 emissions directly from the average speed and distance covered, again taking into account these parameters. The instantaneous model, however, estimates fuel consumed on a second by second basis and uses calculated acceleration or deceleration values at each point in time. Assuming that the instantaneous model is the most accurate, the table clearly shows that there is a difference of approximately 40% in the values calculated using a constant speed model. This concurs with earlier studies undertaken by Woensel (2001) and Palmer (2005). The Highways Agency option produces very similar results to the instantaneous model even though it is based on constant speed.

According to the Department for Transport, it is estimated that by 2015, the level of traffic on the road will increase by 30% over the levels at 2000 (DfT, 2004a). Congestion is occurring over longer periods of time and over a larger network of roads. Therefore, overall speeds are likely to be lower than present which may result in higher emissions as indicated by the graph in figure 2. The need to produce a better means of representing speed and the way it varies in order to produce a more accurate estimate of CO_2 emissions is therefore essential.

2.5   Vehicle Emissions Research using VRP Techniques

A number of studies related to this research have produced emission values using standard, or adapted, VRS software.

Studies by Cairns (1999) and Punakivi and Holmstrom (2000) have addressed the specific issue of the environmental implications of grocery home delivery by converting mileages output from commercial VRS software into emissions, but the robustness of this approach is open to question. They have both used quantitative techniques on a micro scale. One used a GIS package called Transcad to examine home deliveries from a single grocery store in Witney, Oxfordshire (Cairns, 1999), and the other used a VRS package called CAPS to examine grocery home deliveries in a suburb of Helsinki, also from a single store (Punakivi and Holmstrom, 2000). Both of these papers examined a range of home delivery methods and the environmental implications of each were indicated by assessing the mileage differences and converting these into emissions using average grams per km for the various vehicle pollutants. Both papers came to the same approximate conclusion regarding vehicle emissions from the various delivery methods considered. Another study by Ericsson (2006) used a planning tool from the GIS company ESRI, called Network Analysis, to find routes which minimise CO_2 emissions.

A study by Cairns (1999) examined whether any overall mileage savings occur as a result of grocery home delivery as opposed to private consumers driving themselves to retail stores. Her paper describes a hypothetical exercise to examine a home delivery service in the town of Witney, using a geographic information system called TransCAD. This software also generates minimum cost delivery routes using principles of the Clarke and Wright savings algorithm. She started with a quasi-hypothetical road network of 99 links and 20 demand points containing 200 households, and then developed a generalisable sequence of analytical expressions involving variables such as vehicle capacity, mileage by car and by delivery vehicle, customer demand, etc. and covering different home delivery scenarios. These algorithms were then tested against some real data taken from a survey of Witney household travel. This recorded the number of households doing their

main food shop in the town centre store of Waitrose. The results show a substantial reduction in mileage as a result of home delivery by the supermarket. This study omits a number of essential elements such as delivery time windows and variability in customer demand but more importantly, the environmental benefits are only stated in terms of mileage reduction rather than vehicle emissions.

Helsinki University of Technology have published many papers about logistics strategies for grocery home delivery as a result of their ECOMLOG research project. Financed by the National Technology Agency of Finland, this 3 year program was launched in April 1999 with the aim of studying e-grocery challenges. They produced a paper which looked at the environmental implications of grocery home delivery (Punakivi and Holmstrom, 2000). For this research they generated a database of customer demand for home delivery based on traditional grocery shopping POS information from five stores of a major Finnish grocery retailer. They selected 1450 customers who spent more than 25 Euros in a single shopping visit, and who lived in the metropolitan area of Helsinki. The analyses were undertaken using the CAPS RoutePro vehicle scheduling package.

Many of the parameters used in this research are however considerably different from those used by the UK grocery home delivery retailers. Therefore, the outcome from this study cannot be assumed to be relevant to the UK. However, the processes to arriving at a conclusion are consistent with Cairns' approach. They simulated various home delivery strategies to the selected customers from a single store location.

The results from this study concluded that a reduction of between 12% and 15% in mileage could be achieved if visits to stores were replaced by unattended home deliveries, and they cite studies by Cairns whose results also support that view. They then estimated the effect of this reduced mileage on vehicle emissions using average grams per kilometre, and found a considerable reduction in carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (Nox), but a doubling of particulates (TPM) as a result of using

diesel delivery vehicles as opposed to cars with catalytic converters, assumed as the mode of transport for the customers visiting the stores. The researchers do state that the results are a simplistic view of emissions.

It is not possible to minimise CO_2 emissions using the Cairns or Punakivi approach. They have both used VRS software which minimise either time or distance and then estimated CO_2 emissions based on distance travelled using an average value of CO_2 per km.

Unlike the previous two studies which used mileage savings as a proxy for emissions, Ericsson (2006) used a more detailed approach by considering 22 road types in the city of Lund, Sweden, to find the cleanest routes for vehicles. The research considered how driving patterns vary with road design, topography and traffic flow conditions. Although based on cars rather than freight vehicles, this study analysed 109 journeys using Network Analysis for shortest time, distance and lowest fuel consumption. This was based on Dijkstra's shortest path algorithm. The 22 road types were expanded to 61 by including peak and off peak flows. For each road type fuel consumption was estimated based on second by second speed profiles using the models VeTESS, and VETO, developed by the Swedish Road and Transport Research Institute. For this calculation it was necessary to know detailed link and junction information such as locations of traffic signals and traffic calming measures as well as flow data. The fuel consumption was averaged over the road link distance for each road class. The results showed that 50 journeys would benefit from a cleaner route with a total saving 8.2% in fuel consumption. The average fuel consumption saving for all 109 journeys was 4%. The study also showed that for 41 journeys the cleanest route was also the shortest route in terms of distance.

Each of the three studies discussed used the same tactical modelling approach, but have applied different techniques and parameters. From the two grocery home delivery literature discussed, it can be seen that emission levels have been estimated from mileage savings produced from logistics route planning models. This high level of approximation has come about

because there is no integrated logistics route planning and emissions model. The detailed approach undertaken by Ericsson was limited to the city of Lund because of the intensive data requirements.

2.6   Transport Externalities

Although the focus of this research is to do with measuring CO_2 emissions, it is only one of a number of factors considered to be the external impacts of transport, and this research could potentially be expanded to consider these other elements which include noise, accidents, air quality, infrastructure and congestion. These factors are external because they impact, and cost, society as a whole, and are not paid for by the individuals or companies who have caused it. According to Ricci (2007), "Externalities are changes of welfare generated by a given activity without being reflected in market prices. A cost (benefit) is considered external when it is not paid (enjoyed) by those who have generated it".

Tinch (1999) argues that "transport externalities are one of the most significant environmental problems facing western society today", and the European Commission have stated that the development of sustainable forms of transport is one of the key priorities of the commission (European Commission, 1998). The European Conference of Ministers of Transport have also commented on the deficiencies in the pricing of transport because the cost of externalities have been ignored, and that regulation, charges and taxes should be used to provide incentives for reducing the external cost of transport (ECMT, 1998). It could be argued that not taking these externalities into account has encouraged the use of more polluting forms of transport to the detriment of more environmentally friendly modes (Nash et al, 2001). Ricci (2007) also states that "externality valuation provides major contributions to the formulation of sustainable development policies".

There have been a number of studies that have attempted to put a value on these transport externalities (INFRAS,2004; AEA Technology Environment, 2005a; DEFRA, 2007a). Many of the techniques used originate from the field of environmental economics which use subjective, questionnaire based,

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assessments to produce valuations for health, accidents, time, etc. The outcomes are based on principles of "willingness to pay" or "willingness to accept" by the individuals being questioned (Verhoef, 1999). This approach produces wide variations in the cost values because of the differences in the interpretation of the externalities as well as the different methodologies and techniques used (Nash et al, 2001). The theory of environmental policy suggests that marginal social cost pricing as one solution to external costs (Tinch, 1999). However, for this method, accurate statistics are essential and, although many road transport statistics are collected in the UK, the quality is variable (Department for Transport, 2007a)

Despite these issues attempts have been made to put valuations on the various transport externalities.

Traffic accidents, for instance, impose an economic cost from damage to vehicles and roads, or even roadside property which may or may not be covered through insurance premiums, and a social cost in terms of whether the accident caused injury, resulting in pain or reduced quality of life, or a fatality, resulting in suffering by friends and relatives. There is also a cost associated with the support provided by the emergency and medical services that deal with accidents. The INFRAS study (2004) uses "the willingness to pay to reduce accident risks" method to identify a valuation for accidents.

The valuation of infrastructure may include not just the roads, but also the land used for extraction of road building materials, land use and buildings associated with roads such as service areas, garaging and vehicle repair and maintenance facilities, and the impact on habitat, cultural sites and property in the vicinity of roads which are degraded by transportation facilities. To illustrate the difficulties of putting a valuation on this external category Rietveld (1989) argues that according to economic theory, the valuation of infrastructure would be a positive benefit if infrastructure is lacking because it would result in improvements to general mobility and better access for emergency services, but it could result in a neutral or negative benefit if a reasonable infrastructure already exists.

Noise generated by road traffic contributes to health problems such as stress related illnesses, psychiatric illnesses, sleep disturbance and tinnitus (SCC, 1995). It may also result in reduced property prices from local road alterations which cause increases in traffic flows and road traffic noise. In placing a value against noise there are many issues to consider. For instance, a victim of road noise may decide to purchase double glazing, or a vehicle may be equipped with noise reducing technologies. However, many studies have used loss of property value when assessing the external cost of noise (INFRAS, 2004; Verhoef, 1994), and a willingness to pay per person disturbed by a level of exposure to noise.

Roads support a sustainable daily flow according the standard of road and its design capacity (SCC, 1995). However, as traffic builds up the operational conditions of a road gradually deteriorate due to a reduction in speed causing congestion and an increase in delays experienced by drivers. This results in time lost and therefore higher vehicle operating and driver costs. But congestion also impacts on other transport externalities such as higher levels of pollutants from slow moving or idling vehicles, and medical costs treating people with respiratory, stress and other illnesses which may be caused by congestion. Verhoef (1994) and INFRAS (2004) make the distinction between the other external factors and congestion, arguing that congestion only imposes on other road users, not the whole of society, and should therefore be considered as a separate externality.

The air quality externality covers the non greenhouse gas emissions from vehicle engines such as particulates (PM), carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). Typically, the impact on human health, impacts on materials and buildings, and the impacts on crops and agricultural production are included in the valuation estimate which could be based on the principles of willingness to pay. Over the years European legislation has specified ever tighter restrictions on the amounts of these local pollutants from vehicle engines with the consequence that they are predicted to fall over the next decade. However, the increasing growth in traffic may

outweigh the anticipated reduction in the emissions (Tinch, 1999). There have tended to be wide variations in the valuations produced due to different emission figures being used (INFRAS, 2004).

2.6.1 The Social Cost of Carbon

CO_2 emissions are another transport externality against which studies have attempted to put a valuation, but in many cases the term carbon is used for costing rather than CO_2. There is a direct relationship between carbon and CO_2 because carbon atoms are present in fossil fuels and are released as CO_2 when burnt. There are high levels of uncertainty in estimating the social cost of carbon, and previous research has produced wide ranges of values (Tol, 2007).

Carbon is a commodity that can be traded as evidenced by the carbon trading scheme which is a policy established by the European Union to control and reduce the amount of CO_2 emissions produced by industries who are considered high emitters such as the electricity generating companies. Carbon is also a taxable element such as the annual car licence which is levied by the UK government according to the amount of CO_2 emitted from vehicle exhausts. Within the UK government there are many instances of costs being applied to carbon when assessing projects, policies, or long term objectives as shown by the examples in the figure below.

Organisation	Example Applications
Defra	Regulatory Impact Assessment of the proposed F Gas regulations
	Cost-benefit analysis of UK Emission Trading Scheme
	Analysis of waste tax charges (review and consultation)
DfT	Incorporation into New Approach to Appraisal for Road Transport infrastructure appraisal
	Incorporation into National Transport Model/Social Pricing Model
	Analysis of aviation tax in Aviation White Paper (for consultation)
	Analysis of road user charging and differential charges (consultation paper)
DTI	Energy White Paper
	Regulatory Impact Assessment for Renewables Obligation II
ODPM	Proposals for Part L amendment (energy efficiency provisions) of Building Regulations
Ofgem	Energy investment appraisal (gas network extension, electricity transmission infrastructure)
EA	Assessment of Asset Management Programme 4 for Water Sector (AMP4)

Defra = Department for Environment, Food and Rural Affairs.
DfT = Department for Transport
DTI = Department for Trade and Industry.
Ofgem = Office of Gas and Electricity Markets.
OPDM = Office of the Deputy Prime Minister.
EA = Environment Agency.

Figure 6: *Example of the use of the social cost of carbon by the UK government (Source: AEA Technology Environment, 2005),*

In this context much research has been undertaken to estimate the social cost of carbon. This can be defined as "the estimated net present value of climate change impacts over the next 100 years (or longer) of one additional tonne of carbon emitted to the atmosphere today. It is the marginal global damage costs of carbon emissions." (AEA Technology Environment, 2005). Tol (2007) has identified 211 estimates from 47 studies since 1982, but the values indicated are highly speculative because producing a cost is dependent on predicting future climatic risks and their impacts. Models have been used for many studies such as FUND, RICE, DICE and PAGE, (Anthoff, 2004; Ingham and Ulph, 2003), but these do not take into account directly the possibilities of any catastrophes that may occur as a result of climate change (AEA Technology Environment, 2005). It is for this reason that sensitivity analyses are undertaken, using probability distributions of possible events, which have generated results with a wide range of costs. The cost differences produced by the various studies also depend on:

- The discount rate used, related to the future cost of carbon mitigation
- The weighting given to different regions such as developing countries
- The time horizon which is typically 100 years
- Whether median or mean values have been used

For economic appraisals, the UK government economic service (GES) value the social cost of carbon between £35 and £140 per tonne, with a mid point level of £70 per tonne of carbon used (DEFRA, 2007c). In other words, if an extra tonne of carbon were added to the atmosphere it would effectively cost an estimated £70 at 2000 prices to correct the damage it would cause. Following DEFRA's current guidance which is to apply an increase of £1 for each year to account for cumulative damage, and an inflation factor of 2% per year based on the Bank of England target, this means that at 2005 prices, the mid range price per tonne of carbon emitted is £82.59

Other estimates of the social cost of carbon are lower than this but do not include the possibility of catastrophic events such as extreme weather,

regional conflicts, poverty and famine (AEA Technology Environment, 2005). It could therefore be argued that the existing calculations are only a sub set of the true cost of emitting carbon. These costs could be used to establish environmental taxes, charges and subsidies (H.M. Treasury, 2002). In this context it is important that any carbon based assessment such as this research takes into account the social cost of carbon so that a realistic estimate of true costs can be produced for comparison purposes.

Costs in previous studies have related to carbon emissions. A factor is used to convert carbon to carbon dioxide based on the molecular weight of carbon dioxide which is 44 and the molecular weight of carbon which is 12. Therefore, to convert the cost of carbon into CO_2 a ratio of 12/44 must be applied. Thus £82.59 per tonne of carbon is equivalent to £22.52 per tonne of CO_2. This value will be used in the model to assess the impact of CO_2 on the various strategies as well as the direct internal cost of operating a vehicle.

2.7   Summary

The aim of this research is to develop a method to enable freight vehicle routes to be produced which calculate CO_2 emissions and have the option of minimising these emissions.

This chapter has shown that existing research and methods that address this issue are limited in that the calculations only produce estimates based on distance travelled. Research by Palmer (2005) and Woensel et al (2001) has shown that this does not produce a realistic estimate of CO_2 emissions, and nor does it produce routes which minimise these emissions.

The concept of modelling and the possible techniques that could be used have been discussed in this chapter, as have the related topics of transportation planning in the form of traffic volumes, road speeds and speed flow formulae, fuel consumption and emissions in the form of driving cycles and fuel consumption formulae, and the logistics related aspects of vehicle routing and scheduling. To be able to analyse the complex dynamics and

interrelationships of all these factors only a computer based model is capable of producing the results required to achieve the aim of this research.

The outcome from this literature review shows that in order to obtain a good estimate of CO_2 emissions, a realistic estimate of speed and speed variability is required, and that this is linked to the attributes of the freight vehicle and types of roads used, and the volume of traffic on the roads.

The chapter concluded with an assessment of the social cost of carbon, an essential element in government economic appraisal, and a cost that will be incorporated into the model to assess the true cost of vehicle operation.

The next chapter shows the outcome from an initial investigation of CO_2 emissions using a propriety vehicle routing and scheduling model, and then outlines a developmental framework for the proposed model to be used in this research.

3 Research Approach

3.1 Introduction

A balance has to be found between the complexity of the real world operation and the level at which the model is developed and also takes into account model accuracy and computational efficiency. Drew (1968) argued that model development should be kept as simple as possible as long as it achieves a level of accuracy that is acceptable to the user. Therefore, key to model development is a clear understanding of the detail required to produce an appropriate result. The characteristics and issues of route planning are well established by the wide range of literature available, and the techniques of estimating speed and the use of driving cycles, together with fuel estimation formulae have been examined.

This chapter discusses the investigations and experimentation that have taken place prior to developing the model in order to identify an appropriate level of detail, or granularity, to be included within the model. Having established this, the chapter then goes on to discuss the processes within the model.

The aim of this research is to develop a model capable of producing routes which not only minimise CO_2, but also estimate CO_2 emissions for routes minimised by the conventional approach of time or distance. To do this it is necessary to estimate the level of CO_2 emitted on each link of a digitised road network which is input to the model.

Vehicle routing and scheduling (VRS) packages, transportation models and fuel consumption/emission models make use of digitised road networks for their analysis. A road network in this form consists of nodes which represent intersections, or junctions, on the network, and links connecting the nodes which represent the road on which a vehicle travels. A link is typically specified by the node at either end of the link, the road distance between these nodes, and the type of road, often referred to as a road category. Commercial VRS packages such as Paragon or Sidewinder have relatively

few road categories and would classify, say, a motorway as urban or rural. However, transportation models for highway design such as Saturn, Contram or Paramics (Ortuzar and Willumsen,1998), have greater numbers of road categories and would represent a motorway, for instance, as 2, 3, 4, 5 or 6 lanes, urban, suburban or rural. If the road categories are each given a typical speed appropriate to the road, then the time taken to travel along the links can be calculated using the formula:

Time = Distance / Speed

In transportation models, links often have a link capacity which represents the maximum volume of traffic for which the road was designed, and a link flow which represents the volume of traffic as measured at a point in time. This may be a peak period of the day where the volume may exceed the link capacity, such that the road can be considered as congested, or an off peak period of the day when the volume of traffic may be considered light, often referred to as freeflow.

From the literature review, there are two ways in which CO_2 emissions can be calculated on these links. The first is by using an average speed for the entire link distance and to derive CO_2 emissions using a formula such as Akcelik's elemental model (Akcelik, 1982). The second method is to apply a driving cycle to the link and to use an instantaneous formula (Bowyer et al, 1985) to estimate emissions on a second by second basis, accumulated, to derive a CO_2 value for the link. However, speed is also related to the type of road, or road category, and it is important to understand the nature of the road being travelled, as it has a direct impact on fuel consumption.

The following section compares the different methods of using speed on links to derive CO_2 emissions and also examines the issue of road categories and its impact on speed. A number of analyses have been undertaken to identify how fuel consumption varies under different conditions of road category and speed.

3.2   Preliminary Investigation

Before starting the development of a model to examine the CO_2 emissions from freight vehicles, the issue of speed on roads and the way it varies, by road category, was considered. From the literature review, it would seem that the most detailed approach of using driving cycles on each of the links and applying an instantaneous fuel consumption formula would produce the best estimate of CO_2 emissions. However, the high level averaging approach used in previous studies may produce similar results to alternative more detailed analyses incorporating speed variability. Although this possibility is unlikely it is important to demonstrate whether there are differences, and the scale of any differences. Also, commercial VRS software tend to use a maximum of 15 road categories for estimating speeds on roads, but for highway design, using transportation models, the number of road categories tend to be much higher. An example of this is the Paragon VRS software which uses 11 road categories and the Surrey County Council transportation model which uses 48 road categories. Three key questions to answer are therefore:

1. By how much do the estimations of fuel consumption differ between using an average speed on a link and using driving cycles?
2. What difference does using a greater number of road categories make to both these methods?
3. By how much does this calculation differ from using the Cairns (1999) and Punakivi et al (2000) approach of converting total kilometres travelled on a route into CO_2 emissions based on an average value of CO_2 per kilometre?

3.2.1 Analysis

Previous studies have based their assumption of environmental assessment on the high level basis of grams of carbon dioxide per kilometre of distance travelled. Prior to developing a full scale model it is essential to identify what level of detail, in terms of the method of calculating fuel consumption, and hence CO_2 emissions, should be incorporated in the model. With this in mind, an initial analysis was undertaken, using a commercial VRS package, to

examine the fuel consumption for different methods of assessing speed on roads such as:-

- Average speed over an entire route
- Average speed by road link based on 11 road categories

The elemental fuel consumption formula developed by Akcelik (1982), which has been cited and/or used in a number of studies (Hutton, 2002; Affum et al, 2003; Mengguzzer, 1995; Haris et al, 1994), was used for each of these options to produce an estimate of fuel consumption, which was then converted to CO_2 emissions.

