Bostock, Adam K. (1994) Prediction and reduction of traffic pollution in urban areas. PhD thesis, University of Nottingham.

University of Nottingham

Department of Civil Engineering

PREDICTION AND REDUCTION OF TRAFFIC POLLUTION IN URBAN AREAS

by

Adam K Bostock, BSc

Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy

September, 1994

Contents

Chapter 2 Air Pollution

Chapter 3 Air Pollution Studies

Chapter 4 Reduction of Emissions

Chapter 5 Modelling and Prediction

Page

Chapter 6 Model Suite

Chapter 7 Control Strategies

Chapter 8 Modelling Methodology

Chapter 9 Results

Chapter 11 Conclusions

List of Figures

List of Tables

Acknowledgements

I am grateful to those people whose advice and support have contributed to this research. I would like to thank the members of Castle Rock Consultants for their advice and moral support, and Peter Davies who gave me the opportunity to embark on this research and acted as one of my supervisors. Thanks are also due to Margaret Bell, my academic supervisor, whose technical advice and precious time were given willingly.

Members of the Athens PREDICT and QUARTET project consortiums should also be acknowledged for their contribution to the development of pollution control strategies. Particular thanks are due to Dr Antony Stathopoulos, of the National Technical University of Athens, for sharing his expertise in this area, providing input data specific to the Athens study network, and for his role in running part of the PREDICT model suite.

Special thanks are also due to those people who gave me moral support and encouragement, especially at times when I doubted that I would ever complete this research. I would like to thank my mother for her unfailing support, and my father for inspiring me, at an early age, to be inquisitive. As this research aims to add to existing knowledge, it seems appropriate to quote one of his favourite phrases; "all knowledge is good knowledge".

Abstract

This thesis is the result of five years research into road traffic emissions of air pollutants. It includes a review of traffic pollution studies and models, and a description of the PREDICT model suite and PREMIT emissions model. These models were used to evaluate environmentally sensitive traffic control strategies, some of which were based on the use of Advanced Transport Telematics (ATT).

This research has improved our understanding of traffic emissions. It studied emissions of the following pollutants: carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx). PREMIT modelled emissions from each driving mode (cruise, acceleration, deceleration and idling) and, consequently, predicted relatively complex emission characteristics for some scenarios.

Results suggest that emission models should represent emissions by driving mode, instead of using urban driving cycles or average speeds. Emissions of NOx were more complex than those of CO and HC. The change in NOx, caused by a particular strategy, could be similar or opposite to changes in CO and HC. Similarly, for some scenarios, a reduction in stops and delay did not reduce emissions of NOx. It was also noted that the magnitude of changes in emissions of NOx were usually much less than the corresponding changes in CO and HC.

In general, the traffic control strategies based on the adjustment of signal timings were not effective in reducing total network emissions. However, high emissions of pollutants on particular links could, potentially, be reduced by changing signal timings. For many links, mutually exclusive strategies existed for reducing emissions of CO and HC, and emissions of NOx. Hence, a decision maker may have to choose which pollutants are to be reduced, and which can be allowed to increase.

The environmental area licensing strategy gave relatively large reductions in emissions of all pollutants. This strategy was superior to the traffic signal timing strategies because it had no detrimental impact on the efficiency of the traffic network and gave simultaneous reductions in emissions of CO, HC and NOx.

Chapter 1

INTRODUCTION

This thesis describes research undertaken between 1989 and 1994 into road traffic emissions and environmentally sensitive traffic control strategies. Part of this research was conducted by the author in the PREDICT project of the DRIVE I research programme funded by the European Union (EU). The author then built on his work in PREDICT to pursue a more detailed analysis of road traffic emissions and the effectiveness of environmentally sensitive traffic control strategies. The work of PREDICT is now being demonstrated in the DRIVE II QUARTET project, in which the author continues to play a major role.

Road traffic emissions of air pollutants are, in part, responsible for high levels of air pollution within urban areas throughout the world. These pollutant concentrations can have a significant impact on health and the environment. This has been recognised in many countries throughout the world and has led to the introduction and review of air pollution guidelines, such as those set by the World Health Organisation, and air pollution standards, such as those specified by the directives of the European Union. In some cases, these air pollution standards are exceeded.

The author's work aims to assist in the development of innovative short and medium term solutions to this problem, whilst maintaining a relatively high degree of mobility to support late twentieth century lifestyles. The theoretical and modelling aspects are described within this thesis. A field trial demonstration is currently being conducted in Athens to evaluate the implementation aspects of this work.

This thesis focuses, primarily, on the understanding of road traffic emissions and the implications for environmentally sensitive traffic control strategies. The approach is biased towards academic research into emissions, as opposed to the implementation aspects of traffic control strategies.

The author formulated and designed four environmentally sensitive traffic control strategies. These strategies were:

- environmental optimisation of traffic signal timings;
- environmentally sensitive traffic rerouting;
- the introduction of 'clean' vehicles; and
- environmental area licensing.

These strategies are described in this thesis along with an overview of the relevant aspects of the urban air pollution problem caused by road traffic emissions. The structure of this thesis is described in the following paragraphs.

An introduction to air pollution is provided in Chapter 2. This describes atmospheric pollution, its sources, the mechanisms responsible for the dispersion of emissions, and the effects of the resulting pollutant concentrations. A description of air pollution in general is given, along with a specific focus on pollutants emitted by road traffic. A distinction is also drawn between primary and secondary pollutants.

Chapter 3 reviews air pollution studies. This aims to outline some of the issues addressed and techniques used. The chapter describes air quality standards, the significance of traffic emissions, and studies investigating emission characteristics and emission control strategies.

One approach to improving air quality is to develop strategies and technologies which aim to reduce vehicle emissions at source. Chapter 4 describes the concepts of fuel and emission reduction technologies and strategies. It outlines a range of potential options for reducing emissions, including some traditional strategies. Some of the technologies described in this chapter form the basis for two of the strategies described in this thesis: the introduction of clean vehicles; and environmental area licensing.

Chapter 5 contains a review of modelling and prediction techniques for air pollution caused by road traffic emissions. This chapter addresses the different modelling stages that are typically used: traffic; emissions; and dispersion modelling.

To assess the strategies designed by the author, a model suite was selected and the PREMIT emissions model developed. The model suite consisted of four models and a graphics package. This suite is described in Chapter 6, along with its objectives and an assessment of the model suite.

The control strategies designed by the author are based around the adoption of Advanced Transport Telematics (ATT) principles which aim to protect the environment whilst maintaining traffic efficiency and safety. These strategies are described in Chapter 7. The four strategies are described followed by a description of the QUARTET field trial which is demonstrating and evaluating two of these strategies in a real world environment.

The author's work included a detailed analysis of road traffic emissions. Several options within Strategy One (the environmental optimisation of traffic signal timings) of PREDICT have been investigated. This thesis focuses primarily on that work in the methodology and results chapters (8 and 9 respectively). These chapters also describe modelling of the environmental area licensing strategy.

The methodology describes the actual implementation aspects of the model, establishing a base case scenario, the options investigated as part of Strategy One, and the modelling of the environmental area licensing strategy. The results chapter contains the results of sensitivity tests and the two strategies, followed by a discussion of the findings.

Chapter 10 summarises the findings of the author's work, and Chapter 11 provides conclusions and recommendations.

Chapter 2

AIR POLLUTION

2.1 INTRODUCTION

This chapter provides an introduction to air pollution and a review of mechanisms responsible for the generation of traffic emissions, pollutant dispersion, and the effects of air pollution on health and the environment.

But what do we mean by pollution? The Concise Oxford Dictionary describes pollute as: contaminate or defile (the environment); make foul or filthy; destroy the purity or sanctity of. The author suggests that the term pollution may also be associated with the following processes: releasing man made substances into the environment which are not encountered naturally; and releasing substances into the environment at such a rate and/or concentration that the environment, or parts of the environment, are significantly affected as a direct or indirect result of this. It appears that the degree to which emissions impact the environment, may influence whether a process is regarded as polluting. For example, carbon dioxide emissions, at the turn of the century, were not perceived as a significant problem, even though it was suspected that they could eventually lead to climatic change (Arrhenius, 1908). Whereas now, people are assessing ways in which its emissions can be reduced (Mot et al, 1993).

Potentially, air pollution can have a significant impact on health and the environment (WHO, 1987). Pollutant effects can be experienced globally (Ausubel, 1983; Watson et al, 1990; Firor and Jacobsen, 1993), across nations and regions (Derwent and Jenkin, 1991; Borrel et al, 1991; Jayanty and Gay, 1993), or locally (Brown, 1994). There are many sources of air pollution which have wide ranging effects on the environment, buildings, vegetation, animals and human health (Heagle, 1988; Lippmann, 1989 and 1991; Miller et al 1989; Lefohn and Foley, 1992; WHO, 1979, 1984 and 1987).

To set air pollution in its environmental context, this chapter begins by describing the atmosphere, along with the terminology and mechanisms of atmospheric pollution, covering the topics of emission, dispersion and pollutant concentration.

The sources of air pollution, particularly road traffic emissions are described. This includes the primary pollutants carbon monoxide, carbon dioxide, hydrocarbons, oxides of nitrogen, sulphur dioxide, lead, particulates and smoke, and secondary photochemical pollutants.

Pollutant emissions, whether arising from a single point source or several sources, are dispersed in the atmosphere. The emission rate and the dispersion process account for the observed pollutant concentration at a particular point in time and space. A section of this chapter outlines the mechanisms responsible for the dispersion of traffic emissions.

The effects of air pollution on the environment, vegetation and health are wide ranging and, potentially, significant (WHO, 1979, 1984 and 1987). Hence the need to safe guard the environment and health, by ensuring acceptable levels of air quality are maintained. As a result of studies investigating the impact of air pollutants, air quality guidelines are established (WHO, 1987).

2.2 THE ATMOSPHERE AND ITS POLLUTANTS

This section describes the atmosphere, and the terminology used within the topic of air pollution. This terminology is typically used to describe all types of air pollution, not just those resulting from traffic emissions.

The Atmosphere

The Earth's atmosphere has an intricate physical structure and chemical composition. Its structure and composition regulate ambient temperature and provide a major contribution to meteorological and climatic conditions.

Water vapour and carbon dioxide provide the so called greenhouse roof of the Earth (Firor and Jacobsen, 1993). They do so by absorbing radiation reflected from the Earth's surface. Water vapour absorbs six times as much radiation as the other gases, including carbon dioxide. The effect of this is to regulate global temperatures (Charlson and Wigley, 1994).

Nitrogen and oxygen account for most of the chemical content of the atmosphere, making up 78 and 21 percent, of dry air, respectively (Chanlett, 1973). In addition to water vapour, with an average global concentration of three percent, air in some localities also contains a variety of gaseous and particulate pollutants.

Troposphere

The lowest level of the atmosphere, the troposphere, consists of a relatively uniform gaseous mixture. The thickness of the troposphere varies from about 7 km at the poles to 28 km at the equator and in this layer the temperature falls with increasing height (Chanlett, 1973). At sea level the average global temperature is about 17 degrees celsius (Charlson and Wigley, 1994).

Meteorological factors, particularly atmospheric stability, have a significant impact on the dispersal of air pollutants (Bond, Straub and Prober, 1972). When the temperature increases with height it is called a temperature inversion. This can happen at night, especially in the absence of clouds, when the ground cools rapidly and lowers the temperature of the air immediately above it. Inversions can also occur at higher altitudes above the ground. Such inversions present a barrier to the upward movement of air. In conjunction with the local topography, as in the Los Angeles basin, an upper air thermal inversion can result in a stagnated air mass. Thermal inversions can form in valleys at night as the cooler and denser air slides down into the valley and leaves the warmer air on top. Stable equilibrium is the term used to describe the atmosphere when there is no vertical movement of air, as opposed to instability which has vertical air currents.

Ozonosphere

The area between 10 km to 50 km is known as the Ozonosphere (Chanlett, 1973). At this altitude ozone absorbs ultra-violet radiation. At 25 to 30 km the concentration of ozone may reach 10 parts per million (ppm), much higher than the average of 0.04 ppm in the troposphere (Chanlett, 1973). The concentration of ozone in the ozonosphere can be reduced by man-made pollutants in the atmosphere, particularly over the poles of the Earth (Zimmer, 1993). Below these areas higher levels of harmful ultra-violet radiation falls and may result in increased incidents of skin cancer and damage to vegetation (Graedel and Crutzen, 1993).

However, this ozone problem is not the major ozone problem associated with emissions from road transport vehicles. Such emissions are responsible for an increase in the level of ozone at, or near, ground level (Borrel et al, 1991; National Academy of Sciences, 1991; Finlayson-Pitts and Pitts Jr., 1993).

Air Pollution

Air pollution is caused by many emission sources and the emitted pollutants occupy several physical forms. The pollutant is dispersed by meteorological parameters and, in conjunction with the emission rate, determines the resultant concentrations. These phenomena are described below.

Emissions

Emissions may be in the form of a solid, liquid or gas. Depending on the form of the pollutant it may be described as particulate, aerosol, fumes, vapour or gas. It is convenient to describe the emission rate as a mass per unit time, for example grammes per minute (g/min).

Particulates are small solid or liquid particles, typically ranging in size from less than one micrometre to hundreds of micrometres. The larger the particulates the shorter the time they spend suspended in the air. Such colloidal suspensions are known as aerosols (e.g. fog, smoke, etc.) - solutions in the air.

A vapour is the gaseous phase of a material that usually exists in the form of a solid or liquid at normal temperatures and pressures. The vapour may be generated by evaporation from the surface of a liquid or by boiling of the liquid. Some materials undergo sublimation and change directly from the solid phase to the vapour phase. Fumes are vapours which render themselves visible by condensing or reacting in the air to form a mist like suspension or aerosol.

A gas, like the nitrogen and oxygen of the air itself, is one in which the molecules' inter-molecular forces of attraction are unable to hold them together at a given temperature and pressure. A gas will fully occupy a container of any shape.

Dispersion

As pollutants are emitted into the atmosphere they are dispersed and, generally, become more diluted with increasing distance from the source. The profile of a pollutant's concentration will vary with distance from the emission source and direction relative to that of the wind. The main mechanisms responsible for the dispersion of aerosols and gases are the physical movements of air such as: winds, the flow of air around vehicles, warm rising currents and turbulence. The dispersion process is heavily dependent on the meteorology and topography of the surrounding area. Winds and rising air currents can carry pollutants over hundreds or thousands of miles (Nriagu, 1978; Derwent and Jenkin, 1991; Aneja and Kim, 1993).

Pollutant Concentrations

The pollutant concentration represents the quantity of material in a given volume of air. Pollutant concentrations are expressed in different ways depending on the type or form of pollutant.

Gaseous pollutants have physical attributes similar to all other gases of the atmosphere: one mole[1] of gas occupies 22.4 litres at standard temperature (zero degrees celsius) and pressure (760 mm of mercury). So for example, one mole of oxygen would occupy the same volume as one mole of nitrogen under identical conditions even though they each represent different masses. Hence, given the mass of a gaseous pollutant per unit volume, the ratio of the pollutant volume to the volume of air containing it can be calculated and vice-a-versa.

Pollutants of the gaseous form may have their concentration expressed in one of three ways:

- mass per unit volume - the mass of pollutant contained in a unit volume of air, the units usually being micro grammes per metre cubed ($\mu g/m^3$) or milli grammes per metre cubed (mg/m^3); or
- volume per volume - a ratio of the volume of pollutant to the volume of air containing that pollutant, the units usually being parts per million (ppm or ppmv) or parts per billion (ppb); or
- mass per mass - a ratio of the mass of pollutant to the mass of air containing that pollutant, the units being in parts per million or parts per billion by weight though this form is rarely used.

Particulates do not share the same characteristics as gases (i.e. the relationship between mass and volume occupied) and their concentrations are typically expressed as a mass per unit volume ($\mu g/m^3$).

2.3 SOURCES OF AIR POLLUTION

Man-made air pollutants cover a vast range of substances and may be in particulate or gaseous form. Air pollution may be caused by combustion, evaporation, abrasive actions on solid materials, and other mechanisms which generate particulates.

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[1] One mole of a substance represents the molecular weight (mass) of that substance expressed in grammes, e.g. one mole of hydrogen (molecular weight 2) weighs 2 grammes.

Combustion Products

The combustion of fossil fuels (e.g. coal, petrol, diesel and natural gas) provide a major contribution to atmospheric pollution (Bond, Straub and Prober, 1972; Chanlett, 1973). The combustion of fossil fuels when carried out to completion usually results in the production of water vapour and carbon dioxide (and ash in the case of coal). Since several fossil fuels also have a sulphur content the combustion products often contain oxides of sulphur. The combustion process is rarely 100 percent complete and most of the products of incomplete combustion are regarded as pollutants. Until a few decades ago, only the oxides of sulphur and nitrogen, and products of incomplete combustion were thought to warrant concern. However, attention is now also being focused on the emissions of carbon dioxide (Mot et al 1993).

Traffic Emissions

Road traffic represents a major component of twentieth century transport in many countries throughout the world and accounts for many billions of vehicle miles travelled every year. In the US alone, 3500 billion passenger-miles are travelled in one year, a large proportion of which is by road (US Department of Transportation, 1990). Almost all of these road vehicles use an internal combustion engine as their power source and the resulting traffic emissions represent a significant threat to air quality (Watson et al, 1990).

Several pollutants are emitted from road traffic (Eggleston et al 1993). Exhaust emissions from petrol and diesel engines include: carbon monoxide (CO); hydrocarbons (HC); nitrogen oxides (NOx); sulphur dioxide (SO_2); lead (Pb); particulate and smoke emissions; and carbon dioxide (CO_2).

The mechanisms responsible for the production of these pollutants are discussed in subsequent paragraphs. These are called primary pollutants. In sunlight these react to produce secondary pollutants (Derwent and Jenkin, 1991; Finlayson-Pitts and Pitts, 1993). These are the compounds found in smog (Lippmann, 1989; Davidson, 1993).

Because the reactions are stimulated by sunlight, the result is often known as photochemical smog. Two of the major pollutants in photochemical smog are ozone (O_3) and peroxyacetyl nitrate (PAN).

Primary pollutants

Figure 2.1 (Hodges, 1973) shows how the emissions of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx) vary with the air-fuel ratio used in the combustion engine. Conventional petrol engine cars use an air to fuel ratio of about 15 to 1. It can be seen that by increasing the proportion of air in the mixture the emissions of CO and HC fall, while NOx initially rises and then falls.

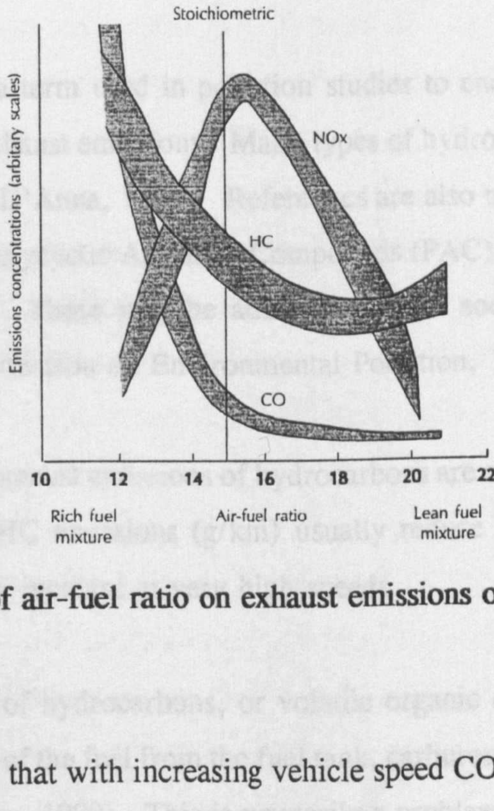

Figure 2.1 **Effect of air-fuel ratio on exhaust emissions of CO, HC and NOx.**

It should also be noted that with increasing vehicle speed CO and HC emissions tend to fall while NOx emissions rise (Potter and Savage, 1983). At low speeds, as encountered in congested conditions, high emissions of CO and HC (measured in grams per kilometre) are typical. These pollutants are described in more detail below.

Carbon Monoxide (CO) is produced as a result of incomplete combustion within the cylinders of a petrol or diesel engine. During the combustion process fuel burns to form firstly carbon monoxide and water vapour. When complete combustion takes place the carbon monoxide is further oxidised to form carbon dioxide.

When there is insufficient air, and hence oxygen, in the air-fuel mixture it is not possible to oxidise all the carbon monoxide to carbon dioxide. Hence a low air-fuel ratio can be expected to result in higher emissions of carbon monoxide. An engine running on a higher air-fuel ratio can be expected to have lower CO emissions, provided the mixture is not too weak to adequately support combustion.

An uneven burn of the fuel in the combustion chamber can also result in an increase of CO and hydrocarbons. The highest levels of CO emissions can occur when a vehicle is cold and choked or when the engine is idling. CO emissions (g/km) usually reduce with increasing vehicle speed, but may slightly increase at very high speeds.

Hydrocarbon (HC) is a term used in pollution studies to encompass all the organic compounds found in exhaust emissions. Many types of hydrocarbons may be emitted (Barbella, Ciajolo and D'Anna, 1989). References are also made to a specific group of hydrocarbons: the Polycyclic Aromatic Compounds (PAC) or Polycyclic Aromatic Hydrocarbons (PAH). These may be adsorbed on the soot particles from diesel emissions (Royal Commission on Environmental Pollution, 1991).