To understand the effect of road categorisation and speed variability, two sample weeks of detailed delivery information covering the UK were obtained from a major retailer, together with detailed vehicle operating parameters and characteristics. The customer delivery data consisted of a delivery address in the form of a postcode, the store servicing the customer, the delivery date and the time window in which the customer required the delivery. The retailer offers the customer seven 2 hour delivery windows every day, starting at 8am and finishing at 10pm. In order to minimise cost, and maximise vehicle fill, delivery vehicles for this retailer take out orders for two 2 hour delivery windows in a single journey. A commercial vehicle scheduling package, Paragon, was used to produce routings for one of the sample weeks. At the time of these deliveries, Paragon was the favoured routing package for the company, who also provided all the set up parameters for this software such as store opening hours, delivery windows, break times, etc. Paragon uses 11 road categories with speeds when calculating the matrix of times, prior to routing, as illustrated in the figure below.
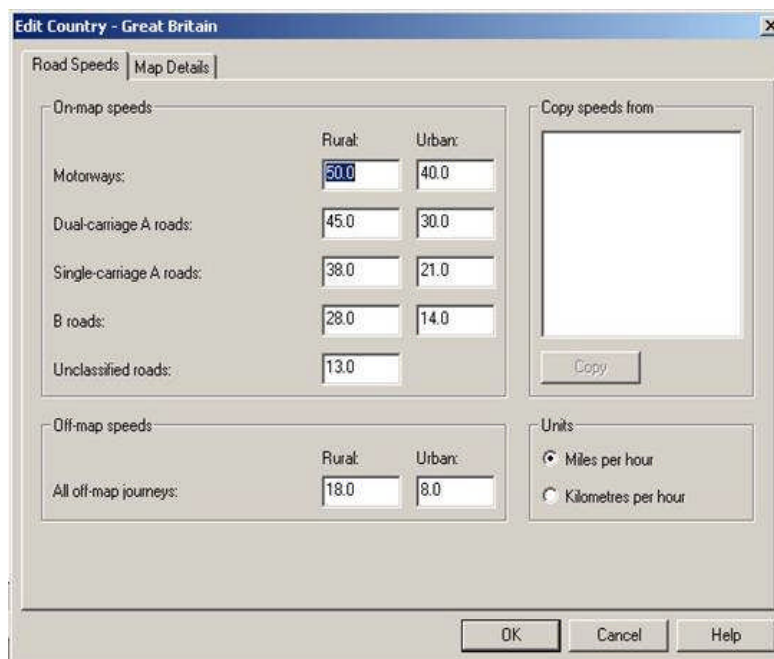
Figure 7: *Paragon road categories and input speeds*

After routing, the software also produces a report of time and distances by each of these 11 road categories. The following table summarises the results produced.

Number of stores	Total trips	Total deliveries	Total hours on the road	Total kilometres travelled
82	4,343	29,049	8,373	279,776
			Method 1 Average speed applied to total distance travelled on all routes	**Method 2** Average speed applied to the total distance by road category travelled
Litres of fuel consumed			36,702	34,227
Average litres/100km			13.12	12.23
% difference from Method 1				6.7%

Table 2: *Summary of results for sample week analysed*

The outcome from this first analysis shows that applying Akcelik's elemental formula to each of the two methods produces a very small difference of 6.7%. The constants used in the formula related to a Mercedes 311 CDI, 3500 GVW

delivery vehicle. According to the manufacturer's literature, fuel consumption is expected to fall in the range of 7.1 litres/100km to 13.5 litres/100km. Since the majority of deliveries in the sample were to households in urban areas, it would seem reasonable to assume that the calculated fuel consumption of 13.12 and 12.23 litres per 100km would be at the higher end of the manufacturers range.

A second analysis was undertaken to examine the fuel consumption impact of varying speeds on each of the links within a digitised road network, and to assess the impact of changing the number of road categories. Unfortunately, it was not possible to access the road network used by the Paragon software.

The author is grateful to the Transportation Planning department of Surrey County Council (SCC) who provided their digitised road network for the county together with detailed road flow information based on traffic volumes in 2005. The road network data was originally developed by Surrey County Council's Transportation Planning Unit as part of the Surrey Structure Plan. It was used in a transportation model called Eval to provide a means of assessing the overall strategic effects of local planning policy, but it has also been used on individual highway schemes for the evaluation of environmental, operational and accident conditions. The network details are shown below.
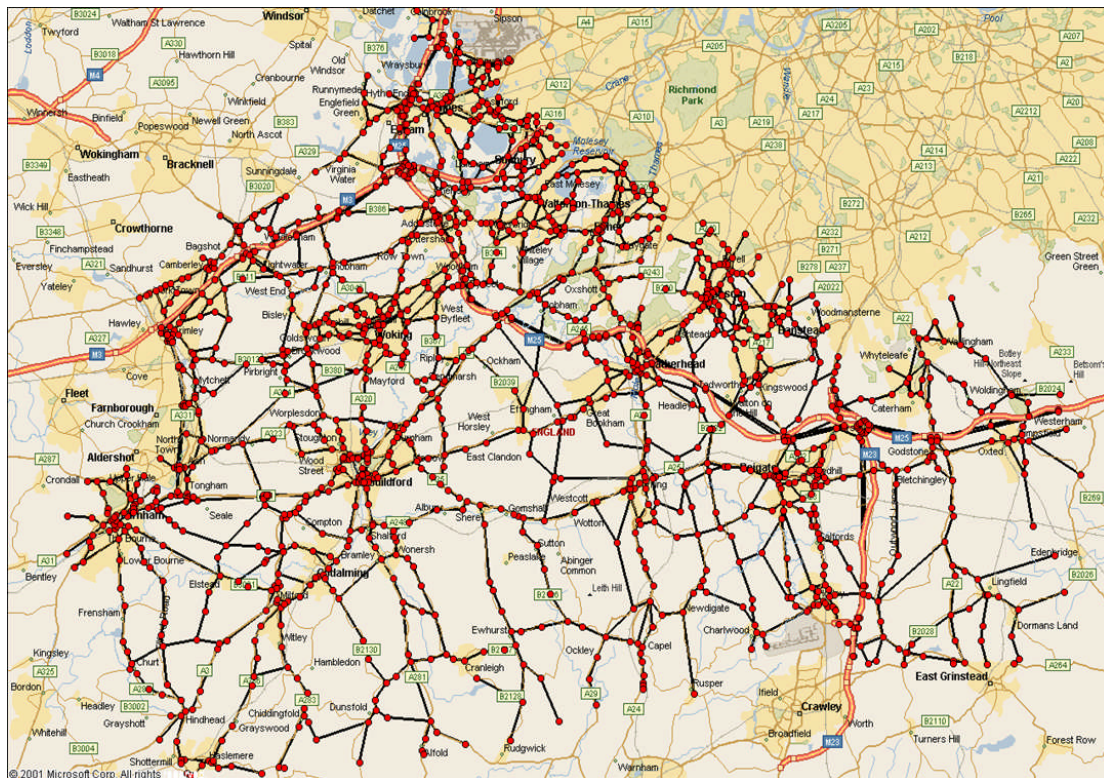
Figure 8: *Digitised road network for the county of Surrey*

This network of Surrey covers an area of 1,700 square kilometres and consists of 1,530 nodes and 1,986 bidirectional links. Each link in the database has information about traffic levels under free flow and congested conditions, and the percentage of heavy goods vehicles (HGV's) on the road, necessary for identifying speed limiting implications. Each link also has a length in kilometres and speed related to one of 48 road categories ranging from 4 lane motorways to 2 lane minor roads. The data provided by SCC covers all the major roads such as motorways, primary roads and A roads, but it is limited in that it only covers other minor roads that can be considered as thoroughfares, or connecting roads, and does not include many of the residential roads, or minor roads off these thoroughfares. More than 50% of the links are classified as urban roads, reflecting the nature of the county and its vicinity to London. Table 3 shows a breakdown of these links by category of road.

Road Type	No of Links	% of Links
Motorway	175	8.80%
Trunk road - rural	46	2.31%
Trunk road - urban	36	1.81%
Primary - rural	160	8.04%
Primary - urban	182	9.15%
A road - rural	137	6.89%
A road - urban	363	18.25%
B road - rural	147	7.39%
B road - urban	265	13.32%
Other road - rural	202	10.16%
Other road - urban	276	13.88%
Grand Total	1989	100.00%

Table 3: *Number of links by type of road*

Analyses by SCC using speed flow curves, as shown in figure 9, produced speeds for each link based on a free flow during the off peak hours between 10am and 5pm, and for a congested flow between 8am and 10am and between 5pm and 7pm.

Figure 9 shows a sample of nine speed flow curves and reflects changing speeds on each of the categories of road dependant on the volume of traffic using the road. On each curve there is a point at which the speed starts to significantly reduce and it is after this point that a road is classified as congested. Prior to that the volume of traffic is within the designed road capacity and is considered free flow.

Speed Flow Relationship
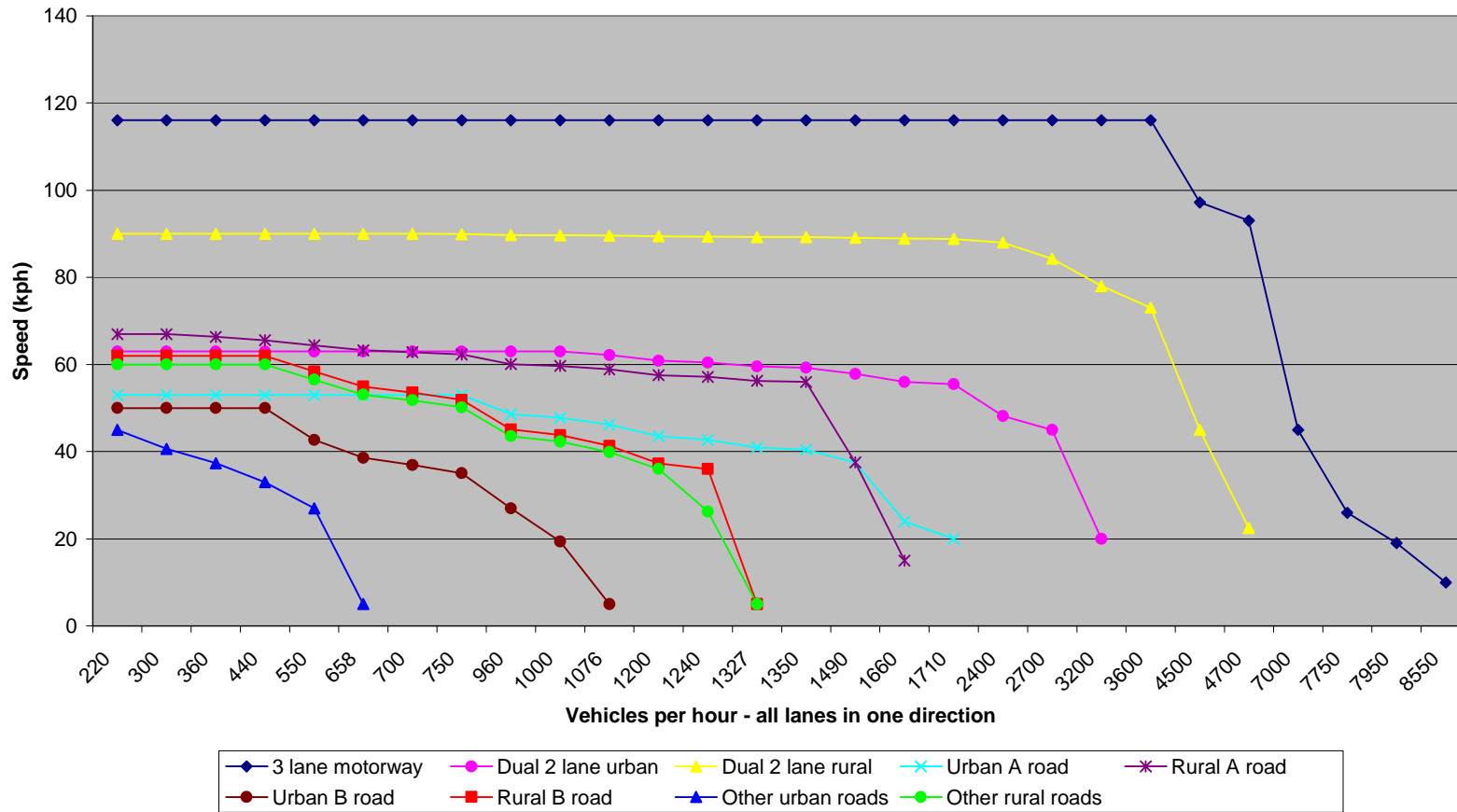
Figure 9: *Speed flow curves derived from the SCC road network database*

For the second analysis, a sample of 24 routes generated by Paragon in the Surrey area were selected and adapted for use within the SCC network. To enable the analysis to compare the effect of a different number of road categories, each of the 11 Paragon road categories was allocated to the 48 road categories in the SCC network to ensure compatibility throughout, as shown in the table below.

Road Category	SCC Road definition	Paragon Road definition
10	Motorway - No Speed Flow	Rural motorway
11	Motorway - 1 lane	Urban motorway
12	Motorway - 6 lane	Rural motorway
13	Motorway - 2 lane rural	Rural motorway
14	Motorway - 2 lane urban	Urban motorway
15	Motorway - 3 lane	Rural motorway
16	Motorway - 4 lane	Rural motorway
17	Motorway - 5 lane	Rural motorway
20	Trunk - No speed flow	Rural dual carriageway A roads
21	Trunk - 2 lane suburban	Urban single carriageway A roads
22	Trunk - 3 lane suburban	Urban dual carriageway A roads
23	Trunk - Dual 2 lane urban	Urban dual carriageway A roads
24	Trunk - Dual 3 lane urban	Urban dual carriageway A roads
25	Trunk - 2 Lane 10 m rural	Rural single carriageway A roads
26	Trunk - Dual 2 lane rural	Rural dual carriageway A roads
27	Trunk - Dual 3 lane rural	Rural dual carriageway A roads
30	Desig / Cty Primary - 2 lane non-central urban	Urban single carriageway A roads
31	Desig / Cty Primary - 2 lane suburban	Urban single carriageway A roads
32	Desig / Cty Primary - 3 lane suburban	Urban single carriageway A roads
33	Desig / Cty Primary - Dual 2 lane urban	Urban dual carriageway A roads
34	Desig / Cty Primary - 2 lane rural 7.3m	Rural single carriageway A roads
35	Desig / Cty Primary - 2 lane 10m rural	Rural single carriageway A roads
36	Desig / Cty Primary - Dual 2 lane rural	Rural dual carriageway A roads
37	Desig / Cty Primary - No speed flow	Rural single carriageway A roads
40	Other A road - 2 lane non-central urban	Urban single carriageway A roads
41	Other A road - 2 lane suburban	Urban single carriageway A roads
42	Other A road - 3 lane suburban	Urban single carriageway A roads
43	Other A road - Dual 2 lane urban	Urban dual carriageway A roads
44	Other A road - 2 lane rural 7.3m	Rural single carriageway A roads
45	Other A road - 2 lane 10m rural	Rural single carriageway A roads
46	Other A road - Dual 2 lane rural	Rural dual carriageway A roads
47	Other A road - No speed flow	Rural single carriageway A roads
50	B road - 2 lane central urban	Urban B roads
51	B road - 2 lane urban suburban	Urban B roads
52	B road - Wide 2 lane urban suburban	Urban B roads
53	B road - Dual 2 lane urban suburban	Urban B roads
54	B road - 2 lane 7.3 rural	Rural B roads
55	B road - 2 lane 10m rural	Rural B roads
56	B road - 2 lane rural poor standard	Rural B roads
57	B road - No speed flow	Rural B roads
60	Other Roads - 2 lane urban	Urban all off map journeys
61	Other Roads - 2 lane BCC	Urban all off map journeys
62	Other Roads - Dual 2 lane urban suburban	Urban all off map journeys
63	Other Roads - 2 lane BCC	Urban all off map journeys
64	Other Roads - 2 lane 7.3m rural	Rural all off map journeys
65	Other Roads - 2 lane BCC	Rural all off map journeys
66	Other Roads - 2 lane BCC	Rural all off map journeys
67	Other Roads - No speed flow	Rural all off map journeys

Table 4: *SCC 48 road categories and Paragon equivalent*

Emulating the retailer's parameters, Paragon's speeds were reduced proportionately by 10% to reflect congested conditions, and the analysis compared fuel and time estimations for these values with the more comprehensive congested speeds calculated in the SCC network using the speed flow formula. The 24 routes ranged from 1 km to 65 kms. The total distance travelled was 533 kms and used 559 links in the SCC network, meaning that the average link length was just less than 1km.

In the first instance, the estimation of fuel consumed calculated from a high level route averaged speed was used as the basis for comparison, and then constant speeds were used for the links in each of the 11 Paragon and 48 SCC road categories. These were compared with the use of generic speed profiles of realistic driving cycles based on the TRL596 study of traffic management schemes (Green et al, 2004) as illustrated in figure 5. The speeds in the driving cycles were adjusted proportionately to ensure the overall average speed for the link was maintained.

3.2.2 Findings

For each of the sample routes, the delivery locations were allocated a node number on the SCC network corresponding to the location. The delivery sequence on each route, as determined by the Paragon VRS software in the first analysis, was maintained. Dijkstra's (1959) shortest path algorithm was applied to Paragon's 11 road categories on the SCC network which was used to minimise time. The sequences of road network links between each of the delivery locations were identified. It is likely that different routes between deliveries would be chosen if the 48 SCC road categories were used rather than the 11 Paragon road categories. However, in order to maintain compatibility between the various speed and road category options, the same links and routes were used.

Once again, Akcelik's (1982) elemental formula was used to estimate fuel consumption for the route averaged speed and constant link speed options, and Bowyers et al (1985) instantaneous fuel consumption formula was used for the TRL driving cycle option (Green et al, 2004). The results based on

speeds of delivery vehicles travelling in an off peak period (i.e. freeflow conditions) are shown in the table below:

	Total litres of fuel consumed in 24 routes			
	Paragon 11 road cats.	**% variance**	**SCC 48 road cats.**	**% variance**
Route averaged speed	34.28		34.59	
Constant link speed	36.01	5%	35.86	4%
TRL driving cycle (Green et al, 2004)	46.66	36%	44.03	27%

Table 5: *Summary of results under free flow conditions*

Clearly, the number of road categories used does not impact greatly on the estimation of fuel consumption. Also, the use of constant speeds only produces small changes from a route averaged speed calculation. The major influence of fuel consumption appears to be the option where high levels of speed variability occur. Delivery vehicles that start and stop regularly along a link such as using the TRL driving cycles show the highest levels of fuel consumption, with a variance of around 36% from a route averaged speed using Paragon's 11 road categories, or 27% variance using SCC 48 road categories.

The results based on speeds of delivery vehicles travelling in a peak period (i.e. congested conditions) are shown in the table below:

	Total litres of fuel consumed in 24 routes			
	Paragon 11 road cats.	**% variance**	**SCC 48 road cats.**	**% variance**
Route averaged speed	34.22		34.46	
Constant link speed	36.36	6%	36.33	5%
TRL driving cycle	49.18	44%	50.69	47%

Table 6: *Summary of results under congested conditions*

The conclusion from the freeflow analysis is also confirmed when the same 24 routes are considered under congested conditions. In this instance the variances from a route averaged speed is considerably greater with an increase of 44% using Paragon's 11 road categories, or 47% using SCC's 48 road categories.

Although based on different data and methodology, these results are similar to the study undertaken by Woensel et al (2001), which showed that calculating CO_2 emissions using flow dependent speed, or speed variability, produced 11% higher emissions than the same calculation using constant speeds. During the congested peak period the difference rose to 40% higher emissions with flow dependent speeds.

Whilst the outcome from this analysis is relevant, for this variability of speed on each link to be valid, it has to be based on a reasonably accurate estimation of the overall average speed on each link of the road network.

As the route taken, and the average link speed, was maintained for each of the options, the time taken to travel each route stayed the same. Where time differences did occur was between the use of different road categories by Paragon and SCC, and between free flow and congested conditions. Table 6 below shows these results.

	Total time for 24 routes (mins)	
	Free flow	**Congested**
Paragon 11 road categories	562.15	624.61
SCC 48 road categories	501.85	689.24
% variance	-10.7%	10.3%

Table 7: *Constant speed analysis*

There are differences of plus or minus 10% between the results produced using Paragon's 11 road categories and SCC's 48 road categories. This outcome shows that different constant speeds on different road categories may well route vehicles along different road links, and this may impact on the allocation of deliveries to routes, and on the sequencing of deliveries within routes. The potential for inaccuracy if the average speeds are incorrect may have significant vehicle efficiency consequences.

3.3   Developmental Framework

Having discussed the way fuel consumption, and therefore CO2 emissions, varies when different representations of speed are used, the chapter now moves on to the development of the model. From the literature reviewed, there are clear relationships between traffic volume, speed, acceleration, fuel consumption and CO_2. The schematic shown below in figure 10 provides an overview of the model development logic. The numbers against each of the boxes correspond to the number in the bulleted notes attached to figure 10. The detail behind this logic is discussed further in the subsequent sections of this chapter.

[1] Digitised road network
Nodes   Links

[2] Apply speed flow logic to produce unique speed on each link

[3] Apply generic driving cycle logic to produce speed variability on each link

[4] Apply instantaneous fuel consumption logic to obtain fuel consumed on each link

[5] Convert fuel consumption into CO_2 emissions

[6] Revised digitised road network
Nodes   Revised Links

[7] Matrix Calculation
Calculation of quickest/shortest/cheapest/cleanest routes between all delivery points

[8] Routing Heuristic

[9] Results

[1] Digitised road networks used by commercial VRS software, do not contain the link parameters to enable CO_2 to be estimated accurately. The main variable that is missing is volume of traffic which can be applied to a speed flow profile such as COBA (DfT, 2007) to derive an estimate of speed on a road. Investigations have shown that a national digitised road network containing the essential road characteristics is not available. A limited county network containing traffic volumes in 2005 has been obtained from Surrey County Council and this has been used in the research.

Figure 10: *Schematic Design of the Model*

[2] In order to estimate speed on roads, there are various speed flow formulae that could be used. However, the formulae from COBA (as discussed in section 2.4.1) are commonly used in UK transportation models. The link data supplied by SCC do not contain some of the parameters required by the COBA formulae so average values, recommended in COBA, have been used. The output from these speed flow calculations produce a unique constant speed for each link.