As in the case of CO, exhaust emissions of hydrocarbons are caused by the incomplete combustion of fuel. HC emissions (g/km) usually reduce with increasing vehicle speed, but may slightly increase at very high speeds.

A significant quantity of hydrocarbons, or volatile organic compounds (VOC), can arise from evaporation of the fuel from the fuel tank, carburettor and engine crankcase (Stump, Knapp and Ray, 1990). This is primarily a problem with some of the older vehicles. In the US this problem was recognised sometime ago and resulted in devices which trap the fuel vapours and route them to the engine to be burnt. Preventative measures are also available on some of the vehicles in the European fleet.

Williams et al (1989) looked at diesel emissions and identified over 50 different PAHs in the aromatic fraction of diesel fuel. This research showed that lubricating oil can contribute up to 90 percent of the solvent organic fraction of diesel particulates. The oil accumulates unburned fuel and PAH. Unburned fuel can then contribute to particulate composition directly and via the lubricating oil. As the oil ages, the latter route becomes dominant and PAH emissions increase.

Nitrogen oxides (NOx) encompass nitric oxide (NO) and nitrogen dioxide (NO_2). Another oxide of nitrogen is nitrous oxide (N_2O).

Nitrous oxide (N_2O) is not generally regarded as being emitted in significant concentrations to be a health problem. However, it has been shown recently (Gould and Gribbin, 1989) from tests carried out in Sweden and France that cars equipped with catalytic converters emit higher quantities of this gas.

Nitric oxide (NO) is a colourless gas, formed almost exclusively during the combustion of fuels when high temperatures and pressures allow some of the nitrogen in the air supply to combine directly with oxygen.

Nitrogen dioxide (NO_2) is formed by the oxidation of nitric oxide. On leaving the high temperature of the flame, nitric oxide can combine with more oxygen to form the reddish-brown gas nitrogen dioxide. The ratio of the concentrations of nitric oxide to nitrogen dioxide varies according to temperature and a number of other ambient factors.

Once nitric oxide has been diluted in the atmosphere, oxidation to nitrogen dioxide at normal temperatures usually proceeds only slowly. However, in California and other places with similar climates, the reaction rate is substantially increased by bright sunlight and the presence of hydrocarbons (Finlayson-Pitts and Pitts Jr., 1993).

Sulphur dioxide (SO_2) is formed when sulphur, or compounds containing it, are burnt. Diesel engines in particular are responsible for high emissions of sulphur dioxide, as diesel fuel has a relatively high sulphur content. Traffic emissions of this pollutant are relatively low compared to some stationary emission sources (Watson et al, 1990). Nevertheless, it contributes to the problem of acid rain (National Research Council, 1983; Brimblecombe, 1993; Firor and Rhodes, 1993). The US plans to reduce its contribution by reducing the sulphur content of diesel fuel to 0.05% compared with

0.3% in the UK.

Lead (Pb) is emitted in particulate form as lead halides which slowly convert to carbonates, oxides and sulphates in the atmosphere. The emissions of lead are primarily caused by 'anti-knock' additives that are present in leaded petrol (Standen, 1967). Their purpose is to control the combustion process within the engine and to reduce wear of the valves within the cylinder. However, car manufacturers are now producing engines which can run on petrol without these additives.

Particulate and smoke emissions are those which consist of small particles of liquid or solid matter. These particles typically consist of carbon, hydrocarbons and sulphates. The diameter of such particles can be less than one micrometre. An agglomeration of particles may be hundreds of micrometres. These particulates are responsible for the reduced visibility of smoke.

Although particulates can be emitted from petrol engine exhausts, these emissions are normally associated with diesel engines (Bryzik and Smith, 1977; Linaritakis, 1983; Williams et al 1989, 1989a; Williams, Abbass, Andrews and Bartle, 1989). The Royal Commission on Environmental Pollution (1991) states that diesel vehicles are the major source of smoke in urban areas. These emissions are typically generated when the engine is under load.

There are many factors responsible for these emissions including engine design, the chemical content of the fuel, vehicle age and vehicle maintenance (Becker and Rutherford, 1979; Rutherford and Waring, 1980; Royal Commission on Environmental Pollution, 1991). Bryzik and Smith (1977) have shown the relationship between smoke opacity and air-fuel ratio for selected diesel engine speeds. This shows that, generally, higher engine speeds produce slightly higher levels of opacity, and as the air-fuel ratio is increased the opacity decreases.

Carbon Dioxide (CO_2) is a commonly occurring gas which is produced from the combustion of many organic compounds and fossil fuels. Complete combustion, for a given quantity of fuel, produces slightly higher emissions of CO_2 than does incomplete combustion. Carbon dioxide is a major product of the combustion process.

Secondary Pollutants

The secondary pollutants are so called, not because of their lesser importance, but because they are produced by reactions between the emitted primary pollutants. Secondary pollutants may form some time after the emission of primary pollutants and downwind of the emission source (Borrell et al, 1991; Derwent and Jenkin, 1991; Uthe, Livingstone, Nielsen, 1992).

Secondary pollutants are produced by the reactions between nitrogen oxides and the hydrocarbons. These reactions are stimulated by the presence of bright sunlight, and because the secondary pollutants are responsible for smog they are also referred to as photo-chemical smog. The two of the secondary pollutants are ozone (O_3) and peroxyacyl nitrate (PAN) (Williams, Grosjean and Grosjean, 1993).

2.4 DISPERSION OF TRAFFIC EMISSIONS

In conjunction with the emission rate, the dispersion process is responsible for determining the rate at which pollutants are diluted and, hence, the pollutant concentration at a given point from the emission source.

Traffic emissions are dispersed by the following mechanisms to varying degrees, depending on the distance from the source, meteorological factors and the surrounding topology. Directly adjacent to the source of air pollution, the exhaust, emissions are dispersed by: air currents flowing around the vehicle as a result of the vehicle's motion and ambient air currents (wind); turbulent air currents; and vertical air currents, including to some extent the rising warm air of the exhaust.

Wind over an emission source will tend to carry the pollutants along with the air current and form a plume in the direction of such an air current. The size and shape of the plume is dependent upon the speed, and variation in speed and direction of the wind (Pasquill, 1974). A strong wind will carry pollutants far away from their source and one varying in direction will broaden the width of the plume (Hickman et al, 1979; Hickman and Colwill, 1982; Aneja and Kim, 1993). In addition to the wind, the emission source is often in motion and experiences a turbulent air current around the vehicle. Hence the net effect is derived from a combination of the wind and the motion of the vehicle. At high wind and/or vehicle speeds the air current flowing over the point source rapidly carries away the pollutants and represents the major dispersive mechanism. The air currents provide an effective dispersion mechanism both local to the source, over many kilometres and even across continents (Derwent and Jenkin, 1991; Uthe et al, 1992).

Tall buildings either side of a street are able to reduce the dispersive effects of wind. This phenomena is known as the canyon effect. Depending on the wind speed and direction relative to the street, vehicle emissions may disperse slowly resulting in relatively high pollutant concentrations. Consequently, during peak hours, air quality standards may be violated (Koushki, 1991).

Studies and modelling of fluids flowing over and around objects have shown that random or chaotic motion is traced out around those objects. This phenomenon is known as turbulence, and a fluid mass performing such random motion is referred to as a turbulent eddy current. These currents can be a significant part of the dispersion process. As turbulent eddies are readily created around vehicles and buildings they contribute to the dispersive mechanism at street level.

Over a conurbation, atmospheric stability can play a major role in the dispersal of pollutants. Temperature inversions and atmospheric stability present poor dispersive powers and pollutants can become trapped at or near ground level. As emissions continue the pollutant concentrations rise, resulting in degradation of air quality and a potential risk to health and the environment (Chanlett, 1973; Creswell, 1974). These high primary pollutant concentrations in the presence of strong sunlight can react to form photochemical smog (Borrell et al 1991; Derwent and Jenkin, 1991).

The Los Angeles basin, California, is sheltered by mountains, exposed to bright sunlight, experiences temperature inversions and has high traffic volumes. These conditions result in the formation of photochemical smog. Consequently, the federal standard for ozone is frequently exceeded (Davidson, 1993). Similar conditions exist in Athens, Greece (Hope, 1992).

2.5 EFFECTS OF AIR POLLUTION

A pollutant may exhibit effects varying from harmless to fatal depending on the concentration and dose that an organism is exposed to. Some pollutants accumulate in the body and, after long periods of exposure, chronic health effects may result. Some cause no ill effects when exposed for long durations to a low concentration; but can be fatal when briefly exposed to a high concentration. Carcinogenic pollutants appear to have no safe level; the higher the exposure the greater the risk of cancer. Pollutants also have effects on vegetation and buildings.

Carbon Dioxide

It has been indicated that the increasing average global concentration of carbon dioxide (Neftel et al, 1982 and 1985) is making a significant contribution to global warming (Oerlemans, 1994; Schneider, 1994). Oerlemans reported that during the last 100 years there has been a linear warming trend of 0.66 kelvin per century.

Global warming involves many complex interactions that are difficult to accurately represent, but it has been predicted that there could be significant climatic changes, and impacts on vegetation (Ausubel, 1983; Firor and Jacobsen, 1993; Bongaarts, 1994; MacKenzie, 1994; Pimm and Sugden, 1994; Reilly, 1994; Rosenzweig and Parry, 1994; Stocker, 1994).

However, observed and predicted climatic trends are further complicated by natural variations in climate and driving forces from other sources (Flan, 1993; Pearce, 1993; Charlson and Wigley, 1994; Christy and McNider, 1994; Groisman, Karl and Knight, 1994; Kerr, 1994; Leuturgler, 1994; Novelli et al, 1994; Foukal, 1994; Schlesinger and Ramankatty, 1994; Stouffer et al, 1994).

Hence, while there appears to be little doubt that carbon dioxide does have a role to play in global warming, the global processes are so complex that it is difficult to accurately quantify the impact of carbon dioxide.

Carbon Monoxide

Carbon monoxide (CO) is a colourless, odourless, tasteless gas. It reacts with haemoglobin to form carboxyhaemoglobin (COHb). The affinity of CO to haemoglobin is more than 200 times higher than for haemoglobin to oxygen. Quantitative levels for COHb are dependent on CO concentration and the degree of exercise during exposure.

Several important relationships between carboxyhaemoglobin levels and physiological parameters, considered in the WHO (1979) and US Environmental Protection Agency (EPA, 1984) criteria documents have continued to be the subject of discussion and it is thought additional research is needed.

Various health effects are reported to be associated with carbon monoxide exposure (EPA, 1984). CO leads to deficient function in sensitive organs and tissues like the brain, heart, the inner wall of blood vessels and platelets. Curtailment of certain physically demanding occupational or recreational activities may take place when exposed to a high dose of carbon monoxide.

Of greater concern at typical ambient levels is the additional stress placed on the heart of those with existing health problems (e.g. chronic angina) during exercise. CO can impair behavioral functions and vigilance tasks. Perinatal effects may result in reduced birth weight and retarded postnatal development WHO (1987).

Guidelines

The WHO (1987) recommends a level of 2.5-3.0 percent carboxyhaemoglobin for the protection of the general population, including sensitive groups. Maximum carbon monoxide concentrations being:

100 mg/m^3 for periods not exceeding 15 minutes;
60 mg/m^3 (50 ppm) for 30 minutes;
30 mg/m^3 (25 ppm) for 1 hour; and
10 mg/m^3 (10 ppm) for 8 hours.

Hydrocarbons

Hydrocarbons represent a wide range (hundreds) of organic compounds and so it is difficult to give a comprehensive review of each substance. However, the hydrocarbons may be classified into groups which have similar effects. Some may have no discernable health effect at typical ambient levels. Others may cause irritation to the eyes and respiratory tract, or be responsible for obnoxious odours. Perhaps more alarming are the carcinogenic (cancer inducing) and mutagenic (mutation of DNA) hydrocarbons.

Some of the hydrocarbons have little or no effect on human health but may represent a threat to the environment in terms of global warming, e.g. methane. Some hydrocarbons are also precursors to the formation of photochemical compounds found in smog, e.g. peroxyacetyl nitrate. In this form they provide irritation, particularly of the eyes (WHO, 1987).

Carcinogens increase the risk of receiving cancer over a lifetime (WHO, 1987). It appears that there may not be a safe threshold level for such substances; higher exposures lead to higher probabilities of receiving cancer. Carcinogens are present in petrol and diesel, and emissions from vehicles powered by such fuels. These include, but are not limited to: benzene, formaldehyde, polynuclear aromatic hydrocarbons (PAH), styrene, and toluene. However, the quantitative impact that vehicle emissions have on health is difficult to establish: the World Health Organisation's health risk evaluation of PAH was mainly based on coke-oven emissions and it points out that diesel emissions include additional carcinogenic agents.

Oxides of Nitrogen

WHO (1987) indicates that asthmatics are likely to be the most sensitive subjects to NO_2 although uncertainties exist in the health database. It has effects on pulmonary function, and at relatively high doses has been shown to produce reversible and irreversible damage to the lungs of animals. Exposure to NO_2 can also lower the resistance of the lungs to infection.

Nitrogen dioxide can damage vegetation. Plant leaf symptoms have been observed as a result of a four hour exposure to an average concentration of 2.5 ppm (Bond, Straub and Prober, 1972.)

Nitrogen oxides, along with sulphur oxides, form acid rain. This is known to damage materials, buildings and plant life. Although these can be caused by other sources, there was sufficient certainty to convince governments to take action against these emissions (Firor and Rhodes, 1993).

Nitrogen dioxide also plays a role in the formation of ozone (Finlayson-Pitts and Pitts, 1993), a strong oxidising agent, which is responsible for damage to plants, materials, animals and humans.

Guidelines

The guidelines recommended by WHO (1987) for nitrogen dioxide levels are 400 μm^3 and 150 μm^3 for 1 hour and 24 hour periods respectively.

Sulphur Dioxide

WHO (1987) reported that the effects of sulphur dioxide on the health of asthmatics were demonstrable down to levels of about 1000 $\mu g/m^3$, with discernible effects of less certain consequence below that level. Of importance to public health is the proportion of people liable to be affected. Detailed information regarding the proportion of asthmatics or other sensitive people in the community were not available, but estimates of around 5 percent have been suggested.

Sulphuric acid aerosols associated with SO_2 emissions also produce adverse health effects. Respiratory effects from exposure to sulphuric acid (350-500 $\mu g/m^3$) have been reported to include increased respiratory rate, decreased flow rates and tidal volume (EPA, 1982; Ericsson and Camner, 1983). Other studies have shown that in healthy non-sensitive adults health is little affected up to 1000 μg/m^3 when exposed from 10 to 120 minutes. Asthmatics, again, are substantially more sensitive in terms of changes in pulmonary mechanics than healthy people. The lowest demonstrated effect level was 100 μg/m^3 in adolescent asthmatics. The effects were relatively small and disappeared within about 15 minutes. In adult asthmatics the lowest observed effect level was 350 μg/m^3 (Ericsson and Camner, 1983; Utell and Morrow, 1986).

The effects of longer term exposure is circumstantial and based on air pollution case histories. Respiratory diseases in 600 people in the Yokkaichi area of Japan were attributed to sulphuric acid (Kitagawa, 1984).

Sulphur dioxide is also a major constituent of acid rain and is known to attack buildings, aquatic life and affect plant growth (Schulze, 1989).

Guidelines

The WHO recommend 500 μg/m^3 as the guideline level for a 10 minute exposure to sulphur dioxide, and a 1 hour maximum of 350 μg/m^3. Recommendations are also provided for acid aerosols and the combined effects of smoke. For example, over a 24 hour period the levels for sulphur dioxide and smoke are 125 μg/m^3 for each pollutant; and over a year, 50 μg/m^3 for each.

Lead

WHO (1987) documents a wide range of effects of lead. Its effects the nervous system, kidneys, reproduction, the immune system, cardiovascular system and gastrointestines. Atmospheric lead contributes between 15 and 70 percent to the total intake in adults, and 2 to 17 percent in children. A study showed that about 25 percent of lead in the body is from petrol (Facchetti and Geiss, 1982).

Smoke and Particulate Matter

The small particulates from road transport emissions distort visibility more than larger particles, and if deposited in the lungs they take much longer to be removed than larger particles (Walsh, 1985 and Burt, 1972).

The effect of particulates on health relates to physical form and the presence of other substances adsorbed onto the particle's surface. In the WHO guidelines, the combine effects of sulphur dioxide, acid aerosol, and particulate are described.

Diesel smoke may represent a threat to health. In diesel smoke, the carbon particles have polynuclear (or polycyclic) aromatic hydrocarbons (PAH) adsorbed onto the surface of the particles (Barbella, Ciajolo, and D'Anna, 1989). In this microscopically concentrated form, the particles can be inhaled deep into the lungs where particles may become trapped, exposing the tissue to mutagenic and carcinogenic PAH. With regard to PAH, the World Health Organisation (WHO, 1987) concluded that, owing to its carcinogenicity, no safe level can be recommended.

According to Dr Sandra Jones at the Polytechnic of North London's pollen research unit (LTT, 1992), diesel smoke combine with high pollen levels seems to be worsening hay fever. More people appear to be suffering, and attacks growing more severe. A rise in patient numbers that was out of proportion with a rise in pollen levels, created the suspicion that pollution was responsible.

Small particulates less than 10 micrometre in diameter (PM_{10}) from road transport emissions, particularly diesel emissions, along with the chemicals adsorbed on them, are suspected of being a health hazard to the elderly and people with pneumonia, and chronic lung and heart disease (Bown, 1994). Schwartz, an epidemiologist at the US Environmental Protection Agency, estimates as much as 60,000 deaths per year are linked to particulate levels. He also estimates that in England and Wales, it could be responsible for about 10,000 deaths. Schwartz says that there is no safe level for particulates, and higher levels result in more deaths.

Particulate matter, along with adsorbed PAH, deposited on soil is taken up into crops. Eating food contaminated in this way is thought to be the major source of exposure to PAHs by non-smokers (Jones et al, 1989).

Since pollution from coal smoke has been reduced, diesel particulates have become the major cause of soiling on buildings (Royal Commission on Environmental Pollution, 1991). Not only does this affect the look of buildings, it is also suspected of accelerating erosion from acidic gases. Diesel particulates are not easily washed off by rain, and are estimated to be three times more effective than coal smoke and six times more effective than particulates from petrol engines, at soiling buildings (Ball and Caswell, 1983).

Ozone

The WHO (1987) describe ozone as a powerful oxidant, able to react with virtually every class of biological substance. It can produce damage to all parts of the respiratory tract. The symptoms include cough, throat dryness, chest pain, increased mucus production, chest tightness and nausea, amongst others. The most sensitive people are not necessarily the same ones who suffer from asthma, allergies or other lung diseases.

Studies have shown that exposure to levels of ozone below the US federal standard (0.12 ppm) produce significant biological effects (Science 1989) and changes in respiratory function, especially during moderate exercise (Lippmann, 1989 and 1991). Levels below the federal standard also have a significant impact on agricultural crops and forest ecosystems (Heagle et al 1988; Miller et al 1989; Lefohn and Foley, 1992). Ozone has a significant impact on crop yield in the US (Heck et al, 1983) and to a lesser extent in the UK (United Kingdom Photochemical Oxidants Review Group, 1987).

James Crapo (Science, 1989) at Duke University found evidence of inflammation and fibrosis in rat lungs after the animals had lived for 18 months in an air-ozone mixture like the summer breezes of Los Angeles.

Recent studies (Finlayson-Pitts and Pitts, 1993; Lefohn and Foley, 1993) suggest that ozone exposure patterns are important for establishing suitable air quality standards. High hourly average concentrations should be weighted higher to account for the damage caused to vegetation. Similarly, for human health, concentration may be more important than exposure or respiration rate.

The WHO (1987) recommend a 1-hour guideline of 150-200 $\mu g/m^3$ (0.076-0.1 ppm), and a 8-hour guideline of 100-120 $\mu g/m^3$ (0.05-0.06 ppm).

2.6 SUMMARY

This chapter has introduced the concepts of air pollution, emission and dispersion mechanisms, and described the effects of air pollution.

Meteorological conditions are a major factor in the dispersal of pollutants. Temperature inversions and stable atmospheric conditions provide an unfavourable environment for the dispersal of pollutants, leading to increased concentrations.

The mechanisms responsible for emissions have been outlined. In the case of carbon monoxide and hydrocarbons, emissions generally fall with increasing speed. Whereas, emissions of nitrogen oxides generally increase with increasing speed. These, and other, inverse relationships suggest that strategies which aim to regulate emissions based on traffic speed control or enhanced engine technology, may have to determine which pollutants should be reduced at the potential expense of increasing others.

Lead and sulphur dioxide emissions are related to fuel content and quantity of fuel consumed. Smoke emissions, from diesel vehicles under load, are a result of incomplete combustion. Emissions of carbon dioxide represent a by-product of the fossil fuel combustion process. The precursors to photochemical smog are hydrocarbons and nitrogen dioxide.

The factors involved in the dispersion of traffic emissions, and unfavourable conditions, have been described in this chapter. Emissions will be dispersed effectively when the source is exposed to relatively high wind speeds and unstable atmospheric conditions, as opposed to stable conditions with little wind.