[3] Speed variability has been incorporated using generic driving cycles produced by the TRL study (Green et al, 2004). It uses a database of second by second speeds for a range of road categories. The speed on each link has been used to estimate the average time, in seconds, to

drive the link distance. A random point selection within the driving cycle for the appropriate road category is then selected and the speeds at each second adjusted proportionally to ensure the overall average speed derived in [2] is maintained.

[4]   Various studies have been undertaken using regression and elemental models to derive equations which link speed and acceleration with fuel consumption (Akcelik et al, 2001). Analysis of various formulae have shown that the instantaneous fuel consumption model (Bowyer et al, 1985) is the most suitable to be used and can be applied to the second by second speeds derived from [3]. Speed and acceleration is accommodated within this model and the fuel consumption parameters adjusted to reflect the road and vehicle conditions in the UK.

[5]   A direct relationship between fuel consumption and CO_2 exists. For diesel fuel, the most common propellant used by freight vehicles, there are a range of estimates as to the amount of CO_2 emitted for each litre of fuel from 2.57 kg/litre for ultra low sulphur city diesel (J Sainsbury, 2002) to 2.85 kg/litre for standard diesel (Dauncey, 2005). However, a mean value of 2.7 kg/litre is used in the model.

[6]   From these analyses a revised digitised road network is created which can now be used by the VRP software

[7]   The revised digitised road network is input to the matrix calculation routine which calculates the shortest routes based on minimisation criteria of time, distance or cost as well as CO_2 emissions, for a set of delivery locations. A shortest path algorithm developed by Dijkstra (1959) is used.

[8]   A standard VRP heuristic with time windows has been adapted to receive the alternative matrices for the minimisation criteria to produce the routing calculations required

[9]   The results show the vehicle route and delivery sequences with emission values as well as time and distance.

3.4 Relationship between Traffic Volume and Speed

The detail in this section covers box 2 in the schematic diagram of figure 10. The development process begins with the digitised road network from Surrey County Council (SCC). A road category database was supplied containing 48 classifications of road each with a unique 2 digit identifier. The road types, as shown in table 3, fall into 6 groups namely:

- motorway
- trunk
- primary
- other A roads
- B roads
- Other roads

Each of the 48 road categories contain a road limiting capacity in vehicles per hour which represents the maximum operational capacity for which the road was designed. The road network data was supplied in the form of nodes and links. This database consists of 1,530 nodes corresponding to a road junction or intersection where a road layout or speed limit changes, and each node contains a unique identification number plus latitude and longitude coordinates. The 1,989 bidirectional links indicate lengths of road joining the nodes and each have the following parameters associated with them:

- a node identification number corresponding to the start of the link
- a node identification number corresponding to the end of the link
- the length of the link in kilometres
- a two digit identifier corresponding to a road category
- the link capacity obtained from the road category database in vehicles per hour
- the percentage of heavy goods vehicles measured during each of these periods
- the measured flow of vehicles during three periods of the day as follows:

i. peak am vehicles per hour (period defined as 8am to 10am)

ii. off peak vehicles per hour (period defined as 10am to 5pm)

iii. peak pm vehicles per hour (period defined as 5pm to 7pm)

The measured flow values have been calculated by SCC's transportation model which has generated predictions of road volumes for those three periods of the day. Discussions with SCC have confirmed that they believe these values to be typical for the county. Without any roadside measurements of traffic flows it is not possible to assess the level of accuracy of these predictions. An alternative method of confirmation may be the use of real time traffic information such as that provided by ITIS Holdings who collect traffic speeds from on road vehicles, or Trafficmaster who have a network of traffic speed sensors, but this would add a significant level of complexity without a commensurate improvement in accuracy to the model, so the SCC predictions are deemed to be the only option.

To obtain speeds for the vehicle flow data on each link in the SCC database, the COBA speed flow formulae are used in the model (Highways Agency, 2003a). There are 11 road categories each having different speed prediction relationships. The 11 road categories are:

RC1   rural single carriageway
RC2   rural all purpose dual 2 lane carriageway
RC3   rural all purpose dual 3 or more lane carriageway
RC4   motorway dual 2 lanes
RC5   motorway dual 3 lanes
RC6   motorway dual 4 or more lanes
RC7   urban non central
RC8   urban central
RC9   small town
RC10 suburban single carriageway
RC11 suburban dual carriageway

These calculations, derived from empirical measurement and regression analysis, gradually reduce the speeds of vehicles as the flow increases until a point is reached (the limiting capacity) when speeds reduce significantly until a minimum speed is reached. A graph of the 11 speed flow relationships in COBA are shown in figure 11 below.
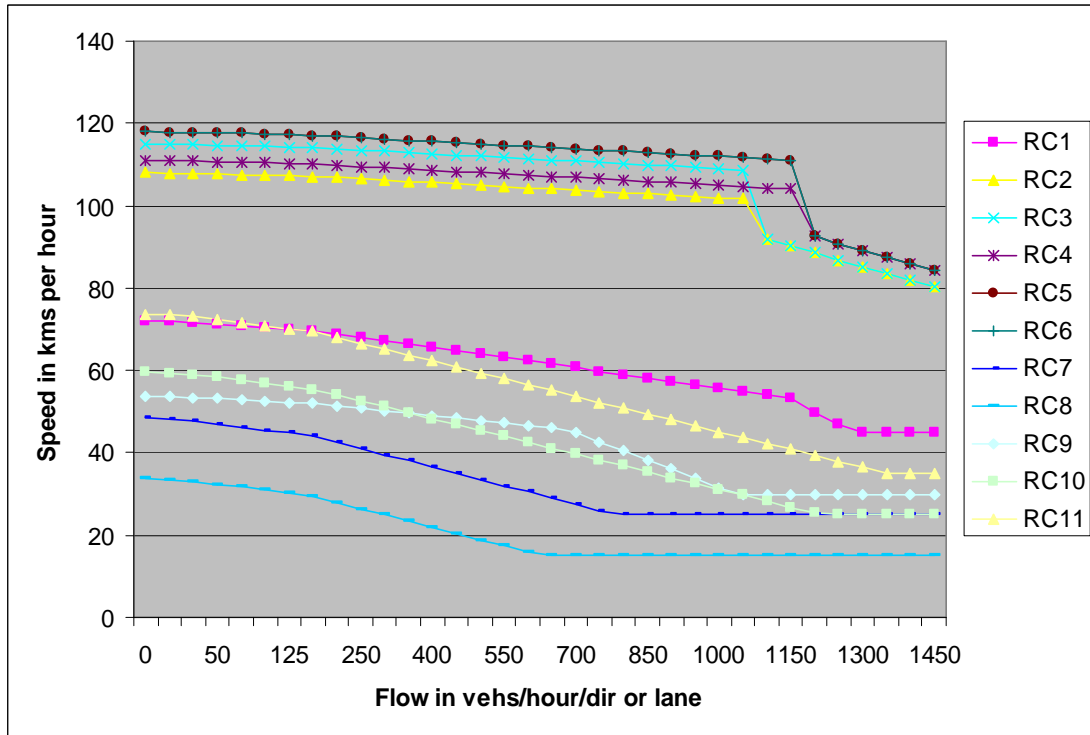
Figure 11: *COBA speed flow graph for 11 classes of road*

Although some of the formulae include allowances for hills, bends, intersecting side roads in rural areas, visibility, and verges or hard strips at the sides of roads, this data is not available for the links in the SCC road network, and therefore default values, as defined in the COBA manual, have been used, and kept constant throughout the analyses. An assessment of the effects of taking these values into account has shown that they only have a small impact on the calculated speeds, ranging between plus and minus 5kph.

The detail behind each of the eleven formulae are shown in Appendix A.

The road category on each link of the SCC data identifies which of the above formulae should be applied. The vehicle capacity for that road category and the estimated flow of vehicles on the link is then used to predict the average

speed on the link. As an example of this consider the following link from the SCC database:

Start Node	End Node	Road	Description	Road Cat	Distance (km)
1	317	B377	Feltham Road	54	0.55

From the SCC database, road category 54 is a 2 lane rural 7.3m wide B road with a link capacity of 620 vehicles per lane per hour. Two lane implies a single lane in each direction. For this link the morning rush hour measurement is 421 vehicles, the off peak flow of vehicles is 379 per hour and the peak evening flow is 724 vehicles per hour. The COBA formula for RC1, rural single carriageway, should be applied which predicts speeds of 65, 66 and 60 kph for the morning peak, off peak and evening peak periods respectively.

3.5   Relationship between Speed and Speed Variability

The detail in this section covers box 3 in the schematic diagram of figure 10. In order to use an instantaneous fuel consumption formula, the predicted average speed on each link then needs to be converted into a second by second variable speed. The speed and acceleration profile used has to maintain the overall average speed for the link.

The TRL data (Green and Barlow, 2004), consists of a number of second by second generic driving cycles, or speed profiles, of which three are for light goods vehicles, and are used in the model, as follows:

- an 881 second suburban control cycle
- a 1142 second congested urban control cycle
- a 1016 second non congested urban control cycle

In each of these cycles, for each second travelled, the speed is known as is the distance travelled and the acceleration or deceleration. An example of the TRL driving cycle for a non congested urban area is shown in figure 5. It can be seen that speed fluctuates between stationary and 60kph over the 1016 second driving period.

To create a second by second variable speed, each link in the SCC database is examined in turn. If the road category of a link is classified as an urban or suburban road the link distance is divided by the average speed (Vc) predicted by the COBA formula (as detailed in Appendix A) to obtain the total time (T) in seconds for a vehicle to drive the link distance. A random starting point is selected in the appropriate driving cycle and the time T from that starting point in the driving cycle is analysed in the model. If the time T from the starting point exceeds the total duration of the driving cycle an alternative random starting point is chosen. The distance travelled (D) over this time T is calculated and the average speed (Vt) is calculated. The speed Vt is then compared with the predicted average COBA speed Vc for the link. A ratio (R) of Vt/Vc is calculated, and each of the second by second speeds from the random starting point, in the TRL driving cycle, over the time T is multiplied by R so that the overall average speed Vt is the same as the COBA speed Vc. This approach enables an instantaneous fuel consumption formula to be applied to produce a realistic assessment of fuel consumed over time T. A graph of this process is shown in figure 12 below.
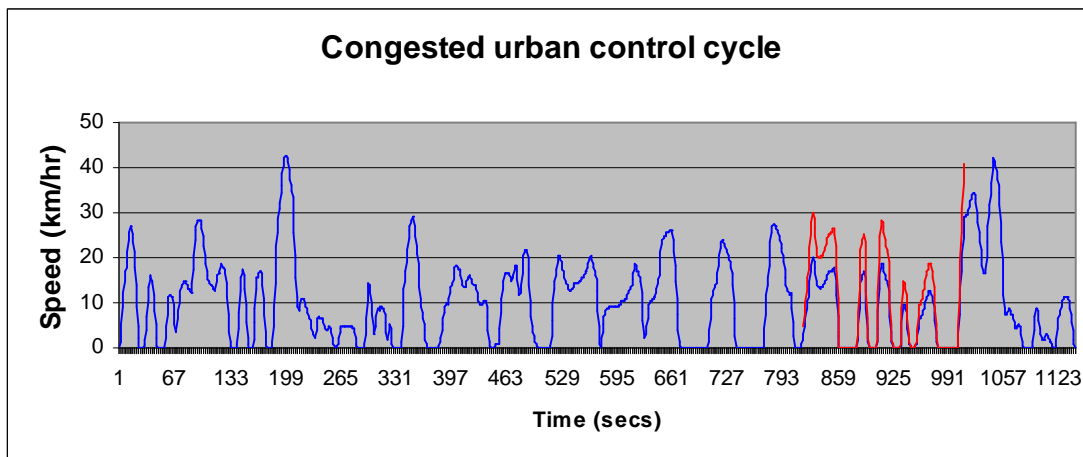
Figure 12: *TRL speed profile with link speed variability applied*

In this example the average COBA link speed (shown in red) is higher than the average TRL speed from the starting point at 818 seconds over time T to 1009 seconds, and the ratio R which is the COBA speed divided by the average TRL speed therefore increases the second by second TRL data to match the average COBA link speed.

Driving cycles are difficult and expensive to obtain and it has not been possible to acquire driving cycles for motorways and rural areas. For links with these road categories the COBA predicted average speed is used in an elemental fuel consumption formula which does not need specific second by second fluctuations in speed.

Delays at junctions are not considered in this research. Within the SCC road network database there is no information as to the type of junctions at any of the nodes. Signalised and give way junctions, and roundabouts, differ in the way queues form at, and vehicles leave, a junction. The techniques for handling these movements are complex and more appropriate to transportation modelling. Within the COBA manual detailed models from TRL such as Picardy, Oscardy and Arcady are expected to be used to simulate flows through the different types of junction (Highways Agency, 2003b). It is not the intention of this research to enable the VRP model to reflect the flow of vehicles along the links in detail but to find a method of representing the flows against which speed and acceleration can be used to estimate fuel consumption. In this respect the generic driving cycle data produced by TRL is appropriate.

3.6   Relationship between Speed Variability and Fuel Consumption

The detail in this section covers box 4 in the schematic diagram of figure 10. For those road links which are classified as suburban or urban, i.e. for which driving cycles are available, an instantaneous fuel consumption formula (Bowyer et al, 1985) is used on each of the speed profiles extracted from the TRL data. The values of the parameters used in the formula reflect a light goods vehicle and are shown in the table below.

Variable	Description	Value
α	An idle fuel rate in mL/sec	0.500
M	Mass in kg	3500
β_1	Energy efficiency parameter in mL/kJ	0.060
β_2	Energy-acceleration efficiency parameter in mL/(kJ.m/sec2)	0.045
b_1	Drag force parameter in kN, mainly related to rolling resistance and the drag associated with the engine	0.768
b_2	Drag force parameter in kN/(m/s)2, mainly related to aerodynamic resistance and the drag associated with the engine	0.00371
c_1	Drag fuel consumption component in mL/m, mainly due to rolling resistance	0.046
c_2	Drag fuel consumption component in (mL/m)/(m/s)2, mainly due to aerodynamic resistance	0.000223

Table 8: *Values used for parameters in instantaneous fuel consumption formula*

These parameters have been described by Bowyer et al (1985) and current values have been obtained from various sources including discussions with commercial vehicle manufacturers, and literature sources such as Sturm and Hausberger (2005) and Freight Best Practice (2006).

The formulae for instantaneous fuel consumption starts by calculating the tractive force RT at a point in time and then uses this value to estimate fuel consumption. The tractive force is the effort, or pulling force, required to move a freight vehicle. RT is defined as

$$RT = b_1 + b_2 * \text{speed in m/sec}^2 + M * \text{acceleration} / 1000 + 9.81 * 10^{-5} * M * \text{gradient}$$

The SCC link parameters do not hold information on road gradients so a default value of zero is used, implying all roads are flat.

If the tractive force RT is less than or equal to zero, the fuel consumed is calculated as the idling rate, α, for that one second period.

$$F = \alpha$$

If RT is greater than zero and the vehicle is shown to be accelerating or decelerating in that one second period, the fuel consumption formula is:

$$F = \alpha + \beta_1 * RT * \text{speed in m/sec} + \beta_2 * M * \text{acceleration}^2 * \text{speed in m/sec}/1000$$

where F is the fuel consumed in millilitres/sec

If RT is greater than zero and the vehicle is not accelerating or decelerating in that one second period, the vehicle is in cruise mode and the fuel consumption formula is:

$$F = \alpha + c_1 * \text{speed in m/sec} + c_2 * \text{speed in m/sec}^3$$

By summing up the fuel consumed in each second over the time T, a total value of fuel consumed for the link distance is obtained.

The other road links for which driving cycles could not be obtained, classified as motorways or rural roads, Kirby's (2006) variation of Akcelik's (1982) elemental formula is used in the model. The formula is described in section 2.3.1 and includes constants

$$k_1 = v_m 3\ (R_{90} - R_{120})\ /\ (v_m^3 - 113400)$$

$$k_2 = (14580\ R_{120} - 25920\ R_{90} + 4\ v_m^3\ R_{120} - 3\ v_m^3\ R_{90})\ /\ 36\ (v_m^3 - 11340)$$

where the numeric values of 113400, 14580, 25920 and 11340 correspond to derived regression values which take into account the vehicles aerodynamic and rolling resistance, weight and energy efficiency. This fuel consumption formula has average speed as the main variable, but takes into account vehicle parameters and driving speed fluctuations through various constants as follows:

Variable	Description	Value
R90	Fuel consumption rate at constant 90 km/h (litres/100km)	5.623630
R120	Fuel consumption rate at constant 120 km/h (litres/100km)	7.209038
vm	Speed returning lowest fuel consumption rate (km/h)	50

Table 9: *Values used for parameters in elemental fuel consumption formula*

3.7 Relationship between Fuel Consumption and CO_2

The detail in this section covers box 5 in the schematic diagram of figure 10. Each link in the SCC road network will now have an estimate of fuel consumed based on either the instantaneous or elemental fuel consumption formulae, depending on the road category. There is a direct relationship between fuel consumed and CO_2 emissions, but the values differ between sources. The table below provides an indication of typical levels of kilograms of CO_2 per litre of diesel consumed.

Description	Kgs of CO_2 per litre	Source
HGV standard diesel fuel	2.82	FTA quoted in J Sainsbury plc, 2002
HGV ultra low sulphur city diesel fuel	2.57	Greenergy quoted in J Sainsbury plc, 2002
HGV all diesel fuel	2.68	DETR quoted in J Sainsbury plc, 2002
Diesel fuel	2.70	Australian Greenhouse Office, 2003
Diesel fuel	2.70	Potter et al, 2003
Diesel fuel	2.62	The UK Parliament, 2003
Diesel fuel	2.85	Dauncey, 2005

Table 10: *Estimates of CO_2 emissions per litre of diesel fuel*

These estimates may vary due to the hydrogen carbon ratio of the diesel fuel which affects emissions of CO_2. The model developed for this research uses a midpoint figure of 2.7 kg per litre of CO_2. The fuel consumption figure for each SCC link is multiplied by this value to obtain the amount of CO_2 emitted.

3.8 Matrix Generation

The detail in this section covers box 7 in the schematic diagram of figure 10. At this stage, all the links in the SCC road network now have the parameters necessary to enable routes to be found between any two nodes that minimise:

- time
- distance
- CO_2 emissions

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To find routes which minimise any one of these parameters, a shortest path algorithm is used. This is defined as a path between two nodes such that the sum of the weights of its constituent links is minimised. In this context, the weight unit would refer to any of the three link parameters above.

There are a number of shortest path algorithms that could be used but one of the most popular in terms of citations, speed of use and efficiency (Zhan, 1997) is by Dijkstra (1959). This algorithm is particularly suitable because

- it does not need to consider negative "weight" values
- it computes the shortest path based on a specified minimisation criteria and
- it can do this from a source node to all other nodes in the road network very rapidly and
- it enables a node by node route sequence to be output so that specific road categories used on the route can be identified

Each customer delivery location is allocated to a node on the road network by matching the nearest latitude and longitude coordinates of the customer's postcode to the latitude and longitude coordinates of the nodes. The model uses Dijkstra's algorithm to create three matrices of shortest routes between all the nodes which are marked as having a customer delivery, and the node from which the vehicle sets out and returns (the depot). The three matrices are for routes minimised by time, distance and CO_2 emissions. For each of these matrices, the values computed for each route from a source node to a destination node are the total time, distance and CO_2 emissions. Thus, if a route is minimised by time, the total distance and CO_2 are calculated for that route. Similarly, if a route is minimised by CO_2 emissions, the total time and distance is also calculated. In all cases the nodes which a vehicle passes through to get from the source node to the destination node are retained so that the total time, distance and CO_2, by road category can be calculated within the model.

3.9   Vehicle Routing with Time Windows Heuristics

The detail in this section covers box 8 in the schematic diagram of figure 10. The aim of the vehicle routing problem (VRP) with time windows heuristic is to generate routes which commence at a depot location, visit a number of delivery points once only, and then return to the depot location. These routes have to minimise either the time taken, distance travelled or CO_2 emitted, but at the same time ensuring that deliveries are sequenced to meet delivery time windows, and that the operating characteristics of the vehicle undertaking the deliveries, or the depot despatching the delivery vehicle, are not violated

This research is not about identifying an optimum VRP heuristic technique for generating routes which minimise CO_2 emissions. Rather than developing a new VRP using existing heuristics, a program was obtained from Dr Wout Dullaert of the University of Antwerp which uses heuristics described in Braysy et al (2004). This software was originally programmed in the object programming language Java but has been reprogrammed in Visual Basic so that it can be used as a macro within Microsoft's Excel spreadsheet program. The software, as provided, was originally written to use Euclidian distances between nodes on a road network so that the heuristics could be used with Solomon's (1988) test data, and the results compared with other VRP algorithms. When the software was converted to Visual Basic, the coding that uses the Euclidian distances was modified to accept the data from the three matrices.

The VRP allocates a level of criticality to each customer delivery to be routed according to:

- the distance from the depot
- the size of the delivery
- the "tightness" of the delivery time window

Each delivery is then allocated its own unique route with the time, distance and CO_2 values from depot node to delivery node and back to the depot node,

read from the selected minimisation matrix. The VRP therefore begins with as many routes as there are deliveries.

A random seed number is then produced which is used to generate a random number for each of the deliveries to be routed. The VRP software then applies a construction heuristic which is a variation of the Clarke and Wright savings algorithm developed by Liu and Shen (1999). The route with the most critical delivery is selected (R) and the other deliveries sorted in ascending sequence of random number. Starting with the delivery with the smallest random number (Rs), the model attempts to insert this delivery within the chosen critical route R. If the combined route is less than the value of the two separate routes, and the delivery windows, vehicle and depot operating constraints aren't violated, then route R with these two deliveries is accepted and the route Rs discarded. Each subsequent delivery in order of random number is considered for this route. The Liu and Shen variation allows these subsequent deliveries to be inserted at any point in route R rather than the Clarke and Wright which only considers inserting at the beginning or end of the route. When all deliveries have been considered, the route with the next most critical delivery is selected and the process repeated. In this way routes are combined and reduced from the initial construction.

Improvements to this sequential insertion heuristic are then attempted using two algorithms. The first is the cross exchange developed by Taillard et al (1997) which attempts to swap individual customer deliveries between neighbouring routes to see if an overall improvement can be achieved. The second improvement algorithm is the I-opt technique developed by Or (1997) which attempts to move segments of routes, or several sequential deliveries at a time, into other routes. The number of deliveries in a segment reflects the value of I, such that 2-opt attempts to move 2 sequential deliveries, 3-opt attempts to move 3 sequential deliveries from one route to another.

The outcome from this VRP process is a set of routes which have been sequenced to minimise the selected criterion of time, distance or CO_2, and to produce the total time, distance and CO_2 for all routes, for that minimisation

criterion. In addition the route sequences are identified, as well as the total distance travelled by type of road.

3.10 Summary

This chapter has presented an initial investigation to assess the level of detail at which the model should be developed. The outcome from this analysis indicates that there is a difference of up to 40% between the estimation of fuel consumption using constant speeds and variable speeds. In order to produce a realistic estimate of fuel consumption, and therefore CO_2 emissions, the model has to be able to reflect the speed variations that occur as a vehicle travels along a road. The chapter then discussed the model framework which indicated the techniques that could be applied to a digitised road network to estimate average speeds from traffic volume, to apply a perturbation to the average speed in the form of generic driving cycles to reflect speed variability, and then to apply an instantaneous fuel consumption formulae to estimate the amount of fuel consumed so that it can be converted into CO_2 emissions.

It has not been possible to obtain driving cycles for motorways or rural roads so a compromise has been used in the form of an elemental fuel consumption formula applied to the average speed, estimated from the traffic volume, for these road categories.

The chapter then went on to consider the way these techniques are used within the VRP heuristic so that routes can be produced based on minimisation criteria of time, distance or CO_2.

The next chapter discusses the computer based model in detail.

4 Model Functionality and Operation

This chapter discusses the functionality and operation of the model, and how the algorithms covered in the previous chapter have been incorporated within the model.

The model has been developed in Microsoft Excel and consists of 16 worksheets and comprehensive Visual Basic macros to facilitate the model operation. The model also includes a bespoke mapping routine to visually represent the routes generated by the model.

The worksheets, with the worksheet names in brackets, are as follows:

[1]   Starting parameters and final results (Parameters)

[2]   Surrey County Council node data (SCC Nodes)

[3]   The Surrey delivery database (SurreyDels)

[4]   Surrey County Council road categories (Road Cats)

[5]   Surrey County Council link data (SCC Links)

[6]   Speed flow formulae (Speed-Flow)

[7]   TRL driving cycles and fuel consumption formulae (SpeedVar+FC)

[8]   Revised Surrey County Council links (Rev SCC Links)

[9]   The extracted store and day delivery database (Customer Calls)

[10]   Store operating details (Depots)

[11]   Delivery vehicle operating details (Vehicles)

[12]   The quickest time matrix (TimeMat)

[13]   The shortest distance matrix (DistMat)

[14]   The cleanest routes matrix (CO2Mat)

[15]   Intermediate model results (Results)

[16]   Visual representation of the routes (Map of Routes)

The model schematic shown in figure 10, in the previous chapter, has been adapted in figure 13 below so that the activity described in each process box is linked with the worksheet name by a number inside square brackets. This number corresponds to the worksheet name in the list above. Some activities

such as the matrix calculation produce results in three worksheets as shown in the process box of figure 13.
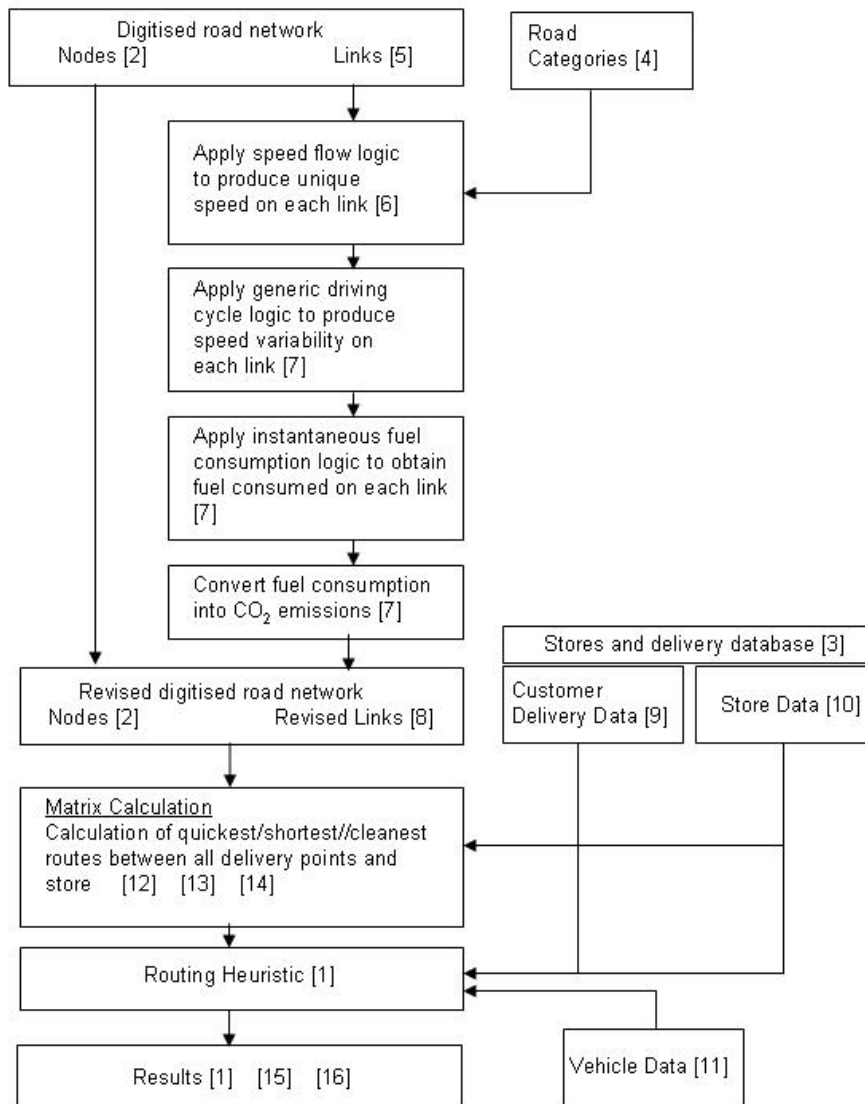
Figure 13: *Model schematic indicating worksheet operation*

The function of each of these worksheets, and the data contained in them, are described in the following sections.

4.1 Starting Parameters and Final Results

Figure 14: *Model start parameters and output*

The main worksheet shown in figure 14 allows the user to select from a range of options and set up parameters before running the model, and it also shows a summary of the results produced by the model. The model has been designed so that alternative speed variability methods and road category options, speed flow options and fuel consumption formulae may be tested in future, but for the purposes of this research, the speed method uses the SCC 48 road categories with the TRL driving cycle data, the speed flow option has been kept as "COBA", and the fuel consumption formula as "Instantaneous". This latter fuel consumption option is only used for urban and suburban classified roads for which TRL driving cycles are available, as discussed in section 3.5. The elemental fuel consumption formula is used for rural roads and motorways. If driving cycles were subsequently obtained for these roads then the instantaneous formula could be applied throughout. For the purposes of comparison, the model can be run with minimisation criteria of time or distance as well as CO_2 emissions. The user can select from one of five Surrey depots from which to route vehicles, and a delivery day. The "Create Calls Data" button extracts the deliveries and starting depot details from the one week test data, for the selected day and depot and then displays the number of deliveries on this worksheet.

Clicking on the button "Create Revised RN Links" causes the model to take each of the original links in the SCC road network and use the COBA speed flow and instantaneous fuel consumption formulae, in conjunction with the driving cycle data, to produce updated links containing the original data plus average speed, time, fuel consumed and CO_2 emissions. The "Create Matrix" button then applies Dijkstras shortest path algorithm to generate three matrices based on the quickest, shortest and cleanest routes between all the delivery locations, including the starting depot. All the matrices produced include a detailed node by node route as well as the time, distance and emissions for each of the "from" and "to" nodes. The VRP heuristic has been modified to receive this data so that when the "Run VRP Heuristic" button is selected, the appropriate matrix for the selected minimisation criteria is input. Because the heuristic includes a level of randomisation, it is not guaranteed to produce the best result on the first run. The main worksheet contains an option to select the number of times the VRP heuristic should be run to find the best solution. As the model runs the worksheet displays the number of iterations that have been run. For each iteration a check is made to see if this result is the best so far, in which case the results are displayed on this worksheet and the next iteration is performed. These results show a summary of the number of routes created by the iteration, the iteration number producing these results, the total driving time in minutes, the total distance in kilometres, the total CO_2 emissions in kilograms, and the total cost of the vehicles to perform these routes. The individual routes are displayed to the right of the main window with the node by node delivery sequence, plus a summary of the kilometres travelled by each of 11 road categories.

The model includes a facility to retain the best results produced by a minimisation criterion, so that when alternative minimisation criteria are selected, these details are kept until the results of a subsequent iteration can improve the solution.

4.2 Surrey County Council Node Data

A digitised road network supplied by Surrey County Council forms the key input data for the model. Part of this data is in the form of a series of nodes representing points in the network such as road junctions, intersections, roundabouts, traffic lights or change of road category. In this worksheet all the nodes are defined as an integer number between 1 and 5627, each with a latitude and longitude coordinate so that the node can be positioned on a map.

4.3 The Surrey Delivery Database

Data to test the model has been provided by a major supermarket chain and consists of one weeks delivery data representing 2,871 deliveries to households from 5 stores, in the Surrey area. The delivery data is held on this worksheet and consists of a delivery day, a two hour delivery window in which the customer delivery is required, and a postcode location which has been geocoded with latitude and longitude coordinates. The store data contains a postcode location which has also been geocoded. As described in section 3.2.1, the SCC road network data is limited in that it does not contain all roads in Surrey. Consequently, the location of a delivery may not coincide exactly with a road node location. Therefore, in order to attach the store and delivery locations to the nearest nodes on the road network, an approximate distance from each location to all nodes has been estimated using the latitude and longitude coordinates. The algorithm to calculate this distance (contained in Appendix B) produces a straight line value which when multiplied by a factor of 1.2 converts it into an approximate road distance. The conversion factor of 1.2 is a standard value within the UK and is used in many commercial VRS packages for estimating "off map" distances. Inevitably this estimation does not take into account any barriers such as railway lines or rivers that may be present between the store and delivery locations and road nodes. The algorithm then allocates the nearest node to the locations, and the estimated "off map" distance is also included so that the model can allow for this in any routing assessment by assuming it to be a minor road. The average "off map" distance is 0.7km.

4.4 Surrey County Council Road Categories

The links connecting the pairs of nodes represent roads and have data associated with them including a road category defined by the broad definitions of motorway, trunk, primary, other A, B and other roads, each of these being further subdivided according to number of lanes, road width and rural or urban/suburban. The road category is a two digit code which is specified for each link on the SCC Links worksheet. For each of these 48 road categories there is a limiting capacity of the road in vehicles per hour. This is sometimes referred to as the operational capacity and is defined as "the maximum volume of traffic that can travel along a section of road without a deterioration in minimum operational conditions" (Surrey County Council, 1995). In other words, if the volume of traffic exceeds this level the road could be considered to be becoming congested and consequently vehicle speed is reduced. Each category of road has also been given an indicator to show whether it is a rural, urban or suburban, so that the TRL driving cycles can be applied appropriately.

4.5 Surrey County Council Link Data

This worksheet contains nearly 2,000 links, representing roads between pairs of nodes. As well as a road category, each link has node numbers to denote the start and end of the link, a link distance which is specified in kilometres, and three traffic levels covering a morning peak hour, evening peak hour, and a typical off peak hour. The traffic volumes on each of the links have been produced by the Surrey County Council (SCC) traffic model which uses origin and destination matrices to estimate the volume of traffic on each of the roads in the SCC road network. Although three traffic periods are available for use, the VRP model does not provide the functionality for adjustments to speed by time of day. It would have made the VRP heuristic considerably more complex to allow for the switching of parameters such as speed and CO_2 emissions, depending on the time of day. Consequently, traffic volumes, and therefore speeds, have been based on the morning peak period only. The total traffic volumes on all roads in the SCC network database is 3.4 million during the morning peak period, 2.5 million during the offpeak period, and 3 million

vehicles during the evening peak period. Surrey has a wide range of road categories with a mixture of urban, suburban and rural areas. The total distances and peak morning traffic volumes by these road types are shown in the table below.

Road Type	Total for Surrey			
	Km	% of Total	Traffic volume	% of Total
Motorway	225	12.4%	662,973	19.5%
Urban Trunk	13	0.7%	73,783	2.2%
Rural Trunk	52	2.9%	245,734	7.2%
Urban Primary	107	5.9%	392,353	11.5%
Rural Primary	146	8.1%	367,060	10.8%
Urban Other A Roads	209	11.5%	607,660	17.8%
Rural Other A Roads	134	7.4%	211,917	6.2%
Urban B Roads	188	10.3%	287,483	8.4%
Rural B Roads	183	10.1%	147,252	4.3%
Urban Other Roads	235	12.9%	266,998	7.8%
Rural Other Roads	323	17.8%	141,885	4.2%
Total	1,815		3,405,098	

Table 11: *Profile of Surrey road network*

4.6 Speed Flow Formulae

This worksheet contains the formulae for three speed flow options namely Akcelik's Time Dependent, the updated BPR (Bureau of Public Roads) and COBA. The main "Parameters" worksheet allows any of these three speed flow techniques to be selected, but this research has concentrated on the COBA speed flow model as this is the accepted approach in UK transportation models (DfT, 2007). The other two options have been included because they have been analysed, used and cited in many research studies (Singh, 1999), but not specifically in the UK. Subsequent research may like to consider how the results produced by the revised vehicle routing model are impacted when these alternative speed flow methods are used.

The worksheet contains the 48 SCC road categories in rows 22 to 69 and the COBA speed flow formulae have been inserted in columns V to AF, each column representing one of the 11 COBA road categories. This is shown in figure 15 below.

	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1	RC1	RC2	RC3	RC4	RC5	RC6	RC7	RC8	RC9	RC10	RC11	
2	5	5	5	5	5	5	-	-	-	5	5	PHV
3	45	45	45	45	45	45	25	15	30	25	35	Min Speed
4	8.5	-	-	-	-	-	-	-	-	-	-	CWID
5	-	108	115	111	118	118	-	-	-	-	-	KI
6	-	6	6	6	6	6	-	-	-	-	-	SI
7	-	-	-	-	-	-	80	80	80	-	-	DEVEL
8	-	-	-	-	-	-	-	4.5	-	1.0	1.0	INT
9	-	-	-	-	-	-	-	-	50	-	-	P30
10	-	-	-	-	-	-	-	-	-	35	35	AXS
11	-	-	-	-	-	-	-	-	-	70	84	C
12												
13	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	Q
14	1489	1953	1953	2167	2167	2167	-	-	1200	1631	1631	Qc
15	1191	1080	1080	1200	1200	1200	-	-	700	1142	1142	Qb
16	50	92.5	92.5	92.5	92.5	92.5	-	-	45	-	-	Vb
17	-	-	-	-	-	-	48.5	33.9	-	59.8	73.8	Vo
18												
19	55.8	102.0	109.0	105.0	112.0	112.0	25.0	15.0	31.5	31.1	45.1	VI =

Figure 15: *Parameters used for each of the 11 COBA speed flow formulae*

The main fixed parameters associated with road characteristics such as road width (CWID), percentage of HGV's (PHV), percentage of route with frontage development (DEVEL), frequency of intersections (INT), various capacity limitations (Q, Qc, Qb, Vb, Vo), etc., are in rows 2 to 17 for each of these 11 columns. Some entries are blank because they are not relevant to the formula for a specific road category. The detailed formulae and variable names are described in Appendix A.

When the button "Create Revised RN Links" is selected on the main "Parameters" worksheet, the vehicle flow information is extracted, in turn, from each the 1,989 links in the SCC road network and inserted sequentially into column R, and in the row corresponding to the road category of the link, in the "Speed Flow" worksheet. The worksheet then automatically calculates the predicted speed for the formula as shown for a number of selected road types in figure 16 below.

90

Road Category	Road Type	COBA Road Class (estimated)	Vo (SO) [Kph]	Vb (SF) [Kph]	Traffic Volume Q (F)	(SC) [Kph]	Qc (C)	Esimated travel speed [Kph]	RC1	RC2	RC3	RC4	RC5	RC6	RC7	RC8	RC9	RC10	RC11
10	Motorway - No Speed Flow	4	68	56	1050	25	1050	49				49							
11	Motorway - 1 lane	4	54	39	188.5	25	2400	97				97							
12	Motorway - 6 lane	6	110	105	1200	45	13650	98						98					
13	Motorway - 2 lane rural	4	111	104	1022.6	45	4800	94				94							
14	Motorway - 2 lane urban	4	105	99	989.9	45	4660	94				94							
15	Motorway - 3 lane	5	110	105	3527.5	45	7000	97					97						
16	Motorway - 4 lane	6	110	105	4820.6	45	9100	89						89					
17	Motorway - 5 lane	6	110	105	1200	45	11375	98						98					
20	Trunk - No speed flow	7	78	64	1026.1	45	5400	47							47				
21	Trunk - 2 lane suburban	10	84	65	1868.1	45	1700	25										25	
22	Trunk - 3 lane suburban	11	91	72	1901.2	45	1700	35											35
23	Trunk - Dual 2 lane urban	7	78	66	609.3	35	2800	60							60				
24	Trunk - Dual 3 lane urban	7	84	64	1100	45	2800	51							51				
25	Trunk - 2 Lane 10 m rural	2	87	71	1901.2	45	1550	49		49									
26	Trunk - Dual 2 lane rural	2	100	95	2170.6	45	3600	95		95									
27	Trunk - Dual 3 lane rural	3	107	102	3069	45	5400	97			97								
30	Desig / Cty Primary - 2 lane non-central urban	7	34	24	1867.2	15	830	25							25				
31	Desig / Cty Primary - 2 lane suburban	10	37	25	1391	15	1570	25										25	
32	Desig / Cty Primary - 3 lane suburban	11	68	56	3690.5	25	1570	35											35
33	Desig / Cty Primary - Dual 2 lane urban	11	78	66	631.4	35	2600	60											60
34	Desig / Cty Primary - 2 lane rural 7.3m	1	78	64	36.8	45	1430	71	71										
35	Desig / Cty Primary - 2 lane 10m rural	1	91	72	1164.3	45	1430	71	71										
36	Desig / Cty Primary - Dual 2 lane rural	2	100	95	1227.4	45	3300	93		93									
37	Desig / Cty Primary - No speed flow	1	87	72	4124.1	45	2388	45	45										
40	Other A road - 2 lane non-central urban	7	34	24	928.1	15	790	25							25				
41	Other A road - 2 lane suburban	10	37	25	1921.1	15	1490	25										25	
42	Other A road - 3 lane suburban	11	68	56	1096.5	25	1490	37											37
43	Other A road - Dual 2 lane urban	11	78	66	1156.2	35	2450	45											45
44	Other A road - 2 lane rural 7.3m	1	78	64	721.3	45	1350	60	60										
45	Other A road - 2 lane 10m rural	1	91	72	726.5	45	1350	60	60										
46	Other A road - Dual 2 lane rural	2	100	95	463.9	45	3150	93		93									
47	Other A road - No speed flow	11	70	58	249.4	45	3150	63											63

Figure 16: *Predicted speed calculations from COBA formulae*

This speed is held in column U of the worksheet, for the appropriate road category. The model then extracts this speed and inserts it in the worksheet "Rev SCC Links" against the link being examined. For each link, the three traffic volumes associated with peak morning, off peak and peak evening are used to obtain three predicted speeds from this "Speed-Flow" worksheet.

On completion a modified set of links containing an estimation of speed derived from the selected speed flow formula, will have been created in the "Rev SCC Links" worksheet. The model then goes on to apply a variability to this average speed so that a realistic fuel consumption can be estimated.

4.7 TRL Driving Cycles and Fuel Consumption Formulae

It has been shown that using an average speed for the entire length of a link produces a value for fuel consumption which could be up to 40% different from a more accurate approach of using driving cycles (Palmer, 2005). This worksheet contains the driving cycle data which consists of second by second speeds for each of three speed profiles, namely urban freeflow, urban congested and suburban freeflow. From these speeds an estimate of distance travelled in each second is calculated. Based on Bowyer's et al (1985) instantaneous fuel consumption model, and the key parameters necessary to apply the formulae, the acceleration is calculated and, from this, fuel consumption is estimated for each second. The parameters necessary to drive the formula are

- An idle fuel rate in mL/sec
- Mass in kg
- Energy efficiency parameter in mL/kJ
- Energy-acceleration efficiency parameter in mL/(kJ.m/sec2)
- Drag force parameter in kN, mainly related to rolling resistance and the drag associated with the engine
- Drag force parameter in kN/(m/s)2, mainly related to aerodynamic resistance and the drag associated with the engine
- Drag fuel consumption component in mL/m, mainly due to rolling resistance
- Drag fuel consumption component in (mL/m)/(m/s)2, mainly due to aerodynamic resistance

The values used, shown in table 7, correspond to a light goods delivery vehicle and have been obtained from discussions with vehicle manufacturers, as well as Freight Best Practice (2006) and Sturm and Hausberger (2005).