The effects of air pollution are wide ranging, affecting the environment, vegetation, and animal and human health. However, the World Health Organisation has indicated that the process of gathering data and conclusively identifying the effects of air pollution is a complex and difficult task, which may be further complicated by interactions and cumulative effects of different pollutant species (WHO, 1987).

Most of the pollutants in traffic emissions have an impact on human health, are irritants or obnoxious smells. Such effects may lead to acute or chronic illness. Some pollutants, namely polycyclic aromatic hydrocarbons found on the particulates of diesel emissions, are carcinogens. The secondary pollutants found in photochemical smog produce irritation and damage to the respiratory track and vegetation.

Chapter 3

AIR POLLUTION STUDIES

3.1 INTRODUCTION

This chapter describes air quality standards, the impact of traffic pollution based on its contribution to ambient levels, and studies specifically related to road traffic emissions.

Given air quality guidelines, along with economic, social and political influences, air quality standards may be defined whereby air pollution levels should not exceed a set value. This chapter summarises the types of standard relevant to traffic emissions, and organisational and regulatory frameworks involved in their enforcement.

The previous chapter described the mechanisms responsible for the generation of air pollution and its associated effects. In this chapter, the contribution which road traffic emissions make to the air pollution problem are discussed. This considers the impact of each pollutant emitted wholly, or partly, by road traffic.

To meet air quality standards a reduction in emissions may be necessary. This chapter describes studies which have investigated road traffic emissions, either to further academic knowledge, improve the data in an emissions inventory/database, or in order to reduce emissions.

3.2 AIR QUALITY STANDARDS AND REGULATION

European Union (EU) law is central to environmental policy and regulation in the UK. Any organisation wishing to know about environmental law needs to consider policy and proposed legislation with the EU, and specifically within Directorate-General XI, the Directorate concerned with environmental protection. EU environmental policy began in 1973 with the first environmental action plan; the fourth running from 1987 -

1992 (Simmons & Simmons, 1991). Environmental law has developed rapidly within the EU. There are many areas of activity in air pollution. The areas that are relevant to road traffic emissions are specified by the following directives:

- air quality limit values for smoke and sulphur dioxide;
- air quality standard for nitrogen dioxide;
- limit value for lead in air and on biological screening for lead;
- content of fuels, e.g. lead in petrol; and
- vehicle emissions.

A directive is binding concerning the ends to be achieved by Member States, but leaves the choice of means to the national authorities. Thus directives are, in effect, blueprints for legislation and can only take effect through national measures. However it may be possible for individuals to rely on the terms of directives in actions against the state. Simmons and Simmons (1991) say, EC statistics show a considerable rise over recent years in complaints made to the Commission by individuals or public interest groups about failure of Member States to implement directives. Such complaints are investigated by the Commission and may result in prosecutions against the relevant governments.

Because traffic is a significant contributor to NOx levels in urban areas, the directive for nitrogen dioxide should be considered when defining the objectives of an environmental traffic control strategy. The 1985 directive (85/203/EEC) on air quality standards for nitrogen dioxide states, measurement points should be selected to: cover examples of the main types of zone predominantly affected by pollution from motor vehicles, particularly 'canyon' streets carrying heavy traffic and major intersections; and be, as far as possible, those in which NO_2 concentrations are likely to be among the highest. The limit value is expressed as the 98th percentile of all readings recorded over a year, with each reading representing a period of one hour or less. For NO_2 the limit value is 200 $\mu g/m^3$ and guide values are 135 $\mu g/m^3$ and

50 $\mu g/m^3$ for the 98th and 50th percentiles, respectively. The limit value should not be exceeded. It is to help protect people against the effects of NO_2 in the environment. The guide values are to improve the protection of human health and contribute to the long-term protection of the environment.

Legislative requirements for vehicle emissions fall into two categories: type approval standards and in-service standards. New production vehicles have to meet limits set in type approval standards, but as vehicles age they must also be able to demonstrate a degree of durability and satisfy the in-service standards. In Europe in 1968 the United Nations Economic Commission for Europe (ECE) set up the ECE 15 standard which has undergone four amendments, ECE 15-01 to ECE 15-04. The regulation was first applied in the UK in 1973. The ECE Regulation 15 test with amendment 4 (Bosch, undated) is given below in Table 3.1.

Vehicle equivalent inertia weight (kg)		*CO g/test*	*HC + NOx g/test*
	< 1020	58	19.0
1020	< 1250	67	20.5
1250	< 1470	76	22.0
1470	< 1700	84	23.5
1700	< 1930	93	25.0
1930	< 2150	101	26.5
	> 2150	110	28.0

Table 3.1 ECE Regulation 15-04

In the UK regulation of air quality may involve local authorities, Her Majesty's Inspectorate of Pollution (HMIP), the Department of the Environment, and in the case of traffic emissions, the Department of Transport. District and borough councils are the enforcing authorities for control over smoke, dust and grit under the Clean Air Acts (1956 and 1968), and for the new system of prior approval under Part I of the Environmental Protection Act 1990 (EPA). Currently, their powers for enforcing air quality levels through the use of environmentally sensitive traffic control strategies appears to be less clearly defined.

3.3 SIGNIFICANCE OF TRAFFIC EMISSIONS

In the past, stationary source emissions played a major role in urban air pollution (Chanlett, 1973; Creswell, 1974; Arvill, 1976). Over the past 10 to 20 years these emissions have declined throughout most of the European region (WHO, 1987). Whereas, emissions from road traffic now account for a significant proportion of urban air pollution (WHO, 1987; U.S. Department of Transportation, 1990; Royal Commission on the Environment, 1991; Watkins, 1991; DTp, 1993; Bown, 1994).

Road transport has become the dominant means of travel in Britain, providing 93 percent of all passenger kilometres travelled, 82 percent of the total tonnage of freight lifted and 59 percent of the tonne kilometres of freight moved (Mitchell, 1991). It is not surprising, therefore, that road transport represents a significant contribution to air pollution.

The impact of traffic emissions is probably most notable in urban areas where traffic densities are relatively high and characterised by slow speeds, and frequent acceleration and deceleration (Watson, 1972; Evans, 1979; Nishimura and Hino, undated). The impact of traffic emissions varies for each pollutant.

In the UK, vehicle emissions of CO in 1991 accounted for 89 percent of the UK's total emissions of CO (DTp, 1993). High pollutant concentrations, referred to as hot spots, of CO are known to occur at busy urban intersections (Ott, 1977; Benesh, 1978; Claggett, Shrock and Noll, 1981; Zamurs and Piracci, 1982). Hot spot levels of CO may exceed air quality standards and guidelines (Koushki, 1991). Levels in London are known to exceed guideline values, but studies do not agree on whether these levels significantly impair the driver and have an impact on safety (Watkins, 1991).

The hydrocarbons emitted by vehicles in 1991, accounting for 46 percent of the UK's total emissions of HC (DTp, 1993). These emissions are precursors of photochemical pollution, and so their indirect impact in this form is significant (Finlayson-Pitts and Pitts, 1993).

In 1991, vehicle emissions accounted for 52 percent of the UK's total emissions of NOx (DTp, 1993). Other studies confirm that cars are the major source of nitrogen oxides in Europe (New Scientist, 1989) and the UK (Royal Commission on Environmental Pollution, 1991). These emissions also make a significant contribution to photochemical pollution (Finlayson-Pitts and Pitts, 1993).

A number of cities throughout Britain exceed advised levels several days a year. For example, in Edinburgh over a 12 month period 13 of the 14 monitoring sites exceeded EC guideline values (Hughes, 1992). This led the researchers to speculate that London, with its greater traffic density, would be worse. However, Hughes points out that more monitoring stations in London need to be sited by the roadside. The author also emphasises the need for this, given the type of sites specified by the EC directive for NO_2. Studies have shown that air quality guidelines are exceeded in London (Watkins, 1991).

So although it is generally recognised that vehicles are the major source of NO_2 emissions, actual pollutant levels at critical sites will not be known unless they are measured. The author suggests that, perhaps, a modelling approach could be used to estimate such levels, or identify where the worst sites are likely to be. These sites could then have their NO_2 levels measured.

The author did not find any recent studies which associate vehicle emissions to ambient levels of sulphur oxides. This may be because urban levels have fallen and vehicle emissions are not a major contributor (WHO, 1987).

Emissions of lead from petrol were thought to account for 15 to 70 percent of the lead intake of adults, and 2 to 17 percent for children (WHO, 1987). Unleaded petrol is not necessarily free from lead and future levels for the maximum lead content are expected to be 0.013 g/litre; leaded being 0.4 g/litre (Russell 1988). Russell indicates that petroleum demand within Europe will reduce slightly throughout the 1990s.

Projections show that about 50 percent of gasoline will be unleaded by 1995 and about 80 percent will be unleaded by the year 2000.

A reduction of lead in petrol makes a significant impact on airborne lead. This was seen in Germany in 1976 when lead concentrations in petrol changed from 0.4 g/l to 0.15 g/l. The corresponding reductions in atmospheric lead in urban and rural areas were 65 percent and 20 percent respectively (Royal Commission on Environmental Pollution, 1983). Falling concentrations of lead have been observed on the M4 and in London, as a consequence of reduced levels in petrol (Bevan et al, 1974; Hogbin and Bevan, 1976; Dorling and Sullivan, 1980; Hickman, 1989). DTp (1993) figures show that the total emission of lead from vehicles in the UK, has fallen from 6.5 thousand tonnes, in 1985, to 2.0 thousand tonnes in 1991.

Diesel emissions make the largest contribution to emissions of particulate carbon, contribute about a third of the UK emissions of black smoke, and represent a potential health problem (WHO, 1987; Royal Commission on the Environment, 1991; Bown, 1994). The Royal Commission on the Environment note that heavy duty diesel vehicles account for a significant and growing source of these emissions. Therefore, the author suggests a cautious approach, when promoting diesel vehicles as environmentally friendly. These emissions should be taken into account.

In the UK, vehicles emitted over 106 million tonnes of CO_2 in 1988 and 120 million tonnes in 1991, 21 percent of total UK emissions (DTp, 1993). Although vehicle emissions are not the major contributor to CO_2 emissions, they make a significant contribution and are the fastest growing source of emissions (Hughes, 1992a). Hughes discusses regulation of these emissions by a sustainable transport policy.

In June 1992, at the United Nations Earth Summit in Rio, Brazil, global warming was discussed. It was generally agreed that steps should be taken to curb carbon dioxide emissions. The European Union aimed to fix 20th century emission levels to those of the 1990s; the UK is committed to returning total emissions to the 1990 level by the year 2000 (DTp, 1993). It has been estimated that European emissions could be reduced by sixty percent (Mot et al, 1993).