The model considers the average speed for each link in turn. If the link corresponds to an urban or suburban area, these driving cycles will be used. If the link is a motorway, or rural road then driving cycles for these roads are not available to the author and fuel consumption is calculated using the average speed with Akcelik's (1982) elemental model. This fuel consumption value, in litres, is added to the corresponding link in the "Rev SCC Links" worksheet, as is the estimate of CO_2 emissions by multiplying the fuel consumption by a factor of 2.7 representing the typical emissions for a litre of diesel fuel.

If the link is an urban or suburban road, the average speed generated by the COBA speed flow formula (Vc) is used to estimate the time (Tc), in seconds, to traverse the link using the formula:

Time Tc = Length of the link / Average speed across the link

The model uses a random number generator to select a block of time (Tr) in the appropriate driving cycle data corresponding to this time Tc. The model then calculates the average speed (Vr) over time Tr. To ensure that the driving cycle data in time Tr is compatible with the average speed Vc, the speed at each second of Tr is adjusted by the ratio Vc/Vr, and a new fuel consumption is automatically calculated for the speeds over time Tr. The fuel consumed is summed over time Tr to produce a fuel consumption figure for the link. This value, in litres, is added to the corresponding link in the "Rev SCC Links" worksheet, as is the estimate of CO_2 emissions which is generated by multiplying the fuel consumption by 2.7kg of CO_2 per litre of diesel fuel.

4.8 Revised Surrey County Council Links

This worksheet contains the output from running the "Create Revised RN Links" option in the "Parameters" worksheet. Each of the links will have the necessary parameters to enable routes to be analysed using the three

minimisation criteria of time, distance and CO_2. Although the values in this worksheet cover the three time periods of peak morning, off peak and peak evening, the VRP model acquired for this research does not have the functionality to create routes with regard to different time periods. Therefore, the model only uses the data calculated for peak morning.

4.9 The Extracted Store and Day Delivery Database

To generate the set of delivery data to be routed from the one week sample of supermarket home deliveries, the depot and delivery day is specified in the "Parameters" worksheet and the "Create Calls Data" button is selected. This causes the model to read through the entire delivery data in the "SurreyDels" worksheet and copy across to the "Customer Calls" worksheet those deliveries that correspond to the specified depot and delivery day. The format of this data is defined by the VRP model and each delivery is held in the "Customer Calls" worksheet with the following parameters:

- Customer number
- Latitude and longitude coordinates so the delivery location can be displayed on a map
- The nearest node code to the customer so that the delivery can be attached to the road network
- A delivery quantity which is always set at 1. This implies that each customer represents one delivery rather than the physical quantity being delivered to the customer. The delivery data provided by the retailer did not include specific delivery quantities. If any customer delivery quantities are used such as boxes, bags, kilograms, or cubic metres, etc, then the vehicle carrying capacity should be expressed in the same quantity units.
- The delivery time window specified as the earliest arrival time and the latest arrival time. The VRP model requires this information in minutes so for instance 8.00am is specified as 480.

- The time to perform the delivery, and covers the time period from when the driver stops the vehicle to begin the delivery until the driver starts the engine to travel to the next delivery location. From discussions with the retailer this value has been set as 10 minutes for all customers. In reality customers would have different times depending on the quantity to be delivered, and the type of delivery such as the top floor of a block of flats which would incur significantly more than 10 minutes. However, on average, a time of 10 minutes was deemed reasonable.

4.10 Store Operating Details

The VRP model has been designed to route deliveries from only one depot at a time. In this worksheet the parameters for a single store (referred to in the model as a depot) are added according to the depot name that has been specified in the "Parameters" worksheet. The details held on this worksheet are:

- A depot code which is always set at 0 as required by the VRP model
- Latitude and longitude coordinates so the depot location can be displayed on a map
- The nearest node code to the depot location so that the depot can be attached to the road network
- The opening hours for the depot corresponding to the earliest time that a vehicle can set off from the depot and the latest time at which a vehicle can return to the depot. As with the customer calls, the VRP model requires this information in minutes

4.11 Delivery Vehicle Operating Details

The details held on this worksheet reflect the requirements of the VRP model. The parameters are:

- A vehicle name which is not used within the model but only required for reference purposes
- A cost per km which has been set at 30p from discussion with the retailer and reference to standard vehicle costing tables (MTCT, 2006). This cost would typically include fuel, oil, maintenance and tyres.

- A cost per minute which has been fixed at 32.5p from discussion with the retailer and reference to standard vehicle costing tables (MTCT, 2006). This would typically include the cost of vehicle depreciation, financing costs, licences, insurance and the cost of a driver.

- The VRP heuristic allows for the use of a fixed vehicle cost but this facility has not been used in this research

- A vehicle capacity in the same quantity units as the customer deliveries

- The gross vehicle weight and tare weight, which is not required by the VRP model and has not been used, but could be subsequently applied in future research to reflect a vehicle gradually getting lighter as deliveries are undertaken, which would result in less CO_2 emissions as a vehicle progresses through a route.

- A value of CO_2 per tonne emitted. This has been set at £22.52 which is derived from a DEFRA central value of £82.59 per tonne of carbon, as discussed in chapter 1, using the standard conversion factor of 12/44 (DEFRA, 2007a).

4.12 Time, Distance and CO_2 Matrices

At this stage all the parameters are in place to enable routes to be identified based on specific minimisation criteria. The VRP model, as is common with most vehicle routing and scheduling software, inputs a matrix of routes between a depot and all customer delivery locations to enable the software to sequence deliveries in the most efficient manner. This matrix represents a set of from and to locations each with a summary of the time taken, distance travelled and CO_2 emitted, and the road network nodes used to travel between the two locations. An example of this is shown in figure 17 below.
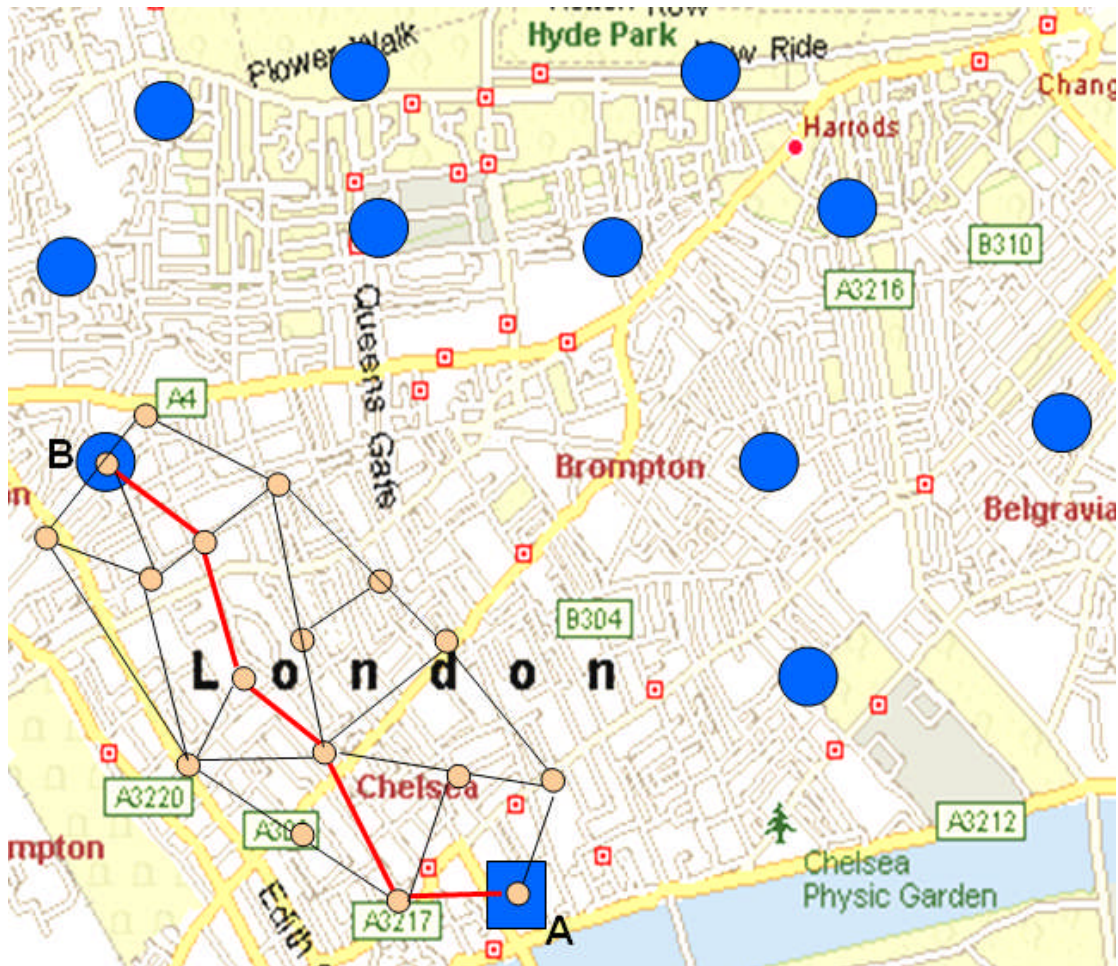
Figure 17: *Schematic example of possible routes between a depot A and customer delivery location B*

In this diagram the blue circles represent the delivery locations and the blue square is the depot location. It can be seen that there are many possible routes between depot location A and a delivery location B. The key parameters for each link are the distance, time and CO_2 emissions. A route which minimises one of these parameters is shown in red. When the option "Create Dist/Time/CO2 Matrix" is selected on the "Parameters" worksheet, Dijkstra's shortest path algorithm is invoked which finds routes which minimise each of these parameters for all the depot and delivery location combinations. For this VRP model, three matrices are required, one for each of the three minimisation criteria. For instance, if the minimisation criterion is time then the quickest route between two locations will be found, together with the distance and CO_2 emissions for this route. If the minimisation criterion is distance then the shortest route between two locations will be found, together with the time and CO_2 emissions for this route. If the minimisation criterion is CO_2 then the

cleanest route between two locations will be found, together with the time and distance for this route. In each of the three matrices, each node used on a route is retained so that a road category analysis can be undertaken.

The output from this option is held in three worksheets called TimeMat, DistMat and CO2Mat.

4.13 Intermediate Model Results

The "Results" worksheet holds detailed information about each iteration as the model runs, and is as much about diagnostic checking as it is about producing results. When the VRP model was being developed a significant amount of data was output to this worksheet to enable detailed checking and validation of the results of each iteration.

When the option "Run VRP Heuristic" is selected from the "Parameters" worksheet, if "New" is shown in the results box, all previous results are cleared ready to accept the best results from this set of iterations. If "Retain" is shown the current results on the "Parameters" worksheet are kept for comparison with the output from this run.

The delivery data, depot data, vehicle data and the routing matrix corresponding to the minimisation criterion specified on the "Parameters" worksheet, are then input to the VRP model. The model uses various heuristics as described in section 3.9 to produce a set of routes that satisfy the minimisation criteria as well as delivery time windows, vehicle and depot operating constraints. The detailed results of each iteration of the model are output to this "Results" worksheet and shows the delivery sequence for each route with arrival and departure times, distances, travel times and CO_2 emitted between deliveries. A check is made to see if the result of this iteration improves any result displayed on the "Parameters" worksheet. If so the result of the current iteration are used to update the values on the "Parameters" worksheet.

4.14 Visual Representation of the Routes

On completion of the VRP run, a map of the routes produced by the best iteration can be shown. Selecting the option "Display Routes" on the "Parameters" worksheet presents the user with a map of Surrey on which are displayed all the routes for the best iteration generated by the model. This map is a standard Excel XY scatter graph with data points connected by smoothed lines. The background map of Surrey has been added as a picture fill effect option, so that it appears as though routes are displayed on a map. Deliveries are identified by the red circle with a schematic of the links between the deliveries. Because of the graph technique used, the actual roads travelled by the vehicles are not shown. On this map individual routes can be displayed if required. Selecting the "Back" option returns the user to the main "Parameters" worksheet.

4.15 Summary

This chapter has described the model which was developed using Microsoft Excel, and consists of 16 worksheets supported by comprehensive macros to produce the required results.

Each of the worksheets have been described together with the way they integrate with each other.

The next chapter discusses the analyses undertaken and the results of using this model to assess the overall implications of CO_2 emissions from using different minimisation criteria.

5 Modelling Analyses and Results

5.1 Introduction

This chapter presents the results of using the vehicle routing model described in the previous chapter. In the first instance the model was used to examine how routes and emission values change when different minimisation criteria are applied. As discussed in the previous chapter, this used a one week sample of home deliveries provided by a supermarket retailer, and the Surrey County Council (SCC) road network with traffic volumes reflecting the road situation in 2005. The model was then used to assess the fuel consumption, distance and time impacts of increasing levels of congestion. According to the Department for Transport, by 2015, total traffic on the roads will have grown by over 30 per cent compared to 2000 levels (Transport Select Committee, 2007). The traffic volumes in the SCC road network data correspond to 2005 so an increase factor of 20% was applied to the traffic volumes on all links in the model to assess the 2015 impact. This affects the various road speeds so that the implications on route decision making, times and fuel consumption can be examined. As well as time, distance and CO_2 emissions, the cost implications were also calculated which included the value of £22.52 per tonne of CO_2 as used by the Department for the Environment, Food and Rural Affairs (DEFRA, 2007c). As discussed in section 2.6, this figure is open to interpretation, and it is likely to change as more information becomes available.

In total the model has been run over 300 times to produce the results discussed below. The model is computationally intensive with the Dijkstra shortest path matrix calculations taking an average of one hour each time it is run and the VRP heuristic model taking approximately 20 minutes for each run. It has therefore taken approximately 400 hours of computation time to produce these results.

5.2 Data Input

The sample of home deliveries provided by the supermarket retailer covered a one week period in July 2005 and covered the whole of Great Britain. To be compatible with the area of the road network used in the model, only those deliveries made in the county of Surrey were selected for analysis. A profile of the deliveries is shown in the graph below.
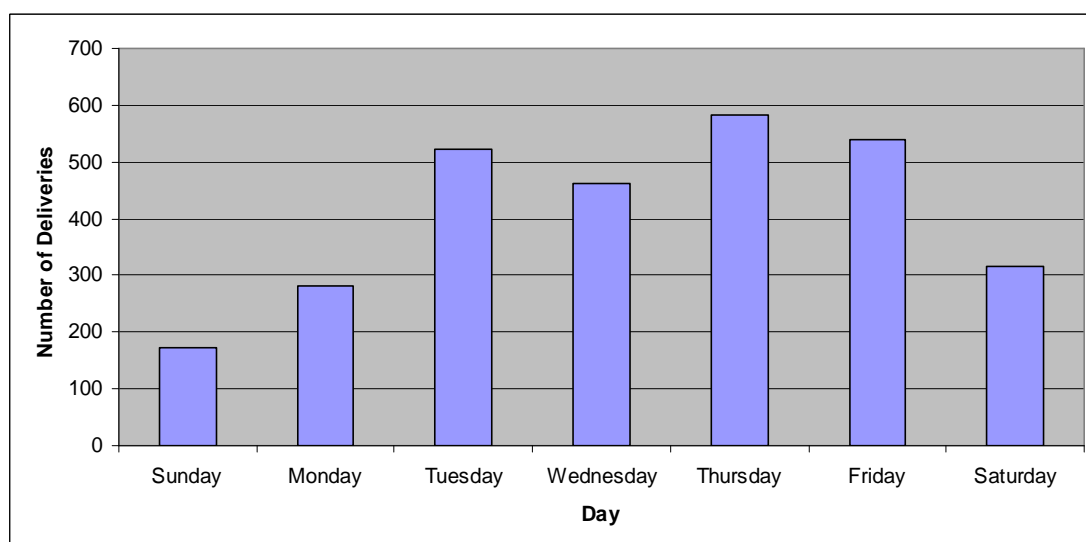
Figure 18: *Profile of all Surrey deliveries by day in the sample week*

In total 2,871 deliveries were made in Surrey in that one week period from five stores located in Brookwood, Cobham, Epsom, Camberley and Farnham, with the profile showing the peak days occurring between Tuesday and Friday representing 73% of the weeks deliveries. Thursday is the peak day with 20% of the weeks deliveries. Prior to July 2005, the retailer had significant peak days on Thursday and Friday of each week but then introduced a delivery charge for orders placed on these two days whilst keeping the other days free of any delivery charge, and this helped to smooth out the daily delivery volumes. This enables the number of vehicles in the fleet to be used more efficiently and cost effectively. The profile above shows the effect of this peak day delivery charge.

The vehicle used for these deliveries was a Mercedes 311 CDI with a gross vehicle weight of 3500 kg, and capable of carrying up to 12 customer orders. The vehicles were operated on behalf of the supermarket by a third party

logistics company and the costs of operating these vehicles were confidential to the supermarket. Consequently costs were derived from Motor Transport Cost Tables of June 2004, and were £156 per day representing the fixed cost of the vehicle including driver and national insurance, depreciation, licences, insurance and overheads, and 30 pence per km representing the variable cost of running the vehicle including diesel fuel, tyres, maintenance and oil.

5.3 Results

The model was used to produce routes for the 7 days over which the deliveries were made from 5 store locations, for the three minimisation criteria of time, distance and CO_2 emissions. The model contains certain randomisation elements as described in section 3.9, so for each of these 105 runs, the model performed 20 iterations to try and ensure the minimisation criterion was achieved. At the completion of these iterations the final results were displayed and recorded as shown in table 11 below.

No. of Deliveries	171	282	522	461	581	539	315	2871
MC=Time	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Total
Routes	17	29	52	47	57	53	30	285
Driving time (mins)	1741	2924	4667	4315	5217	4927	3159	26950
Distance travelled (km)	1108	1830	2912	2693	3254	3117	2006	16920
CO_2 emitted	294	495	805	736	896	853	527	4606
Cost	£898	£1,499	£2,390	£2,210	£2,672	£2,536	£1,629	£13,834
Cost including CO_2	£905	£1,510	£2,408	£2,227	£2,692	£2,555	£1,640	£13,938
MC=Dist	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Total
Routes	16	31	51	47	57	51	29	282
Driving time (mins)	1741	3038	4955	4385	5367	5145	3200	27831
Distance travelled (km)	1021	1687	2766	2461	3105	2893	1774	15706
CO_2 emitted	272	478	781	707	880	825	496	4439
Cost	£872	£1,493	£2,440	£2,164	£2,676	£2,540	£1,572	£13,757
Cost including CO_2	£878	£1,504	£2,458	£2,179	£2,695	£2,558	£1,584	£13,857
MC=CO_2	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Total
Routes	16	30	50	47	57	54	30	284
Driving time (mins)	1742	3087	4909	4433	5480	5139	3170	27960
Distance travelled (km)	1026	1793	2825	2508	3171	2979	1787	16091
CO_2 emitted	271	469	781	704	865	809	485	4384
Cost	£874	£1,541	£2,443	£2,193	£2,732	£2,564	£1,566	£13,914
Cost including CO_2	£880	£1,552	£2,461	£2,209	£2,752	£2,582	£1,577	£14,013

Table 12: *Summary results of one week's analysis of the base year*

This table shows, for each of the three minimisation criteria (MC), the number of deliveries to be routed for each day of the week, as a total for all five stores, and the number of routes produced by the model, which indicates that on average about 10 deliveries can be achieved per route. The vehicle being used has a maximum capacity of 12 deliveries so the vehicle, typically, has a capacity utilisation of 83%. Also shown on table 11 is the total driving time,

distance travelled, CO_2 emitted, and the cost of the vehicles, which includes the cost of CO_2.

As would be expected, the results in table 11, shows that the time minimisation criteria produces the least time taken than any of the other options, similarly, the distance minimisation criteria produces the least number of kilometres, and the CO_2 minimisation criteria produces the least emissions, for the base year. For the deliveries minimised by time, a total of 285 routes for the week were produced by the model, compared to 282 routes for distance minimised deliveries and 284 for CO_2 minimised deliveries. The difference between the number of routes generated for the three minimisation criteria are caused by the different roads used to travel between the deliveries, and the way the three heuristic processes in the VRP model sequence deliveries on the vehicle routes. This sequencing is also affected by the two hour time window for each of the deliveries. The routes generated on Sunday, for instance, vary between 16 and 17 routes depending on the minimisation criterion. Although there are fewer deliveries on Sunday, the traffic volumes on the roads are the same for each day of the week, and this could also influence the sequencing of deliveries, and therefore number of routes. If the cleanest routes were chosen the overall time increases by 3.7% in the base year, although there is one less route generated. When examining the detail there are a significant number of instances were the cleanest routes were also shown to be the shortest routes. Of the 35 runs of the model, representing 5 stores for 7 days, 15 of the runs produced the same time, distance and CO_2 emission values for both minimisation criteria of distance and CO_2. Four runs produced the same time, distance and CO_2 emission values for all 3 minimisation criteria. These tended to be on days were there were few deliveries to be made and hence the opportunity for finding better routes and delivery sequences was limited.

The VRP model incorporates two elements of randomisation which are used in the initial construction heuristic. Therefore, a series of sensitivity tests were undertaken to assess the implications of this randomisation, and to check the stability of the base year results. The first random element within the VRP

model produces a seed value which is used in the second randomisation process. Each delivery is weighted according to the quantity to be delivered, the distance from the depot and the narrowness, or tightness, of the delivery time window. In all the analyses undertaken, all the deliveries have a two hour delivery time window and they all have a delivery quantity of one Therefore, the weighting of deliveries is only related to the distance from the depot. In the initial route construction process, the delivery with the highest weighting, i.e. the delivery furthest from the depot, is selected and allocated its own route. All the remaining unallocated deliveries are given a random value using the random seed generated previously. Unallocated deliveries are then selected, one at a time, in a sequential order of increasing random value, and added at the most appropriate position within this route, each time checking that journey time and vehicle carrying capacity is not exceeded. When this route is complete, the next unallocated delivery with the highest weighting is selected, and the remaining deliveries added in the same way according to the random values. The VRP model then uses two further heuristic techniques to try and improve the efficiency of these routes according to the selected minimisation criterion. It is clear from this approach that the efficiency of these routes may depend on the initial randomised route construction process. The results for the base year are based on 20 iterations of the model for each depot, day and minimisation criterion combination. The solution which produces the lowest value to satisfy the minimisation criterion is selected out of the results produced from the 20 iterations.