As a result of the volume of traffic and its associated emissions, Los Angeles is well known for its photochemical smog (Arvill, 1976; Maclean & Thomson, 1981; Science, 1989). In spite of strict environmental controls it still has an air pollution problem (Davidson, 1993). Traffic pollution is also a major contributor to air pollution in Athens (Hope, 1992). This results in a rising number of admissions to hospital and people with respiratory problems are warned to stay indoors. Under these conditions the environment ministry imposes a traffic ban. Pan-European photochemical pollution is significant and its complex transport and chemistry have been studied by many experts (Borrel et al, 1991; Derwent and Jenkin, 1991). It has been suggested that concurrent controls on the emissions of hydrocarbons and oxides of nitrogen are needed to control ozone levels (Finlayson-Pitts and Pitts, 1993).

3.4 TRAFFIC POLLUTION STUDIES

It has been shown above that road transport makes a significant contribution to air pollution. Consequently, there appears to be a need for traffic pollution studies to understand vehicle emissions and provide solutions which improve air quality.

Emission Studies

Air quality is strongly influenced by source emissions, therefore, for pollution control strategies to be effective a good understanding of emission characteristics can be particularly useful. Analysis of vehicle emission data is useful for understanding the significance of various factors on emission rates, and provides valuable insight into what factors an emission model should represent. The collection of emission data is also necessary for the calibration of emission models.

Driving Cycles

The purpose of a dynamometer is to be able to 'drive' the vehicle over a standard cycle consisting of cruise, idling, acceleration and deceleration with the dynamometer absorbing the power and, in some cases, simulating vehicle inertia. The standard cycle is usually designed to represent typical driving conditions and, in some cases provides the basis for the modelling of on-road vehicle emissions.

Worldwide there are a number of standard driving cycles, the most common being the US, European and Japanese cycles (Watkins, 1991). Some of these driving cycles also have variations. If the cycle is based only on urban driving patterns, high speed driving may not be represented and so the cycle may have a high speed extra cycle added. Although the standard driving cycle is ideally suited to emissions legislation tests, study groups often use these driving cycles to model emissions for other non-legislative research projects.

The dynamometer provides a useful tool allowing various vehicle driving modes to be simulated and allows detailed models for vehicle emissions and fuel consumption as a function of driving mode to be developed (Post et al, 1985). Many studies have used this tool to investigate vehicle emissions over the ECE 15 driving cycle (Eggleston et al, 1988; Potter and Savage, 1986; Potter and Simmonds, 1988; Samaras, 1988; Williams et al, 1989). This can be used for new production and in-service vehicles, different production type years across different vehicle types and engine capacities, before and after maintenance, and with and without emission reduction devices fitted. Generally, the methodology used in such studies is based on a standard driving cycle, for example ECE 15, and their experimental approaches are usually similar.

Colwill, Hickman and Waterfield (undated) investigated emissions from vehicles using the ECE Regulation 15 test procedure with its various amendments. The cars chosen represented 85 percent of the best selling cars in the UK. They were selected from garages, car hire firms, private individuals and a few company cars. Exhaust measurements were made to investigate changes in CO, HC and NOx emissions as a function of amendments made to ECE regulation 15, vehicle speed, and unmaintained vehicles.

The study's findings are, generally, in agreement with those of other studies. It had three major conclusions:-

1) Vehicles built before the ECE 15 period had a very wide range of emissions, particularly those that were 'as received'. However, the mean emissions from tuned vehicles generally fell within the required limits. NOx emissions complied with the limits most easily.

2) Speed was an important factor in estimating exhaust emissions. HC and CO emissions dropped rapidly with speed, but NOx emissions increased. Due to the low test speed for ECE 15, the test results gave slightly high values for CO and HC emissions and low values for NOx emissions.

3) Vehicle age had a considerable effect on emissions. Emissions of CO increased by a factor of four over a year. However, servicing generally brought the emissions back down to levels complying with ECE 15.

The CORINAIR Working Group on Emission Factors made use of a comprehensive set of investigations and analyzed emissions over driving cycles and as a function of speed (Eggleston, 1988; Samaras, 1988). The results represented an extensive emissions inventory, including work carried out in Britain, Holland, France, Germany, Greece and Switzerland. This study's comprehensive analysis of emissions from vehicles throughout Europe provides a useful emissions inventory, indicating how vehicle emissions vary with production type period, and country. There were many findings from this study and the main points are summarised below.

In general, emissions of CO and HC, and fuel consumption, fell with the introduction of the ECE 15 test and with each of its amendments. Conversely, the introduction of ECE 15, through to 15-03, led, in many cases, to an increase of NOx emissions. With the introduction of the ECE 15-04 regulation, emissions of NOx fell slightly, compared with ECE 15-03, but levels were still slightly higher than those before the introduction of the first ECE 15 regulation. This illustrates that the engine conditions required to minimise emissions of CO and HC are not necessarily those required to reduce emissions of NOx.

The CORINAIR study illustrates that, in general, emissions of CO and HC fall with increasing vehicle speed, up to about 60 to 70 km/h. The influence of engine capacity is to change the speed at which minimum emissions occur, but its effect is not very significant. Emissions of NOx increase with increasing speed, over the whole speed range tested. Engine capacity clearly affects NOx emission, with higher capacities emitting more over the speed range.

This work has been updated to produce emission factors for 1990 emissions from road traffic (Eggleston et al, 1993). This later study has provided additional detail and added new classes of vehicle to its database. In particular, it includes passenger cars equipped with catalysts. The list of pollutants has also been extended and includes NOx, N_20, SOx, VOC, CH_4, CO, CO_2, NH_3, diesel particulates and lead.

It has also been shown that emissions of NOx can behave differently to emissions of CO and HC, when a vehicle's engine is tuned. Williams and Everett (1983) investigated the effect of tuning in-service vehicles and found that tuning to manufacturer's specifications reduced idle CO, mass CO and mass HC emissions on average by 38, 36 and 14 percent, respectively. However, NOx emissions increased by 19 percent.

Potter and Savage (1982 and 1983) have also confirmed that tuning can reduce CO and HC emissions whilst increasing NOx. Their work also illustrated that there was a wide range in vehicle emissions for a given speed, indicating that some vehicles emit significantly more than others.

Indeed, recent studies have shown that as little as 10 percent of the traffic fleet can be responsible for about half the fleet's total emissions (Hansen and Rosen, 1990; Stephens and Cadle, 1991; Beaton et al, 1992). There also appears to be little correlation between their emissions and the length of time since their routine inspection (Lawson et al, 1990). A wide variation in emission rates exist for these high emitting vehicles (Cadle, Gorse and Lawson, 1993).

The standard driving cycle cannot always accurately represent driving patterns found in all real life situations, and may become outdated. For example, research in

Holland indicated that the European test did not represent current driving conditions (MacKenzie and Watts, 1989). The test put cars through the equivalent of a 4 km drive at 40 kph, but actual on-road driving patterns included more long distance motorway driving. Consequently, in 1985 the European Commission asked car companies to redesign this test to bring it into line with the American version. Car manufacturers then proposed a test with an added "extra-urban cycle", simulating an extra 7 km at speeds from 90 to 120 kph.

It is interesting to note that it was recently pointed out that the U.S. FTP driving cycle does not adequately represent on-road driving patterns and emissions. It was recommended that the FTP cycle should include high speed driving, and high acceleration and deceleration rates (Cadle et al, 1991; Cadle, Gorse and Lawson, 1993). The absence of emission data for high accelerations is thought to be even more significant than the absence of emission data for high emission vehicles.

MacKenzie and Watts (1989) tested a variety of engines under the new extra-urban test cycle . They found that the most significant effect of this new cycle was on emissions of nitrogen oxides. Lean burn engines emit five times as much NOx during the fast driving as they do under the old urban cycle. Whereas, that emitted by cars equipped with closed-loop, three-way catalytic converters was still low. The researches found that engines with lambda-controlled closed loop catalysts, which hold the mixture to strict limits, burn 15 percent less fuel than standard engines. This leaves only a 5 percent advantage for lean burn engines; the researchers said this fell to 2 percent under realistic driving conditions.

More recent studies also indicate that an average speed approach may not be suitable for predicting emission rates and concentrations on a street by street basis. A representation of emissions from each driving mode seems to be an important requirement for the accurate modelling of emissions at an intersection, for example (Zamurs, 1990). It has been suggested that for models to perform accurately, they should represent emissions by driving mode (Cadle et al, 1991).

For the purpose of urban traffic management, some of the earlier results of Potter and Savage (1982) may be more appropriate to the prediction of curbside concentrations on individual streets. These results showed that, CO emission rates at steady-state (constant) speeds vary with speed and selected gear, but do not follow a consistent pattern. Emission rates for CO and HC increase with the acceleration rate. Hill ascents and roundabout negotiations are characterised by relatively high NOx emissions, whilst descents result in low NOx emissions. Generally, emissions of CO and HC increase, in terms of mass per unit time and mass per unit distance, with increasing acceleration rate. For NOx, rapid accelerations may not always produce the highest emissions.

On-Road Emissions

Recent studies have measured actual on-the-road emissions using in-vehicle gas analysis equipment (Andre, Hickman and Hassel, 1992). These data can be used to calibrate laboratory test-benches, and calibrate and validate emission models. On-vehicle equipment has also been used to measure propshaft torque, engine speed, vehicle inclination and road speed of selected heavy duty vehicles (Rendell, 1989). The results of these measurements are then used to simulate, on an engine test bed, the typical lifecycle of a truck in daily use, and to model truck emissions.

Technology is now available to monitor individual vehicle emissions as they pass a particular point (Lawson et al, 1990). For example, in October 1991, the RAC carried out a roadside survey of CO emissions involving 21,000 vehicles, using open path spectroscopic apparatus (Hughes, 1992). An infrared beam was directed through the path of vehicles' exhaust emissions to measure CO concentration. The measurement was superimposed on video images of passing traffic, to allow the study team to identify the types of vehicles producing the most pollution.

The measurement of on-road vehicle emissions in the US has shown that a small proportion of the vehicle fleet is responsible for a major proportion of total emissions (Pierson, Gertler and Bradlow, 1990; Stephens and Cadle, 1991; Bishop and Stedman, 1992). In Chicago, 10 percent of the vehicles emitted half the total amount of CO, and in Los Angeles 10 percent of the vehicles emitted 55 percent of the CO. Another study has shown that 20 percent of vehicles accounted for 65 percent of the emissions of black carbon (Hasen and Rosen, 1990).

Based on such results, Cadle et al (1991) proposed that the existing Federal driving cycle was not adequate and needs to be supplemented with addtional driving cycles. They also recommended that more information should be obtained on in-use driving patterns, and the effect of high engine loads on emissions. It was noted that heavy duty vehicle emissions are becoming more significant, but little data exists on their real-world emissions.