To test the stability of these results a sensitivity analysis was undertaken. The model was run 10 times, each time finding the lowest value from 8 iterations of the model, that satisfied the minimisation criterion for a given depot and day combination. Five depot and day combinations were selected for the three minimisation criteria of time, distance and CO_2. The coefficient of variation, which is the standard deviation expressed as a percentage of the mean, was calculated from the results produced by each of the 10 model runs, and are shown in table 12 below.

		Store 1 Thursday	Store 2 Thursday	Store 3 Thursday	Store 1 Monday	Store 4 Friday
	No of deliveries	184	149	118	92	65
Minimum Time	Total driving time	2.6%	2.1%	1.3%	1.5%	1.8%
	Total distance	2.9%	2.3%	0.8%	2.3%	1.9%
	Total CO_2 emissions	2.0%	1.9%	0.6%	1.4%	1.4%
	Total cost inc CO_2	2.6%	2.1%	1.0%	1.7%	1.8%
Minimum Distance	Total driving time	2.4%	1.6%	1.0%	2.0%	1.1%
	Total distance	2.6%	1.4%	0.7%	2.5%	1.0%
	Total CO_2 emissions	2.3%	1.2%	0.7%	2.1%	0.9%
	Total cost inc CO_2	2.4%	1.5%	0.9%	2.2%	0.9%
Minimum CO_2	Total driving time	2.4%	1.6%	1.6%	2.5%	1.0%
	Total distance	2.7%	2.5%	1.7%	3.1%	1.0%
	Total CO_2 emissions	1.9%	1.4%	1.5%	2.4%	0.4%
	Total cost inc CO_2	2.5%	1.7%	1.6%	2.7%	0.8%
Redn in CO_2 - Time v CO_2		2.4%	1.7%	1.1%	1.8%	1.2%
Redn in CO_2 - Dist v CO_2		2.2%	1.2%	1.6%	3.1%	1.1%

Table 13: *Coefficient of variation for sensitivity testing*

The table shows the average variability that can be expected for each of the four output values of driving time, distance, CO_2 emissions and cost, for each of the three minimisation criteria. The table also shows the coefficient of variation associated with the potential reduction in CO_2 between time and CO_2 minimised routes and between distance and CO_2 minimised routes. The values produced by the sensitivity analysis are very low and vary from 0.4% to 2.9%, indicating that the randomisation process within the VRP model does not significantly affect the outcomes. The reason for this could be that the VRP model only uses this randomisation process in the first heuristic, and the routes produced are then refined by two further heuristics. The refining process may therefore reduce the effect of the randomisation. The time values generated by the base case analysis could vary by between 1.6% and 1.8%, depending on the minimisation criterion. Similarly, the distance could vary between 1.6% and 2.2%, and the CO_2 emission values between 1.6% and 1.8%.

The results of this sensitivity analysis were used to examine the reduction in CO_2 between time minimised and CO_2 minimised routes. The 50 model runs (10 runs for each of the 5 store/day combinations) produced an average reduction of 5.02%, at a 95% confidence interval of +/- 0.7%. This suggests that average reduction values would fall within a range of 4.32% to 5.72%. A

similar analysis for CO_2 reduction between distance and CO_2 minimised routes produced an average reduction of 5.2% at a 95% confidence interval of +/- 1.2%, giving a slightly wider range of 4% to 6.4%

Table 13 below shows a summarised analysis of the base year results and it indicates that if the minimisation criterion is changed from time, which is the common method within commercial VRS software, to CO_2, then a reduction of 4.8% in CO_2 emissions could be expected. This value falls within the 95% confidence interval of 4.32% to 5.72% produced by the sensitivity analysis. If the minimisation criterion is changed from distance to CO_2 then a smaller saving of 1.2% in CO_2 emissions could be expected, in the base year. However this value falls outside the 95% confidence interval produced by the sensitivity analysis.

	Min Time	Min CO_2	% difference
Routes	285	284	-0.4%
Mins	26950	27960	3.8%
Kms	16920	16091	-4.9%
CO_2	4606	4384	-4.8%
Cost	£13,834	£13,914	0.6%
Cost inc CO_2	£13,938	£14,013	0.5%

	Min Dist	Min CO_2	% difference
Routes	282	284	0.7%
Mins	27831	27960	0.5%
Kms	15706	16091	2.4%
CO_2	4439	4384	-1.2%
Cost	£13,757	£13,914	1.1%
Cost inc CO_2	£13,857	£14,013	1.1%

Table 14: *Percentage difference between minimisation criteria for base year results*

These figures represent a weighted average across the five stores and seven days on which the deliveries were made. An analysis was undertaken to assess the variability of the possible reduction in CO_2 emissions between stores and between the days. The overall reduction in CO_2 emissions between time minimised and CO_2 minimised routes for each store is:

- Store 1: 3.02%
- Store 2: 2.94%
- Store 3: 5.00%
- Store 4: 7.81%
- Store 5: 2.52%

producing an overall average reduction of 4.8%

There is a variation in CO_2 reduction of between 2.94% and 7.81% between the five stores. Examining the characteristics of the roads in the delivery areas of each store have not shed any light on the possible reasons for these differences. All the stores deliver to a similar mixture of urban and rural areas, with a similar mix of road types used by the vehicles. The reasons could be to do with the traffic volumes on the roads used to make the deliveries, and it may be related to the density of deliveries within each store delivery area.

A similar analysis of the individual days also tends to show that the greatest savings occur on those days were there are fewer deliveries as follows:

- Sunday   7.56%
- Monday   5.20%
- Tuesday   3.03%
- Wednesday 4.32%
- Thursday   3.50%
- Friday   5.17%
- Saturday   7.97%

producing an overall average reduction of 4.8%

It is significant that those days with fewer deliveries (Sunday, Monday and Saturday) tend to show a greater opportunity for reducing CO_2 emissions which indicates that there may be a relationship between CO_2 reduction and density of deliveries.

Of concern to companies would be the impact on costs. If CO_2 is minimised then the overall time increases by 3.8% over the minimised time option, though the distance travelled is reduced by 4.9%. With time based costs of a

vehicle approximately twice that of distance based costs, this causes the overall cost of the routes to increase marginally by 0.6% (0.5% if the cost of CO_2 is included). When comparing CO_2 minimised routes with distance minimised routes, the time increases by 0.5% and the distance by 2.4% resulting in a slightly higher cost increase of 1.1%. Therefore, the opportunity to reduce CO_2 emissions is not achieved at the risk of large increases in time, distance or cost.

An analysis was undertaken to see if there were any distinct patterns, relationships or consistencies across each of the seven days modelled, or between the minimisation criteria. Table 14 shows the distribution of values for all five stores, by the three minimisation criteria (MC) of time, distance and CO_2.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Average	Coefficient of variation
Driving time per delivery (mins)									
MC=Time	10.18	10.37	8.94	9.36	8.98	9.14	10.03	9.39	6.4%
MC=Distance	10.18	10.77	9.49	9.51	9.24	9.55	10.16	9.69	5.6%
MC=CO2	10.19	10.95	9.40	9.62	9.43	9.54	10.06	9.74	5.8%
Average distance per delivery (km)									
MC=Time	6.48	6.49	5.58	5.84	5.60	5.78	6.37	5.89	7.0%
MC=Distance	5.97	5.98	5.30	5.34	5.34	5.37	5.63	5.47	5.5%
MC=CO2	6.00	6.36	5.41	5.44	5.46	5.53	5.67	5.60	6.4%
CO2 emissions per delivery (kg)									
MC=Time	1.72	1.75	1.54	1.60	1.54	1.58	1.67	1.60	5.3%
MC=Distance	1.59	1.69	1.50	1.53	1.52	1.53	1.57	1.55	4.3%
MC=CO2	1.59	1.66	1.50	1.53	1.49	1.50	1.54	1.53	4.1%
Average cost (inc CO_2) per delivery									
MC=Time	£5.29	£5.36	£4.61	£4.83	£4.63	£4.74	£5.21	£4.82	6.7%
MC=Distance	£5.14	£5.33	£4.71	£4.73	£4.64	£4.75	£5.03	£4.79	5.5%
MC=CO_2	£5.15	£5.50	£4.71	£4.79	£4.74	£4.79	£5.01	£4.85	6.0%
Average deliveries per route									
MC=Time	10.06	9.72	10.04	9.81	10.19	10.17	10.50	10.07	2.6%
MC=Distance	10.69	9.10	10.24	9.81	10.19	10.57	10.86	10.18	5.9%
MC=CO2	10.69	9.40	10.44	9.81	10.19	9.98	10.50	10.11	4.4%
Average speed of the vehicle (km/hr)									
MC=Time	38.19	37.56	37.44	37.44	37.43	37.95	38.09	37.67	0.9%
MC=Distance	35.19	33.31	33.49	33.68	34.71	33.73	33.26	33.86	2.2%
MC=CO2	35.34	34.86	34.53	33.94	34.72	34.78	33.84	34.53	1.5%

Table 15: *Analysis of base year results by day of the week*

This analysis of the base year results shows that the overall average driving time per delivery was lowest for the time minimised routes, with distance minimised routes just over 3% higher followed by CO_2 minimised routes at nearly 4% higher. The average distance travelled per delivery was lowest for

the distance minimised routes, and the CO_2 emissions per delivery was lowest for the CO_2 minimised routes.

On the days were there are fewer deliveries (Sunday, Monday and Saturday) there are higher values for time, distance, emissions and cost per delivery than the other four days of the week. This is to be expected considering the vehicle would have further to travel between deliveries because of a lower density of demand.

The average speeds of the vehicles during these three off peak days are also slightly higher than the four peak days, reflecting the longer distances travelled and therefore the opportunity to achieve higher speeds. The average speeds achieved by the vehicles when deliveries are minimised by time are also slightly higher than when deliveries are minimised by distance or CO_2. This may reflect the greater use of motorways to achieve these higher speeds and reduce the time between deliveries. The average speed for CO_2 minimised routes falls between the time and distance minimised options suggesting that the cleanest routes do differ from the quickest or fastest routes. The differences between the average speed values for each of the days is small. This could be due to the fact that the model uses a given traffic volume for a link in the road network, but in reality this value will change by day, particularly on a Sunday when traffic tends to be lighter.

Table 15 below shows a comparison of the kilometres travelled by different road categories, between the three minimisation criteria. This analysis is based on one store over three peak days Wednesday, Thursday and Friday, in the base year.

Km Travelled	MC=Time	MC=Dist	MC=CO$_2$	Percentage change	
				CO$_2$ v Time	CO$_2$ v Dist
Motorway	290	152	146	-50%	-4%
Urban Trunk	47	53	56	20%	7%
Rural Trunk	247	274	329	33%	20%
Urban Primary	98	62	90	-9%	44%
Rural Primary	208	96	143	-31%	49%
Urban Other A Roads	263	325	336	28%	3%
Rural Other A Roads	303	320	342	13%	7%
Urban B Roads	105	169	114	9%	-33%
Rural B Roads	221	242	209	-6%	-14%
Urban Other Roads	143	183	178	24%	-3%
Rural Other Roads	345	299	292	-15%	-2%
Total	2,271	2,175	2,235	-2%	3%

Table 16: *Distance travelled by road categories used by minimisation criteria*

Because of the differences in the values produced by the model for the three minimisation criteria, different routes are being chosen. Comparing deliveries minimised by CO$_2$ with deliveries minimised by time, the table shows a reduction of 50% in the use of motorways which increases the amount of time travelled by the vehicles but, based on the results, contributes towards a reduction in CO$_2$. This reduction in motorway mileage is compensated by an increase in the use of urban roads. Although motorways provide faster routes, the results for minimising CO$_2$ emissions indicate that shorter, more direct routes, using roads that are less congested, thereby achieving an optimum level of speed, produce the least amount of CO$_2$. It also shows a reduction of 31% in rural primary roads with increases in the use of A roads and trunk roads. Whereas comparing the distances by road categories minimised by CO$_2$ and distance, there is a distinct shift from B roads to primary roads. Overall the results tend to show a move away from B roads and minor roads classified as other, towards more major roads, excluding motorways. Rural roads represent over 50% of all distance travelled whatever the minimisation criteria.

Figure 19 below shows a graph of the number of deliveries plotted against the percentage reduction in CO$_2$ emissions between time minimised and CO$_2$ minimised options, and the percentage reduction in CO$_2$ emissions between distance minimised and CO$_2$ minimised options, for each of the seven days.
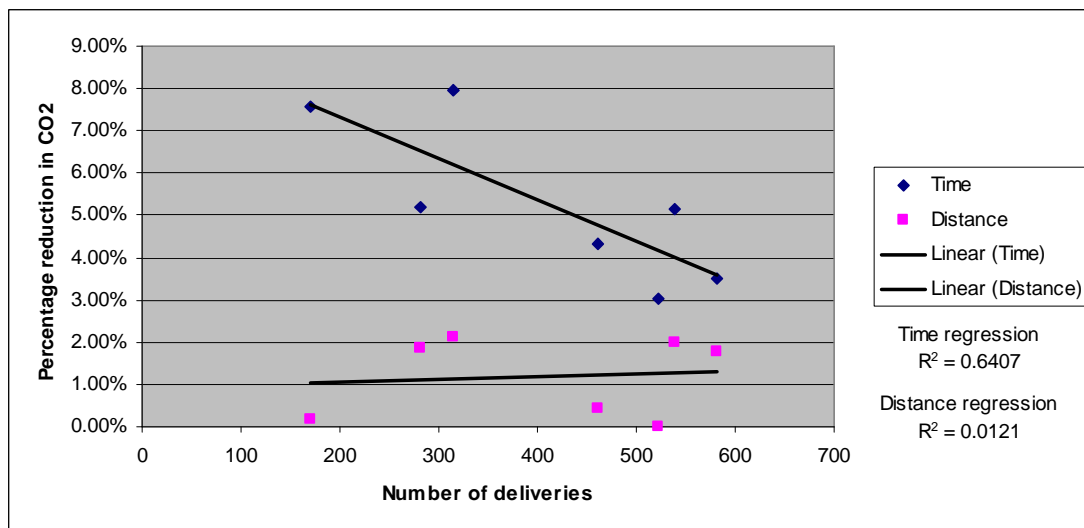
Figure 19: *Graph of percentage reduction in CO_2 emissions against number of deliveries*

The linear regression lines above have the form y = mx + c. The linear time regression line has a negative gradient (m) of -0.0001 and a Y intercept (c) of 9.28%. The linear distance regression line has a slight positive gradient (m) of 0.000007 and a Y intercept (c) of 0.92%.

The graph shows that the more deliveries that are made on any day, there is a declining opportunity to save any CO_2 emissions by running the model on CO_2 minimised criterion compared to time minimised. This is possibly due to the distances travelled between deliveries. The more deliveries there are, the tighter the vehicle routes and the less distance travelled between deliveries. This results in less differential between quicker and cleaner routes and therefore less opportunity to reduce CO_2 emissions. The calculated coefficient of determination of 0.64 indicates that 64% of the variation in the reduction of CO_2 can be explained by the regression line. However, a reduction in CO_2 emissions for routes produced using a CO_2 minimisation criterion compared with a distance minimisation criterion indicates a flat regression line and is insignificant at the 5% level with a coefficient of determination of 0.012.

Figure 20 shows the chart of CO_2 emissions per delivery for each of the three minimisation criteria, over the seven days deliveries took place. The emissions from time minimised deliveries are higher than the other two

options on each day of the week. The emissions per delivery are also shown to be higher on Sunday, Monday and Saturday which have relatively lower numbers of deliveries. The graph also shows that there is a relatively small difference in emissions per delivery between the CO_2 and distance minimised options.
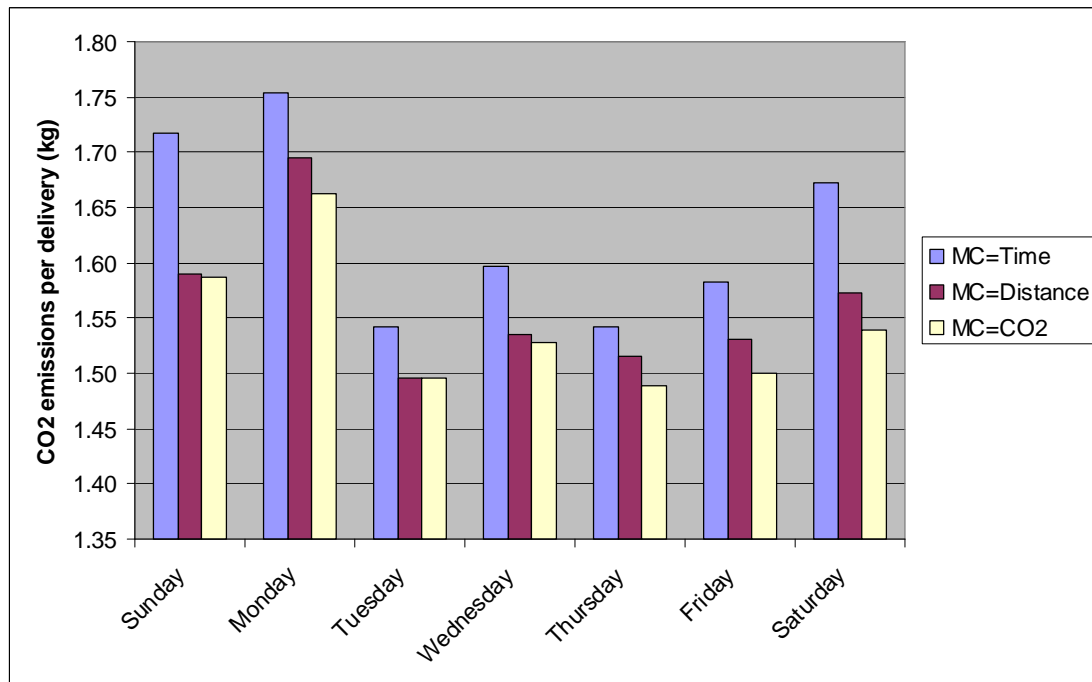
Figure 20: *Chart of CO_2 emissions per delivery*

To reflect the increase in congestion predicted by the Department for Transport for 2015 (Transport Select Committee, 2007), an increase factor of 20% was applied to the traffic volume on each link in the road network. The revised links with updated speeds, fuel consumption and emissions were then generated, and the Dijkstra shortest path algorithm run to produce the three minimisation matrices required by the model. The model was then used to produce routes for each of the 7 days, from the 5 store locations, for each of the minimisation criteria. The results of this set of runs is summarised in table 16 below, together with the base year results for comparison.

Total	Minimisation criteria - Time			Minimisation criteria - Distance			Minimisation criteria - CO2		
	Base Year	Year 2015	Inc %	Base Year	Year 2015	Inc %	Base Year	Year 2015	Inc %
Routes	285	285		282	282		284	284	
Minutes	26950	28170	4.5%	27831	29373	5.5%	27960	28693	2.6%
Kilometres	16920	17373	2.7%	15706	15948	1.5%	16091	16101	0.1%
CO_2	4606	4658	1.1%	4439	4516	1.7%	4384	4394	0.2%
Cost	£13,834	£14,367	1.1%	£13,757	£14,330	1.1%	£13,914	£14,156	1.1%
Cost inc CO_2	£13,938	£14,473	3.8%	£13,857	£14,432	4.1%	£14,013	£14,255	1.5%

Table 17: *Comparison of summary results of one week's analysis for base year 2005 and 2015*

As with the original base year, the results for 2015 also show that the time minimisation criteria produces the least time taken than any of the other options, similarly, the distance minimisation criteria produces the least number of kilometres, and the CO_2 minimisation criteria produces the least emissions.

The percentage increases for time, distance, CO_2 and cost in 2015 over the 2005 base year are relatively small when considering a 20% increase in traffic volume has occurred. Therefore, an analysis of the traffic volumes, which are an attribute of the links in the digitised road network of Surrey, in both years, was undertaken, and it showed that in the base year 1,160 links out of 1,989 were below the roads design capacity. The speed flow formula would therefore estimate a speed near to the maximum for these road sections. The map of the Surrey area in figure 21 shows the links in the road network in either black which indicates a free flowing road, or red indicating a congested road.
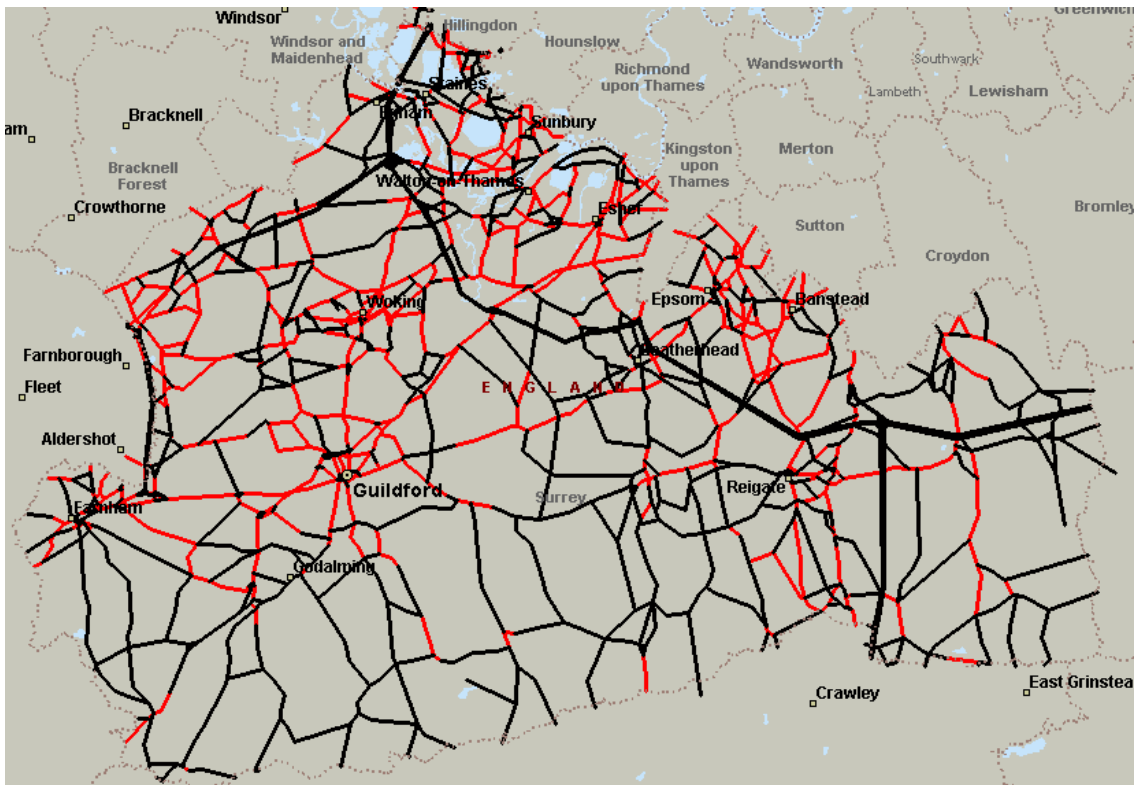
Figure 21: *Road network indicating congested links in the base year*

When a 20% traffic increase is applied, 968 links remain below the roads design capacity and therefore the speed is likely to be slightly lower but remain near to the maximum for these road sections. For those 192 links that exceed the design capacity with the 20% traffic increase, the speed flow formula would reflect a much lower speed as shown in figure 11. The map in figure 22 shows the congested roads in red reflecting this additional traffic volume in 2015.
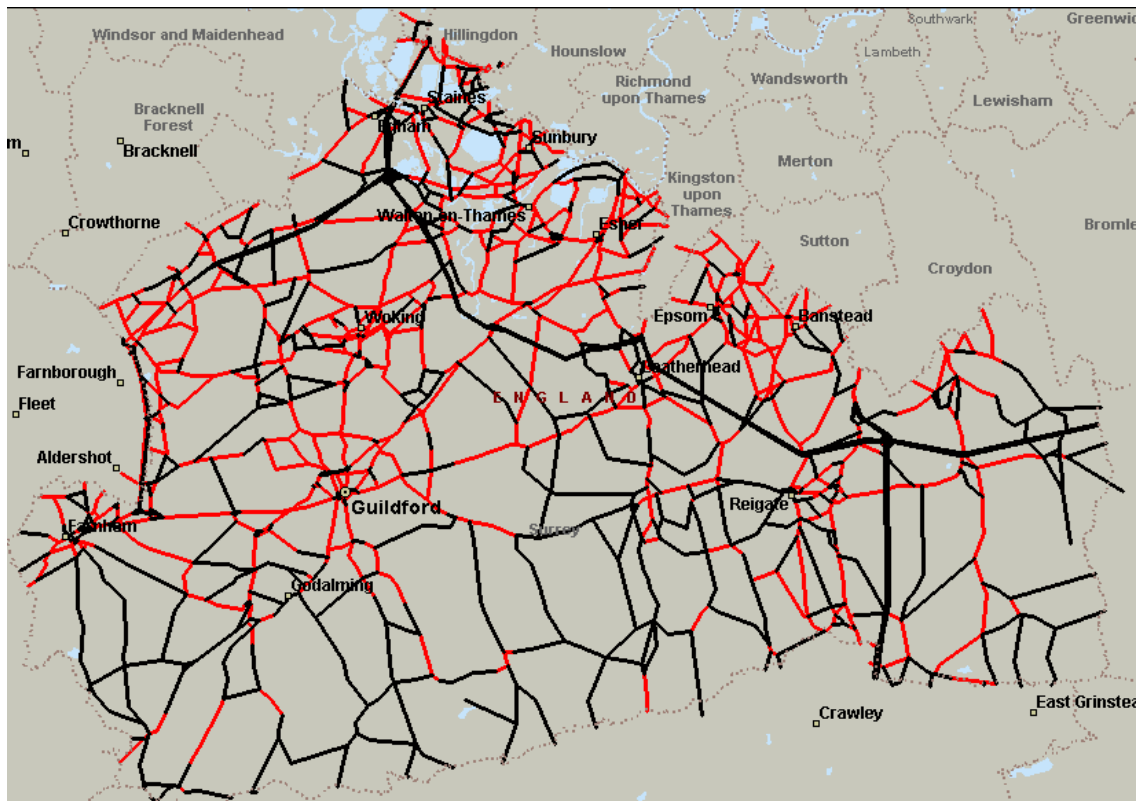
Figure 22: *Road network indicating congested links in 2015*

The results also show that between 2005 and 2015 CO_2 emissions increased by 1.1% for routes minimised by time, but only increased by 0.2% for routes minimised by CO_2 emissions, therefore selecting the CO_2 minimisation criteria instead of the typical commercial requirement of time, produces a 4.8% reduction in emissions for the base year which increases to a 5.7% reduction with higher traffic volumes in 2015. These figures compare favourably with the outcome of a study which examined the quickest and most fuel efficient routes for cars around the city of Lund, Sweden. The results of this study showed a reduction of 8.2% in the amount of fuel used if the most fuel efficient routes were chosen. (Ericsson, 2006).

When the cost of CO_2 is taken into account, for the base year, the shortest routes produce the least cost, followed by the quickest routes and then the routes produced by minimising CO_2 emissions. However, with increasing congestion, alternative routes are found which show that the lowest overall cost occurs with the cleanest routes in 2015. This could be explained by the higher percentage increase in time taken, between the two years, irrespective

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of the minimisation criteria. The fixed time based costs are generally higher than the variable distance based costs.

An analysis was undertaken to look at the change in roads used between the base year and 2015. A sample of three peak delivery days from one store produced the results shown in table 17.

Kilometres	Minimisation criteria - Time			Minimisation criteria - Distance			Minimisation criteria - CO2		
	Base Year	2015	Inc %	Base Year	2015	Inc %	Base Year	2015	Inc %
Motorway	290	259	-10.7%	152	161	5.9%	146	154	5.8%
Urban Trunk	47	49	5.3%	53	57	8.4%	56	59	4.8%
Rural Trunk	247	237	-4.0%	274	277	1.0%	329	309	-5.9%
Urban Primary	98	89	-9.4%	62	63	1.6%	90	90	0.7%
Rural Primary	208	175	-15.7%	96	106	10.8%	143	164	14.8%
Urban Other A Roads	263	282	7.3%	325	319	-1.7%	336	305	-9.2%
Rural Other A Roads	303	331	9.1%	320	325	1.6%	342	304	-11.3%
Urban B Roads	105	140	33.9%	169	170	0.6%	114	115	1.0%
Rural B Roads	221	230	4.1%	242	241	-0.4%	209	244	16.7%
Urban Other Roads	143	159	11.1%	183	184	0.5%	178	164	-7.9%
Rural Other Roads	345	367	6.4%	299	296	-1.0%	292	323	10.3%
Total	2,271	2,320	2.1%	2,175	2,200	1.2%	2,235	2,231	-0.2%

Table 18: *Comparison of roads used for routes between the base year 2005 and 2015*

In the base year, the roads used with the CO_2 minimisation criteria indicate a reduction in the use of motorways and minor rural roads, and an increase in more rural trunk roads, urban and A roads, compared to the time minimisation criteria. The reason for this preference for A roads could possibly be due to freer flowing traffic which would enable the delivery vehicles to achieve the better fuel consumption to produce the lowest emissions. The use of A roads also indicates a preference for shorter routes to achieve the lowest fuel consumption.

As with the base year, there is a significant use of rural roads in 2015 of between 57% and 60% of all mileage, depending on the minimisation criteria.

With the time minimisation criteria, there is a decrease in the motorway mileage by 10.7% and, as before, a general increase in minor roads, between the base year and 2015.

However, there is a similar amount of distance travelled in 2015 for all urban and rural roads between the time and CO_2 minimised criteria. Motorway

usage is reduced by 40% implying that shorter routes are preferred to quicker routes in order to save CO_2 emissions.

Because the reduction in CO_2 emissions between time and CO_2 minimised routes increased from 4.8% in the base year to 5.7% in 2015 with a 20% increase in traffic volumes, a further set of runs were undertaken using a 40% increase in traffic volumes on all roads to test whether this was likely to continue the increasing level of reduction in CO_2 emissions, and to see if there was a correlation between the results. The outcome, shown in the table below, contradicted this hypothesis with an average 4.6% reduction in CO_2 between time and CO_2 minimised routes for this latest set of runs.

Total	Minimisation criteria - Time			Minimisation criteria - Distance			Minimisation criteria - CO2		
	Base Year	Year 2015	Base + 40%	Base Year	Year 2015	Base + 40%	Base Year	Year 2015	Base + 40%
Routes	285	285	286	282	282	286	284	284	284
Minutes	26950	28170	29711	27831	29373	31039	27960	28693	30788
Kilometres	16920	17373	17736	15706	15948	16568	16091	16101	16841
CO_2	4606	4658	4749	4439	4516	4668	4384	4394	4529
Cost	£13,834	£14,367	£14,977	£13,757	£14,330	£15,058	£13,914	£14,156	£15,058
Cost inc CO_2	£13,938	£14,473	£15,084	£13,857	£14,432	£15,164	£14,013	£14,255	£15,161

Table 19: *Comparison of results for three levels of traffic volumes*

Applying a 40% increase in traffic volume to all the links in the road network resulted in 781 links out of a total of 1989 links having flows that were considered to be freeflowing, and the speed flow formulae would have predicted speeds at or near the maximum legal limit for these links. The map in figure 23 below shows the congested roads in red reflecting this additional 40% traffic volume.
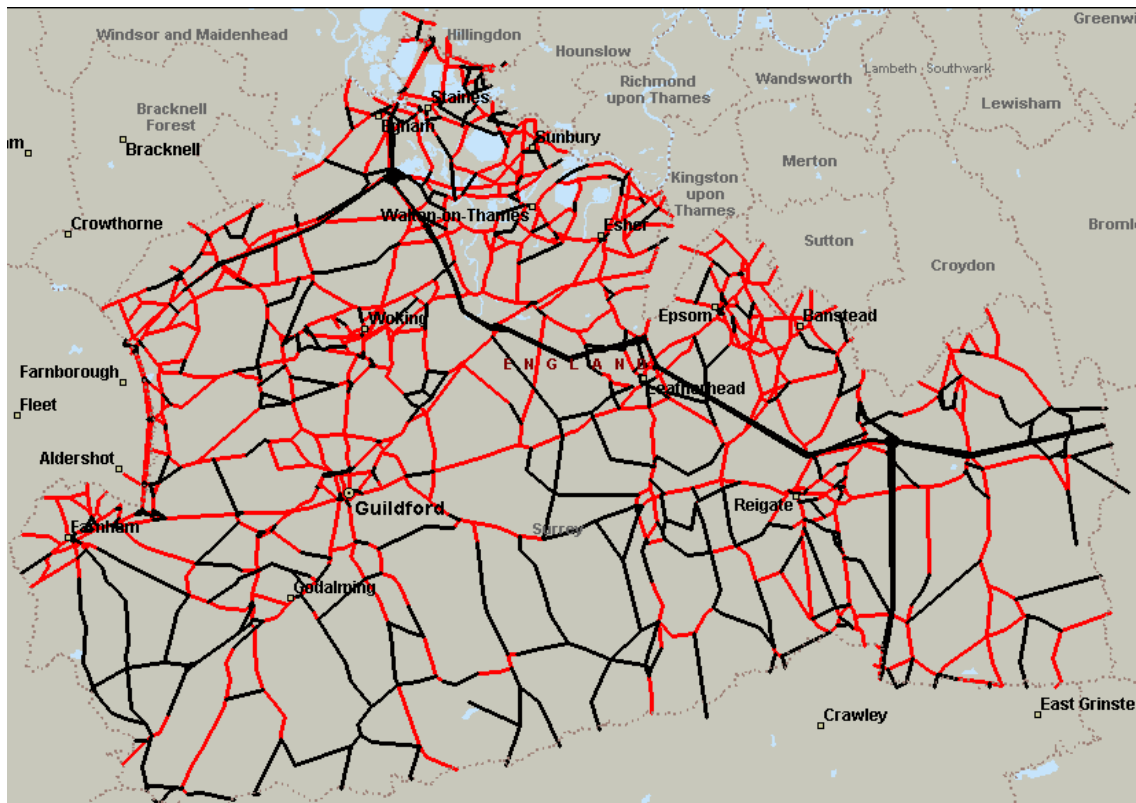
Figure 23: *Road network indicating congested links with 40% extra traffic volume*

When comparing the maps in figures 21, 22 and 23, the increasing number of congested roads in red is apparent.

5.4 The Impact of Other External Transport Cost Factors

Although the issue of reducing CO_2 emissions is of major importance to the UK government, so is the wider issue of long term sustainability. Sustainability is defined by Brundtland (1987) as "meeting the needs of the present generation without compromising the ability of future generations to meet their needs" and encompasses environmental, social and economic factors. Taking into account the cost of transport externalities such as air quality, noise, infrastructure, accidents and congestion as well as CO_2, promotes the concept of sustainable transport and encourages the development of sustainable transport solutions. Several studies have attempted to put valuations on these externalities (INFRAS, 2004; AEA Technology Environment, 2005a; DEFRA, 2007a).

The most recent values specified in the DEFRA report (2007a) have been applied to the results of this research to check if the cost benefits from reducing CO_2 emissions identified in section 5.3 are maintained when the other transport externalities are included. The valuations have been classified by type of road, by type of vehicle, and by time of day as shown in table 19 below.

Vehicle Type	Road Category	Time of Day
Light Goods Vehicle	Urban	Peak 07:00-10:00 and 16:00-19:00
Rigid Vehicles 3.5T – 7.5T	Rural	Off peak 10:00-16:00
Rigid Vehicles Over 7.5T – 17T	Motorway	Night 19:00-07:00
Rigid Vehicles Over 17T – 25T		
Rigid Vehicles Over 25T		
Articulated Vehicles Up to 33T		
Articulated Vehicles Over 33T		

Table 20: *Classifications used for valuations in DEFRA (2007a)*

In this research, only the external costs associated with light goods vehicles are applicable. The cost per kilometre for this vehicle, for each of the six external categories, by road and time period is shown in table 20.

pence per veh km	Noise	Congestion	Infrastructure	CO$_2$	Air Quality	Accidents
Urban Peak	0.25	24.17	0.09	0.48	0.86	2.05
Urban Off Peak	0.25	12.83	0.09	0.48	0.86	2.55
Urban Night	0.83	12.83	0.09	0.48	0.86	4.38
Rural Peak	0.07	2.74	0.09	0.55	0.34	1.64
Rural Off Peak	0.07	1.45	0.09	0.55	0.34	2.04
Rural Night	0.07	1.45	0.09	0.55	0.34	3.56
Motorway Peak	0.16	3.49	0.01	0.76	0.51	0.66
Motorway Off-Peak	0.16	1.86	0.01	0.76	0.51	0.81
Motorway Night	0.16	1.86	0.01	0.76	0.51	1.41

Table 21: *Pence per kilometre by vehicle type and externality factor for a light goods vehicle (Source: DEFRA, 2007a)*

It is clear from this table that congestion costs dominate the externalities and could significantly affect any results, but according to INFRAS (2004), congestion is not an external transport cost since it does not affect society as a whole. "Users (of transport) mutually disturb each other, but do not impose extra costs on the rest of society. Considering delays in freight or business transport, which entail additional production costs to certain industries, the shippers or business traveller is assumed to account for these effects and thus they are not external." (INFRAS, 2004). However, these costs associated with congestion may be added to the goods and services supplied by the business, in which case much of society would be impacted.

However, DEFRA include congestion in their external transport cost categories so it has been included in this analysis of the model results. The method of costing congestion is fraught with problems and wide ranges of values have been produced by different reports (INFRAS, 2004; AEA Technology Environment, 2005a; DEFRA, 2007a). The method used within the DEFRA (2007a) study was based on data from a study by the Institute of Transport Studies, Leeds and estimates congestion costs based on

the time lost by all traffic when an extra vehicle joins the traffic flow

multiplied by

the relevant "values of time" (as used in standard transport appraisal)

This is referred to as the marginal congestion cost. The reason why congestion incurs such a high cost compared to other externalities is that time is highly rated.

Infrastructure costs were provided by the DfT, by different vehicle types, and cover the costs of repairing, maintaining and operating existing roads, but not the external cost of road building such as damage to local ecosystems, noise and impact on the landscape. New road building is also not included in these costs. Table 20 clearly shows that urban and rural roads have the highest infrastructure costs.

Accident rates were taken from DfT statistics for 2005 for different vehicle types, road types and accident severity, and costs were applied based on Highways Economics Note 1 2005, which uses values according to "willingness to pay" (DEFRA, 2007a)

As well as CO_2, road based vehicles emit pollutants that affect air quality such NOX (nitrogen oxides), PM10 (particulates), CO (carbon monoxide) and hydrocarbon VOCs (volatile organic compounds, including methane, benzene and 1,3-butadiene). These are local pollutants that affect air quality and are responsible for a wide range of health issues including respiratory diseases, cardiovascular illnesses, asthma and chronic bronchitis. Emission rates per km were obtained from the National Atmospheric Emissions Inventory (NAEI) and fuel consumption and emission factors were obtained from TRL. Average speeds, by road type were obtained from the DfT. Valuations of these pollutants were derived from two reports, Air Quality Damage Cost Guidance (2006) and Damage Costs for Air Pollutants (2006).

The monetary social cost of noise was estimated using the relationship between noise levels and property prices. The costs were provided by the DfT by type of route and by time period. Noise pollution is valued much more highly on urban roads. These costs were assumed to be the same for peak and off peak periods. The noise costs for motorways and rural roads were the same for all time periods (DEFRA, 2007a).

The light goods vehicle based costs per km for each of the external cost factors, in table 20, were applied to the distances, by road category, (shown in table 17) for those model runs which produced routes minimised by time, and by CO_2. Table 21 shows the total external costs for time minimised and CO_2 minimised routes for the base year, year 2015 and base year +40%.

Cost (£)	Minimised routes based on		Percentage saving
	Time	CO2	
Base Year	£27,107	£29,523	-19.1%
Year 2015	£28,798	£28,594	14.0%
Base Year +40%	£28,398	£29,245	-4.4%

Table 22: *Total external costs applied to time and CO$_2$ minimised routes*

The percentage difference between the two minimisation criteria is also shown. A negative percentage shows a worse outcome by using routes minimised by CO_2, and a positive percentage shows a benefit to using routes minimised by CO_2. In the base year the effect of using those roads that minimise CO_2 emissions cause an overall 19.1% increase in the cost of externalities. This is transformed into a cost reduction of 14% in 2015, but by increasing traffic volumes by 40%, a small increase of 4.4% in external costs is produced. In order to understand why these values change it is necessary to examine the individual external factors that contribute to the total costs, as shown in the table below.

Scenario	Percentage Saving						
	Congestion Costs	Infrastructure Costs	Accident Costs	Air Quality Costs	CO2 Costs	Noise Costs	Overall Saving
Base Year	-11.3%	-4.9%	-3.5%	-2.0%	4.8%	-2.2%	-19.1%
Year 2015	0.2%	-0.3%	1.0%	3.5%	5.7%	4.1%	14.0%
Base year + 40%	-3.6%	-2.4%	-1.7%	-0.7%	4.6%	-0.5%	-4.4%

Table 23: *Percentage saving on external cost factors*

In the base year, the use of more direct urban roads to reduce CO_2 has an added impact on congestion which produces the greatest cost increase, reflecting the concern expressed earlier about whether congestion should be considered an externality. This factor contributes 60% of the overall cost increase for externalities in the base year. Infrastructure, accidents and noise

costs also increase in the base year if CO_2 minimised routes are used. Although CO_2 costs reduce by 4.8%, air quality costs increase by 2%. The reason for this can be seen in table 20 which shows a proportionally higher air quality cost per vehicle kilometre when using urban roads. Although there are cost benefits caused by the reduction of CO_2 emissions in the base year, the other five external cost factors have a negative effect due to the increased use of urban A and B roads compared to motorways. The overall effect is an increase of 19.1% in the cost of transport externalities if CO_2 minimised routes are used instead of time minimised routes in the base year. Without congestion the overall cost increase is reduced to 7.9%.

However, with increased traffic volume, this negative effect is reversed in the 2015 results with an overall reduction in transport externalities of 14%. The greatest contribution to this reduction is CO_2 with a 5.7% reduction followed by noise (4.1%) and air quality (3.5%). The only increase occurs with a 0.3% rise in infrastructure costs. In 2015, the higher traffic volumes on motorways, typically used in the time minimised routes, could have a negative impact on the total external costs, therefore there is more benefit in moving towards use of urban A and B roads which not only reduce CO_2 emissions but also causes a favourable impact on the other external cost factors.

However, increasing traffic volumes by 40% over the base year incurs an increase of 4.4% in the cost of externalities. The 4.6% reduction in CO_2 represents the greatest benefit, but is offset by cost increases in the other five external factors, caused mainly by an increase of 3.6% in congestion costs. If this were excluded from these figures the net effect would be an overall increase of 0.8%.

5.5   Summary

This chapter has presented the results of running the model for deliveries from five stores in the county of Surrey over a one week, seven day, period, using three route minimisation criteria of time, distance and CO_2 emissions. An analysis was undertaken to validate these results, which are based on

randomisation elements within the model, and was shown have coefficients of variance of about 2%.

The model results for the base year 2005, and for the year 2015 which reflected a 20% increase in traffic volume, showed that a potential reduction of 4.8% in CO_2 emissions could be achieved in 2005, rising to 5.7% in 2015, if the cleanest routes were chosen rather than the quickest routes.