A study used a remote sensor to identify vehicles with high CO emissions (Lawson et al, 1990). Their current emissions were compared against those recorded as part of the U.S. inspection and maintenance programme. It was found that their emissions were much higher than when they received their inspection/maintenance test. Further, the length of time since the routine test had little influence on the emissions found in the roadside inspection.

Emissions from Catalytic Converters

Catalytic converters, described in Chapter 4, represent an effective technology for reducing vehicle emissions. Certification emission values may be used for calculating ambient concentrations of pollutants. However, climatic conditions throughout Europe result in a wide range of temperatures, and their effects on the efficiency of catalytic converters may become increasingly significant as the number of vehicles equipped with catalysts rise.

Laveskog et al (undated) investigated emissions from catalytic converters at sub-zero temperatures and the use of block-heaters to reduce emissions and fuel consumption. The ECE test procedure was modified, making it more suitable for testing advanced catalyst vehicles in a cold climate. Their performance over a range of operating, ageing and failed conditions was also assessed.

In some cases, equipment failure caused emissions of CO and HC to increase by a factor of 100. This indicated a need for on board diagnostic systems, as failures are not always noticeable in terms of drivability and fuel consumption. Ageing of the catalyst and lambda oxygen sensor resulted in a significant increase in emissions of CO, HC and NOx, with little effect on fuel consumption.

Other tests indicated that emissions from vehicles equipped with catalytic converters can be influenced in a significant and complex way. The study concluded air pollution modelling will require much more detailed input of emissions data compared to that used for non-catalyst vehicles. For example, it also showed that test cycles and test fuels have to be scrutinized in order to get comparable results, and results that reflect reality.

Improving the Efficiency of Traffic Networks

Having described studies which aim to understand the characteristics of vehicle emissions, the following paragraphs describe studies which apply this knowledge in order to reduce road traffic emissions. For example, delays and slow speeds often result in higher emissions of carbon monoxide and hydrocarbons, along with increased fuel consumption. Consequently, studies have aimed to improve the efficiency of traffic networks and reduce delay.

Red Routes

Red Routes were introduced into London to improve traffic efficiency (Jourdain, 1990). Red lines, replacing the conventional yellow no-parking lines, over 300 miles of clearway indicated no parking during peak hours, with extra high penalties for parking. In theory this would lead to increased efficiency of the traffic network, by improving the smoothness of flows along links. It was estimated that this would reduce fuel consumption by approximately one million litres a day.

However, Jourdain (1990) indicated that this strategy may not have been as effective as was expected. Some of the savings could be taken up by longer crawl in queues at 'difficult' junctions. The prohibition of stopping has a greater effect near junctions, but the improved link capacities place a higher burden on the junctions. The saving in greenhouse gases could also be annulled if any extra mileage was undertaken to take advantage of the improved journey time. Jourdain believes that only changes in habit will confirm the potential fuel savings which Red Routes offer.

Environmentally Optimised Traffic Signal Timings

A study, based on the Athens road network, developed a control mechanism that took into account both air quality and traffic performance of the transportation system (Costas Abacoumkin and Associates, 1988).

The control mechanism was designed to route vehicles around pollution sensitive areas and optimise traffic flow. Traffic was assigned according to historical traffic data, meteorological data, and pollution forecasts. The control strategy assigned traffic in a manner that reduced overall pollution in the central area of Athens. The result was a 13 percent reduction in emissions of CO and an 11 percent reduction in NOx. Within this area, the strategy reduced distance travelled by 14 percent, total travel time by 34 percent, and delay by 39 percent. The average speed was increased by 31 percent. These savings were traded for a slight, 2 percent, increase in carbon monoxide emissions over the outer urban area.

The study also included work on emission levels, conducted by Bell and Lear with Castle Rock Consultants; these results were included in the final report (Costas Abacoumkin and Associates, 1988). This used the TRANSYT traffic model and an air pollution model based on average speed, to predict link emissions in the network.

Varying the ratio of delay to stop costs from 0.01 to 100, in the West area of Athens, showed no significant variation in emissions. The study team concluded that this could have been because the traffic network was of a radial type and there was no scope for further optimisation. In the central area (a grid based network) emissions of CO and HC, per vehicle per unit distance, increased with increased stops and delay. Whereas, emissions of NOx reduced slightly. Overall, coordination of traffic signals gave an average reduction in link emissions of three percent.

The use of green waves to improve traffic movements were investigated (Lear and Bell, 1988). It was found that once a network's signal timings have been coordinated, further enhancements to reduce delay or stops on all, or particular, links of the network do not affect overall emission levels provided the network remained unsaturated.

The study team investigated the effect of redistributing traffic throughout the network ("after" flows), followed by the effect of reducing traffic in the central area ("new" flows). Comparisons were made between the congested "before" and "after" flows, and between "after and "new" flows. These are summarised in Table 3.2.

	Flow	*CO*	*HC*	*NOx*
percentage reduction between 'before' and 'after'	13.0	43.6	36.1	10.5
percentage reduction between 'after' and 'new'	35.5	22.7	23.9	32.4

Table 3.2 Comparisons between before, after and new scenarios

It was found that the major factors influencing emissions were the total network flow and link lengths. Over-saturated junctions in the network had relatively high emissions of CO and HC. The study concluded that emissions are highly correlated with flow levels and traffic restraint is the only effective measure to reduce pollution significantly.

Prediction of Future Traffic Emissions

The Earth Resources Research study (Holman et al, undated) using a computer model commissioned by the World Wide Fund for Nature has predicted the effect of traffic growth on pollutant emissions up to the year 2020. The study investigated the effect of introducing three-way catalytic converters on new cars from 1992, on emissions of NOx, HC and CO. For heavy goods vehicles the model assumed that there would be a change in emissions reflected by the introduction of turbocharged and turbocharged with after-cooled engines. Predictions were also made for carbon dioxide using the assumption that new cars in the future will have the same fuel efficiency as current new cars.

In general, the results showed that pollutant emissions would fall until about 2005 when a minimum would be reached and after this date emissions would rise again.

Whereas, carbon dioxide emissions were predicted to increase every year. These results also agree with a statement from, the former, Warren Spring Laboratory (LTT, 1990). The results also showed that heavy goods vehicles would remain a significant contributor to emissions of CO_2 and perhaps more importantly, become the dominant vehicle emission source of nitrogen oxides. Emissions of NOx were predicted to fall to a minimum of 70 percent of current levels.

By the year 2020, CO emissions were projected to be 50 to 63 percent of current levels, and hydrocarbons being 56 to 74 percent of current levels. Perhaps alarmingly, the high traffic growth forecast resulted in more than a 100 percent increase of CO_2 emissions between the years 1988 and 2020. Also, although emissions for NOx, CO and HC were predicted to be lower in 2020 than in 1988, emissions had started to increase again after about 2005, indicating potential problems for the long term.

Hence, although three-way catalytic converters have a major part to play in reducing pollution levels in the short term, if traffic growth continues to increase as predicted (DTp, 1989), these benefits will be overtaken by the volume of traffic.

Their research investigated the effects of speed limits, removal of company car subsidies, improved traffic management, modal split and technical innovation in vehicle efficiencies on emissions. Enforced speed limits at 70, 60 and 50 mph resulted in predicted savings of 2.4, 4.4 and 5.8 percent for CO_2 emissions respectively. Removal of subsidies to company car users were predicted to reduce annual emissions of CO_2 in the UK by up to 8.5 percent. Better traffic management and improved traffic flow in urban areas could lead to a 5 percent saving in fuel consumption in urban areas, and an overall reduction of about 2.5 percent in carbon dioxide emissions in the UK.

In a scenario where the number of passengers using buses and trains doubled by the year 2005, a reduction of nearly 15 percent of CO_2 emissions, taking into account those from buses and trains, was predicted. Optimistic assumptions for the rate of technical innovation and market penetration of new improved efficient vehicle technologies were thought to bring up to a 25 percent reduction in CO_2 emissions.

Overall System Studies

Studies need to address the overall concept of transportation and vehicle emissions in order to seek ways of reducing both vehicle usage and their associated emissions. Though an important area, the literature appears to indicate that there have been fewer comprehensive European studies of this type.

The Royal Commission on Environmental Pollution has begun a study on transport and the environment which will produce its final report in 1994. They will investigate the contribution of transport to greenhouse gas emissions, taking into account the relationship between transport, land use and planning policies.

A study in Athens (NTUA, 1988) investigated the development of a city center bus system. It considered a wide range of issues in order to determine the overall impact on the environment and, in particular, addressed emission measurements and standards. The study built on emission characteristics established earlier in Athens (Pattas and Samaras, 1987). The study indicated that a reduction in car journeys, in favour of the bus, would approximately result in a proportional reduction in emissions of CO and HC. However, as diesel buses have relatively high NOx emission rates, in some cases transit improvements that reduce CO and HC emissions may cause NOx to increase. It was also shown that the relationship between emissions and traffic quality, or speed, was a complex one.

3.5 THE DRIVE PROGRAMME

In 1988 the European Community approved a three year R&D programme for a Dedicated Road Infrastructure for Vehicle safety in Europe (DRIVE). The objectives of the programme were defined as the improvement of road safety, transport efficiency and environmental quality (CEC, 1990, 1991 and 1991a). Innovations and cost reductions in information technology, telecommunications and broadcasting were seen to offer new effective means of achieving these objectives. If brought together to provide integrated advanced communications, control and information systems they would enable new, more flexible and responsive forms of traffic management and safety systems to be created for the benefit of all road users. This concept is know as Advanced Transport Telematics (ATT).

The programme contained 71 projects. Of these, 15 projects were assigned to the general approach and modelling group of which two projects would model the environmental effects of road traffic air pollution. The two projects were PREDICT (Pollution reduction by information and control techniques) and MODEM (Modelling of emission and consumption in urban areas). These projects made major contributions to the programme's environmental objective.

MODEM

As this chapter has shown, many research activities have concentrated their efforts on exhaust emissions, mainly cruise emissions, partly idling emissions and less often emissions during acceleration and deceleration. Many have attempted to incorporate the contributions from all driving modes by using a standardised urban driving cycle. The MODEM project has extended this work, within a pan-European context, and recorded actual urban driving cycles, determined a realistic driving cycle model based on the collected on-road data, and tested actual emissions both in the laboratory and on the road (LTT, 1989; CEC, 1991; Andre, Hickman & Hassel, 1992).

Twenty vehicles selected from each of the countries (England, France and Germany) were fitted with in-vehicle monitoring equipment which monitored the following parameters every second: vehicle speed, engine rotation speed, throttle opening, fuel consumption, oil and water temperatures, the use of manual choke and wipers and external ambient temperature. Monitoring of these parameters provided an extensive database on vehicle use and driving cycles and from this the project team were able to analyze real driving modes and urban driving cycles.