However, taking into account external factors such as accidents, congestion, noise, infrastructure and air quality as well as CO_2, there is a negative impact in the base year due to the increased use of A and B roads as opposed to motorways, but a positive impact in 2015 due to the higher traffic volumes and a similar increased move from motorways to A and B roads.

6 Conclusions

The objective of the research presented in this thesis has been to find an effective method of identifying freight vehicle routes that minimised CO_2 emitted by the vehicles, to see if more environmentally beneficial routes, in terms of CO_2, could be produced.

To analyse the complex dynamics of the interrelationships between all the different variables involved in this research only a computer based model would be able to produce the results required. A model has been developed which incorporates novel techniques for measuring the CO_2 emitted by a vehicle. It integrates concepts from transportation planning, fuel consumption and emissions research and logistics based routing and scheduling. The aim has not been to develop new routing and scheduling algorithms but to adapt an existing model and to integrate it with a new powerful software tool involving the use of a digitised road network containing road links which have traffic volume and road categories as attributes. The traffic volume is used with speed flow formulae to estimate a unique average speed on each of the links. This average speed is then used as the basis for applying second by second speed variability to reflect the acceleration and deceleration that typically occurs as a vehicle travels along a road. Driving cycles are used for this perturbation, which is then converted into fuel consumed by means of fuel consumption formulae, which is subsequently converted into CO_2 emissions.

A range of strategies were examined involving increasing levels of traffic volume to reflect predictions by the UK Department for Transport. Delivery data for a sample week were routed from five stores in Surrey, using three minimisation criteria of time, distance and CO_2 emissions, for a base year of 2005, for 2015 which involved increasing traffic levels by 20%, and for a strategy which involved increasing traffic volumes by 40% over the 2005 base. In each of these 315 runs of the model, the output showed the route details including the delivery sequences, the total time taken, distance travelled, CO_2 emitted, and vehicle cost with and without the external cost of CO_2 which was applied at the rate of £22.59 per tonne.

The results produced by the model, including a sensitivity analysis, indicate that there is a potential saving in CO_2 emissions of 4.8% in the base year by changing from time minimised to CO_2 minimised routes. The total time for the routes rises by 4% and the vehicle costs rise by about 0.5% as a result of this. When traffic volumes are increased by 20% and 40%, there is a reduction of 5.7% and 4.6% in CO_2 emissions, respectively.

An analysis of the results shows that the further the distance between deliveries, the greater the potential opportunity of reducing CO_2 emissions, as shown in figure 19. The likely reason for this is that as more deliveries are made, distances between the deliveries become shorter; therefore there is less opportunity to find routes which differ between the three minimisation criteria.

CO_2 is one of six factors classified as transport externalities. The others are noise, infrastructure, accidents, air quality and congestion, though there is some debate as to whether this latter factor should be considered an externality, especially as the costs significantly exceeds the cost of any of the other factors. The costs of these externalities, obtained from DEFRA (2007a), are expressed by type of road and time of day, for various vehicle types. The costs for the light goods vehicle have been used and indicate that the routes produced by the CO_2 minimised option incur 19.1% higher external costs than the routes produced by the time minimised option in the base year. With a 20% increase in traffic volume, the external costs show a reduction of 14% in favour of CO_2 minimised routes. This is reversed to become a higher cost of 4.4% with a 40% increase in traffic volume.

The results have shown that there are savings in CO_2 emissions to be made but they are very small in the scheme of total UK emissions of CO_2. Road freight transport has been shown to be approximately 6% of all UK emissions of CO_2. Therefore if, say, 50% of freight companies adopt the approach of using routes that minimise CO_2, then extrapolating the research results would produce a reduction of approximately 0.015% in total UK emissions of CO_2. The results also show that if the cost per tonne of CO_2 is set at an appropriate

level and internalised, then it is possible to achieve a cost effective set of routes. However, if the wider context of transport externalities is included then, in the base year, the benefits from reducing the CO_2 emissions are outweighed by the additional costs associated with using A and B roads compared to motorways. If the results for 2015 are considered in this wider context then there is an overall saving in these external costs.

6.1 Contributions

A PhD thesis should contribute to knowledge "through the discovery of new knowledge, or the application of existing knowledge to new situations, or the connection of previously unrelated facts" (Cranfield University, 2004), and this research has made a number of significant contributions.

6.1.1 Academic Contribution

Logistics research has tended to be conducted quite separately from transportation planning and vehicle environmental research. Although transport planners have been concerned about environmental impacts, transportation models have used fairly high level methods for estimating CO_2 emissions. They do not, for instance, incorporate the second by second driving cycles necessary to produce a good estimate of CO_2 (Bowkett, 2007). Certain transportation models use the output from fuel consumption and emission models such as VeTESS within the simulation (Ericsson et al, 2006). One of the contributions in this research is that, individually, models exist that examine aspects of each of these three areas, but there are no integrated models in either the environmental, transportation planning or logistics sectors which have the ability to examine the movement of freight delivery vehicles, and produce a good estimate of the resultant level of emissions. This research has integrated theories and methodologies developed in these areas to create a computer based vehicle routing model with an emissions component.

A further contribution is in the method used to address congestion. Research has shown that vehicle routing software will generate a matrix of times or distances between depot and delivery locations based on a digitised road

network using constant speeds by road category. With increasing levels of congestion this approach has been shown to be inaccurate. However, some commercial VRS software companies such as Paragon Software Systems are starting to move away from fixed speeds by road category and use speed data from a UK based company ITIS Holdings, who collect information from up to 50,000 on road vehicles in 15 minute time buckets. This provides VRS software with more accurate speed data with which to estimate travel time. However, it is not possible to assess congestion implications with this data. Average speed on a road link reduces as traffic volume increases beyond the design capacity of the road. The model developed for this research uses traffic volume and speed flow formulae as a means of establishing an average speed on a road link. Therefore, the reduced speed from congestion, in the form of increased traffic volume, can easily be estimated with the speed flow formulae. Adding in these concepts from traffic and transportation planning has provided the ability to produce a better estimation of speed and, together with the detailed fuel consumption formulae, has provided the ability to produce a better estimate of CO_2 emissions within the model. The improved method of representing speed can also provide benefits for more efficient routing and scheduling algorithms.

The results from the model represent a contribution in the form of new knowledge. The outputs have shown that a saving of about 5% of CO_2 emissions can be made by following alternative routes to the time minimised option, and it has also shown that the use of the roads on these routes may have adverse effects if other transport externalities are included.

6.1.2 Contribution to Practice and Policy

An improvement to the method of representing road speed may mean that routes produced by the model result in a more cost effective and cleaner, (in terms of CO_2 emissions) operation. The achievement of more timely and accurate deliveries is also likely to improve customer satisfaction.

With companies becoming more aware of a need to demonstrate their green credentials and efforts being made to try and reduce their CO_2 emissions, this

model in its finished form is a working tool that transport planners could use in traffic offices to assist companies towards achieving a more sustainable transport operation by enabling routes and routing strategy to be evaluated based on CO_2 emissions.

The model developed for this research is capable of identifying and planning routes that can be used to minimise CO_2 emissions and to more accurately estimate CO_2 emissions from freight delivery vehicles. Therefore this model can also make a contribution towards various transport and logistics related government policies such as DEFRA's UK Climate Change Programme which encourages sustainable distribution programmes to support efficient operating practices, and is aimed at helping the UK government achieve the targets set by the Kyoto protocol. The use of the model can also contribute to the DfT's Sustainable Travel programme which promotes initiatives to reduce congestion and improve local environments, and the Freight Best Practice programme which is a key part of the UK government's commitment to encourage companies to improve the energy efficiency of their vehicle fleets.

This thesis will also make a contribution to the policy debate within industry organisations such as the Freight Transport Association, the Road Haulage Association and the Chartered Institute of Logistics and Transport.

In practice and policy terms, care must be taken on purely minimising CO_2 emissions without taking into account the other externalities. The model clearly shows that there are negative factors associated with using routes which minimise CO_2.

6.2   Future Research

Although the methods used in the development of this model produce a high level of accuracy in the estimation of CO_2 emissions, the conclusions from the results are relevant to the county of Surrey and the delivery data being routed. There are opportunities to expand on this research by refining and developing the model, and considering alternative data as follows:

- Expanding the research to cover a wider area with a larger set of alternative delivery data
- The use of alternative delivery vehicles
- The use of alternative fuels
- Enhancing the model by:
    - Allowing different traffic volumes by time of day and day of the week
    - Allowing for vehicle weight adjustments
    - The inclusion of driving cycles for motorways and rural areas
    - Assessing the impact of randomly selecting time periods within the generic driving cycles
    - Incorporating functionality to minimise all externalities

Although this research has been limited to the Surrey area because of the availability of an appropriate road network database, specifically one that contains traffic volume, other county councils may have similar road network data such that further research could be undertaken. Also, the Highways Agency collect traffic flow data, across the road network for which they have responsibility, by means of 3,783 loop detectors throughout England. From this information the annual average daily traffic volumes, and annual average hourly flows throughout the day, can be calculated for each road on which loop detectors are situated. Traffic speed is not currently measured but these traffic volumes can be used within the model and speeds estimated using the COBA speed flow formulae. If the model could be tested over a wider area this may well produce results showing a greater opportunity to save CO_2 emissions by switching from time minimised to CO_2 minimised routes. The reason for this is that the greater the distances between locations, the more opportunity of finding alternative routes to satisfy the minimisation criteria. However, certain longer routes, particularly between the north and south of the country are more likely to use a motorway whatever the minimisation criteria, and therefore may not show any saving in CO_2. The DfT obtain a weekly sample of vehicle movements around the UK with information about the type of goods carried, the type of vehicle used and the origin and destination locations. This trip data from the Continuing Survey of Road

Goods Transported (CSRGT) could be used as the basis for assessing the economic and environmental impact of routes with different minimisation criteria of time, distance and CO_2. The locations in this data are at the NUTS4 level and contain 29,536 unique origin and destination combinations. NUTS which stands for Nomenclature of Territorial Units for Statistics, is a European Union classification, used for statistical purposes, which divides European countries into areas at different hierarchical levels. Level 3 equates approximately to county and unitary authority boundaries. NUTS4 is a more detailed subdivision of these boundaries. This future research could identify flows between specific locations within the UK that could benefit from following CO_2 minimised routes.

The formulae used in the model have been obtained from sound sources grounded in the areas of transportation, fuel consumption and emissions, and logistics route planning, and in many cases have been derived from empirical sources using regression analysis. The formulae and the constants used within them reflect the operation of a light goods vehicle and would need to be changed if larger freight vehicles are to be considered. Subsequent research could consider alternative freight vehicles delivering over a wider area. This may well highlight new information and possibilities for routing vehicles to minimise CO_2 emissions. Again the information provided within the CSRGT trip data could be used to assess the impact. It would be necessary to change the constants within the fuel consumption formulae used in the model. These constants relate to the efficiency with which fuel is consumed by a vehicle and the drag forces relating to aerodynamic and rolling resistances.

This research has based all the CO_2 calculations on freight vehicles that use diesel at the rate of 2.7kg of CO_2 per litre of fuel. If alternative fuels are used the value of CO_2 emissions will change. However, the principles of this research in finding routes which minimise CO_2 emissions remain the same irrespective of the type of fuel used. In practice, vehicle fleets may use a mix of different fuels and future research could enhance the capability of the model to include CO_2 emissions for biodiesel and LPG.

The UK government has set up the Renewable Transport Fuel Obligation Programme which, from April 2008, requires fuel suppliers to achieve 5% of fuel sales from biofuels (Department for Trade and Industry, 2006). Diesel mixed with 5% biofuel is currently the maximum allowed under EU specifications. There are varying estimates that biofuels will reduce CO_2 emissions by between 50% and 80%. With a blend of 5% biofuel in diesel the emissions of CO_2 per litre of blended fuel would reduce to between 2.59kg and 2.63kg.

It has been estimated that LPG emits less CO_2 than diesel, with LPG having 0.64 tonnes of carbon per tonne of oil equivalent and diesel having 0.85 tonnes (Quiggin, 2006). However, vehicles using LPG fuel will emit approximately the same amount of CO_2 as diesel because of the higher thermal efficiency of diesel engines which gives a 40% improvement in fuel consumption compared to LPG (DfT, 2003). Thus although LPG emits 1.51kg of CO_2 per litre of LPG, this is equivalent to 2.16kg at the same level of fuel consumption as diesel.

It is likely that if these alternative fuels were substituted for diesel in the model, the same outcome of a 4.8% reduction in CO_2 in the base year, and a 5.7% reduction in 2015, would still occur. However, the overall total emissions of CO_2 would be different as would the total vehicle costs, although the cost of CO_2 is minimal compared to the internal standard fixed and variable costs of operating a vehicle.

Future research could enable the model to be enhanced in a number of other areas:

1. The results have been produced based on predicted traffic volumes on the road during a single morning peak period. The functionality of the VRP model did not allow for variable speeds to be used by time of day. Also, the same traffic volumes were used for each of the seven days of delivery data analysed. In reality traffic volumes, and therefore speeds, would vary by day of the week and within the day. The functionality of

the model could be enhanced to allow for route timings to reflect changing traffic volumes, and therefore speeds, at different times of the day and also by day of the week.

2. One of the parameters in the instantaneous fuel consumption formula used in the model relates to the mass of the vehicle. An empty vehicle uses less fuel than a fully loaded vehicle. Therefore, the model could be enhanced to calculate the fuel consumed by a vehicle setting off from a store or depot fully loaded, and to recalculate the fuel consumed as the vehicle gets lighter following each delivery, by adjusting the vehicle mass parameter. With this approach, CO_2 emitted can be estimated more accurately.

3. The model uses an instantaneous fuel consumption formula on generic driving cycles for urban areas, but an elemental model on motorways and rural roads for which it has not been possible to obtain driving cycles. If subsequently this data becomes available it could be easily incorporated to produce a higher degree of accuracy in the calculation of CO_2 emissions. Also, driving style will impact fuel consumption and this is reflected in the TRL generic driving cycles in the form of the rate of acceleration and deceleration. These are constant for all the strategies modelled, therefore, all results are on a comparable basis. However, future research could consider the routing and CO_2 impact of different driving styles.

4. In discussions with representatives of TRL, it has been suggested, though not proven, that when the model adjusts a portion of the driving cycle data to reflect an average speed, the amplitude of the driving cycle may diminish the higher the average speed. This is a speculative assumption since no research in this area has previously been undertaken. If this assumption were proven then again a higher degree of calculation accuracy would ensue.

5. The model could be enhanced by extending the current CO_2 minimising concept to include the other external factors of noise, infrastructure, congestion, accidents and air quality. An understanding of how these factors change by road type and traffic volume would be required, and the model modified to incorporate these elements. The model could then be used to identify routes which take into account all externalities.

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APPENDICES

Appendix A – The COBA speed flow formulae

The formula for RC1 has been derived from a TRL study in 1991 where the type of road studied did not have local speed limits and there were no junctions to affect the vehicle flows. The study had observed journey speeds from 30 to 95 kph. It has the form:

    Vl = 72.1-(0.015+(0.00027*PHV))*Q   up to Q<Qb
    Vl = Vb-0.05*(Q-Qb)   when Q>=Qb

where   Vl =   Speed of light vehicle (kph)
        Vb =   Speed at Q = Qb (kph)
        PHV = Percentage of heavy goods vehicles (%)
        Q   = Flow of all vehicles (vehs/hr/direction)

        and   Qb = 0.8*Qc
               Qc = 2400*(CWID - 3.65)*(92-PHV)/(CWID*80)

        where Qb = Breakpoint: the value of Q at which the speed flow slope
               of light vehicles changes (vehs/hr/dir)
               Qc = Capacity flag: defined as the maximum realistic value of
               Q (vehs/hr/dir)
               CWID = Carriageway width (between 6 & 11m)

The value for minimum speed, as defined in the COBA manual has been set at 45kph for this road class. In the absence of more information, default values, as specified in COBA 10, have been assumed for some variables namely:

    Vb = 50kph
    PHV = 5%
    CWID = 8.5m

The speed prediction formulae for RC2 to RC6 have been derived from a TRL study in 1990 where the type of road studied was similar to RC1 in that they did not have local speed limits and there were no junctions to affect the vehicle flows. The study had observed journey speeds from 40 to 125 kph. It has the form:

$$VI = KI - SI*Q \qquad \text{up to } Q<Qb$$
$$VI = Vb - 33*(Q-Qb)/1000 \qquad \text{when } Q>=Qb$$

where VI = Speed of light vehicle (kph)
       KI = A constant speed by category of road and defined as
- 108 kph for RC2
- 115 kph for RC3
- 111 kph for RC4
- 118 kph for RC5 and RC6

       SI = Speed flow slope of light and heavy vehicles equal to a 6kph reduction per 1000 vehicle increase in Q
       Vb = Speed of vehicles at flow Qb (between 80 & 105 kph)
       Q = Flow of all vehicles (vehs/hr/lane) (maximum of 2300)
      Qb = Breakpoint: the value of Q at which the speed flow slope of light vehicles changes (vehs/hr/dir) and taken as 1200 vehicles per hour per lane for RC2 to RC4, and 1080 vehicles per hour per lane for RC5 and RC6

The value for minimum speed on these road categories, as specified in COBA 10, has been set at 45kph.

The speed flow formulae for RC7 and RC8 are for non central and central urban roads and have been derived from a TRL study in 1976. The speed limit is typically 48kph on these roads and allowances are made for junctions which will influence the speed. The formula for these two road categories is:

$$VI = Vo - 30 * Q / 1000$$

where VI = Speed of light vehicle (kph)
       Vo = Speed at zero flow (kph)
       Q = Total flow, all vehicles, per standard lane (vehs/hr/3.65m lane) (maximum 1200)

and Vo = 64.5 - DEVEL / 5kph for non central areas
        Vo = 39.5 - 5 * INT / 4kph for central areas

      where DEVEL = Percentage of route with frontage development
           INT = Frequency of major intersections averaged over main road network (number of intersections/km)

For RC7 the minimum speed is 25kph and for RC8 the minimum speed is 15kph. In the absence of information about percentage of development frontage (DEVEL) and number of intersections (INT) in the SCC link data, default values of 80% and 4.5 have been used, respectively.

RC9 covers roads that pass through small towns and villages. The speed prediction formula was derived from a study undertaken by Halcrow Fox and Associates in 1982, and is of the form:

VI = 70 - DEVEL/8 - P30/8 -12*Q/1000   up to Q<Qb
VI = Vb - 45*(Q-Qb)/1000   when Q>=Qb

where VI = Speed of light vehicle (kph)
          DEVEL = Percentage of route with frontage development
          P30 = Percentage of route subject to a 30mph speed limit
          Q = Flow of all vehicles (vehs/hr/3.65m lane)
          Qb = Breakpoint: the value of Q at which the speed flow slope of
               light vehicles changes (vehs/hr/3.65m lane)
          Vb = Speed at Q = Qb (kph) (between 38 & 57 kph)

The minimum speed for this category of road is set at 30kph in the COBA manual. As with previous road categories, default values have been used for certain parameters as follows:

DEVEL = 80%
P30 = 50%
Qb = 700

The last set of road categories, RC10 and RC11, cover suburban roads with typical speed limits of 64kph. The speed prediction formula was derived from a study undertaken by Freeman Fox and Associates in 1972 and is of the form:

VI = Vo - SI*Q/1000

where   VI = Speed of light vehicle (kph)
          Vo = Speed at zero flow (kph)
          Q =   Total flow, all vehicles, per standard lane (vehs/hr/3.65m
                lane) (max 1200)

and   Vo = C - 5*INT - 3*AXS/20
          SI = 12 + 50*INT/3kph per 1000 vehs   up to Q<Qb
          SI = 45kph per 1000 vehs   when Q>=Qb

and   Qb = 0.7 * Qc
          Qc = 1500*(92 - PHV)/80 veh/hr/3.65m lane

          where   Qb = Breakpoint: the value of Q at which the
                    speed flow slope of light vehicles changes (vehs/hr/3.65m
                    lane)

Qc = Capacity flag: defined as the maximum realistic
    value of Q (vehs/hr/3.65m lane)
PHV = Percentage of heavy goods vehicles (%)
INT = Frequency of major intersections averaged over
    main road network (number/km between 0 & 2)
AXS = No of minor intersections and private drives
    (number/km between 5 & 75)
C is a constant set at 70 for RC10 and 84 for RC11

The minimum speed for RC10, a single carriageway, is 25kph and for RC11, a dual carriageway, it is 35 kph. The default values used for these road categories are:

PHV = 5%
INT = 1.0
AXS = 35

Appendix B – Algorithm to Estimate Distance from Latitude and Longitude Coordinates

```
Private Function Distance(FromLat As Double, FromLong As Double, _
ToLat As Double, ToLong As Double) As Double

    Dim L1 As Double          ' Start Point Latitude in radians
    Dim L2 As Double          ' End Point Latitude in radians
    Dim N1 As Double          ' Start Point Longitude in radians
    Dim N2 As Double          ' End Point Longitude in radians
    Dim C As Double           ' Cosine of the angle subtended by the
                              ' segment of the great circle path
                              ' between the two points
    Dim A As Double           ' Angle derived from C
    Dim R As Double           ' Radius of the Earth
    Dim Pi As Double
    Pi = 3.14159
    R = 6378

    If FromLat = ToLat And FromLong = ToLong Then
      Distance = 0
      Exit Function
    End If

    ' Convert to radians
    L1 = FromLat * (Pi / 180)
    N1 = FromLong * (Pi / 180)
    L2 = ToLat * (Pi / 180)
    N2 = ToLong * (Pi / 180)

    C = (Sin(L1) * Sin(L2)) + (Cos(L1) * Cos(L2) * Cos(N2 - N1))
    A = Atn(Sqr(1 - (C * C)) / C) + Pi * (C - Abs(C)) / (2 * C)

    Distance = A * R * DCF * DistConv

End Function
```