This led to the production of test cycles for the measurement and modelling of exhaust emissions in urban areas. In order, to determine typical emission characteristics the project had to address the variations in vehicle emissions across different types of vehicles of varying ages, with and without catalytic converters. Although the testing of 150 vehicles would not allow a statistically significant representation of all vehicle types, the main types were believed to be sufficiently well represented.

The results of the project have provided additional information on European vehicle emissions and led to an increased understanding of the relationship between urban driving cycles and emissions. The project provided information on actual speed profiles, vehicle usage in urban areas and was a step towards understanding the effects of traffic control systems on the environment.

PREDICT and QUARTET

PREDICT was the only DRIVE project to specifically design and evaluate environmentally sensitive traffic control strategies based on ATT. As a member of the project team, the author was responsible for a major contribution to the PREDICT project, particularly in the areas of review, strategy selection and design, modelling and evaluation. Control strategies were developed for reducing environmental pollution in urban areas. A comprehensive environmental modelling approach was developed and used to evaluate the control strategies.

A follow-up programme, DRIVE II, is demonstrating and evaluating the Advanced Transport Telematics (ATT) applications required to meet the programme's objectives (CEC, 1993). A work-module of the QUARTET project directly addresses the DRIVE programme's environmental objective. This module is demonstrating and evaluating environmentally sensitive traffic control strategies.

QUARTET consists of field trials in Birmingham, Stuttgart, Torino and Athens. In Athens the field trial demonstrates an ATT system architecture for the implementation of environmentally sensitive strategies designed to improve urban air quality (QUARTET Consortium, 1992b and 1993a). These field trials build on the early work of the author and that of PREDICT. The author continues to play a significant role within the QUARTET project, in system design, modelling and evaluation. He is also responsible for compiling the final "Overall Assessment" report.

3.6 SUMMARY

Air pollution studies are required to understand the mechanisms responsible for the generation and dispersion of traffic emissions, and to evaluate potential solutions for improving air quality and achieving air quality standards.

Air quality standards aim to establish safe levels. These should be enforced by local or national organisations. The regulatory framework in the UK has been described in this chapter and it shows the role of standards and organisations at various levels. Standards are not always achieved, and in urban areas, traffic can be a significant contributor to poor air quality levels. In particular, CO, NOx and particulate levels are frequently associated with road traffic. It is also worth noting that heavy duty diesel vehicles make a significant contribution to NOx and particulate levels.

Many studies involve monitoring emissions over a standard driving cycle, usually ECE Regulation 15. These have analysed emissions as a function of speed, driving mode, and many other factors. Emissions of CO and NOx often behave differently; an increase in one may correspond to a decrease in the other. A wide range in vehicle emissions have been observed, with a relatively small number of vehicles accounting for a substantial proportion of total traffic emissions. The results of these studies indicate that if an emission model aims to acurately represent reality it should be able to represent these factors and have a comprehensive set of corresponding emissions input data. Some studies have also indicated that the standard driving cycle may not always be adequate for representing real on-road emissions.

Overall, the literature shows a large number of studies have investigated vehicle emissions, but fewer studies have investigated strategies aimed at reducing urban air pollution, particularly the implementation aspects of such strategies. This chapter has, however, identified studies which have considered several aspects of the air pollution problem in an attempt to improve air quality. This state-of-art review provided a sound basis on which to author was able to build, identifying new and important areas of research which could be undertaken without the need for duplication of effort.

Chapter 4

REDUCTION OF EMISSIONS

4.1 INTRODUCTION

Earlier chapters have shown the effects of air pollution on health and the environment, and as a result of these effects air quality guidelines and standards have been specified. However, in some urban areas these standards are not achieved. Given the recent advances in Advanced Transport Telematics (ATT), there may be an opportunity to develop new strategies for urban traffic management and control. These strategies could take into account both air quality and performance of the transport system. The author has evaluated the potential of this approach for reducing urban air pollution from road traffic. Part of this approach is based on new vehicle technologies which result in lower vehicle emissions.

This chapter outlines the technological options available. Other strategies, that are not necessarily based on ATT, with the aim of improving air quality are also described.

4.2 FUEL AND EMISSION OPTIMISATION TECHNOLOGIES

This section shows that vehicle modifications, and alternative fuels, have the potential to significantly reduce vehicle emissions. There are many possibilities in terms of vehicle and fuel modifications (Watkins, 1991). These modifications and enhancements include:

- engine modifications to improve efficiency (Barrie, 1989a, 1989b);
- alternative sources of fuel or energy (Mech. Eng., 1989; Science, 1989);

- emission reducing devices on the exhaust system (Watkins, 1991);
- improved transmission systems and reduced friction (Monaghan, 1988; Engineers Digest, 1989);
- lower vehicle weights (Ashley, 1992); and
- aerodynamically improved vehicles (Ashley, 1992).

Potentially, vehicle modifications have a significant role to play in Fuel and Emission Optimisation Strategies (FEOS) which aim to reduce fuel consumption and exhaust emissions. As shown in Chapter 2, emissions of carbon dioxide are the result of combustion of fossil and organic fuels. Their emissions are approximately proportional to the quantity of fuel consumed. Hence, improvements in fuel economy can reduce carbon dioxide emissions. Vehicle modifications also have the potential to reduce the by-products arising from incomplete combustion, namely carbon monoxide, hydrocarbons and particulates. Modifications can also be made to reduce emissions of nitrogen oxides.

Engine Modifications

Engine modifications may decrease fuel consumption, although some modifications increase consumption (CEC, 1983). For a given modification, some pollutant emissions may be decreased while others are increased (Watkins, 1991). These modifications are primarily concerned with ways in which the combustion process can be made more efficient. Improved combustion efficiency usually leads to a reduction in the emissions of CO, HC and particulates (Siuru, 1992). In addition, if efficiency is improved, fuel economy improves along with a reduction in emissions of carbon dioxide. When an engine's efficiency is increased this may increase the engine temperature, and as a result NOx emissions. Consequently, additional modifications are specifically designed to reduce emissions of NOx (Watkins, 1991).

Lean Burn Engines

Lean burn engines have a higher ratio of air to fuel than the rich air-fuel mixture (15:1) found in conventional engines. This gives a plentiful supply of oxygen resulting in higher combustion efficiency and lower emissions of carbon monoxide, compared with a conventional engine. Emissions of NOx are also reduced. Because of better combustion, these engines also consume less fuel and emit less carbon dioxide.

Conventional engines have difficulty running on a mixture of air and fuel in a ratio of more than 15:1; any ratio higher than this can be regarded as lean. In conventional engine designs, a lean mixture burns slowly and the engine can stall. This can be prevented by modifying the shape of the intake manifold, the pistons and the cylinder heads. The manifold has fewer bends to ease the flow of air and fuel. It is designed to generate turbulence in the cylinders to ensure thorough mixing of the air-fuel mixture and so speed up combustion. The cylinder heads are hemispherical rather than square-cylindrical shape with a concave cup in the piston. These modifications are meant to minimise the areas where the combustion flame is quenched.

However, lean burn engines emit five times as much NOx during fast driving as they do under the urban cycle (MacKenzie and Watts, 1989). MacKenzie and Watts also point out that if a catalytic converter was added to reduce these emissions, difficulties may be encountered. Three-way catalytic converters are usually designed to work best with emissions from a conventional engine which has a richer air-fuel mixture.

Fuel Injection

Fuel injection systems allow engine characteristics, to be controlled much more precisely than in engines which use a carburetor. The corresponding benefits, including reduced emissions, have led to an increasing number of fuel injection systems in Europe, Japan and the US (Glocker, 1985; Bradshaw, 1988).

A carburetor is responsible for producing the air-fuel mixture. This process relies on a flow of air over a fuel nozzle picking up fuel. This may be influenced by ambient temperature, air pressure and humidity. The result is that the air-fuel ratio is not accurately controlled and an optimum mixture cannot be guaranteed.

In contrast, the fuel injection system consists of a fuel injection valve for the cylinders of the engine. These valves may inject indirectly, into the intake manifold just before the cylinder, or directly into the cylinder (Bradshaw, 1988). The fuel injection system delivers an exact measure of fuel on each squirt, resulting in an accurately controlled air-fuel ratio and a finer fuel vapour which mixes more uniformly with the air. This can result in improved combustion and lower emissions (Kosowski, 1985; Bradshaw, 1988; Barrie, 1989a). A precise air fuel ratio is also important for the efficient operation of three-way catalytic converters (Hodgson, 1987).

Research has been undertaken to improve fuel injection systems further (Grenier et al, 1987). Different methods of fuel injection give different benefits (Hoonhorst, 1986). Diesel engines burn about 30 percent less fossil fuel than petrol engines, but by using direct injection systems, instead indirect ones, fuel consumption can be improved by 10 to 15 percent (Barrie, 1989a). Each injection valve only squirts fuel when its corresponding cylinder requires it, on the cylinders intake stroke. Further benefits are obtained when used with an electronic control unit or an engine management system (Hamburg, 1982; Marshall, 1987). It has also been shown that the use of an injector with a supersonic atomizer promotes better combustion by reducing the fuel adhesion (Matthes and McGill, 1976; Barrie, 1989a).

Conventional diesel engines emit some unburnt fuel, including soot, because fuel touches the walls of the cylinder, which quenches combustion. In a newer system, less diesel reaches the cylinder walls because the fuel is injected more slowly. The developers claim pollutants are reduced by a third compared with conventional diesel engines (Barrie, 1989a).

Turbochargers

Turbochargers and charge coolers are methods of increasing the power output of an engine (Watkins, 1991). A turbocharger uses exhaust gases to drive a turbine which forces more air into the engine. The turbocharger operates at high speeds and has two advantages. The increased air pressure ensures that air and fuel mix more thoroughly and are delivered more evenly. This increases the performance of an engine giving up to a third more power, from a small engine. It also boosts the flow and pressure of the exhaust gases, which helps to oxidise unburnt and partially burnt fuel in the exhaust pipe. Turbochargers can reduce emissions of CO and HC from engines by 10 percent. However, they raise the temperature of a diesel engine which increases the emissions of NOx. This can be overcome by cooling the air that is blown into the cylinder, a system known as turbo-intercooling. Charge coolers result in lower peak temperatures and reduce emissions of NOx.

However, turbochargers are partly to blame for the smoke when buses and lorries accelerate from rest. This is because the turbo takes time to build up speed and until it does the engine runs on the wrong air-fuel mixture (Barrie, 1989a). Barrie indicates that the development of variable geometry turbochargers will reduce this problem.

Engine Management Systems

Engine management systems are likely to become much more widely used in the near future, especially with the introduction of catalytic converters (Watkins, 1991), and stricter emission legislation. These systems can be used on both diesel and petrol engines. They are essentially small computers (Scrimshaw, 1985) responsible for monitoring the engine's performance and setting engine parameters to give optimum performance in terms of fuel consumption and exhaust emissions.

Sensors can be placed in the combustion chamber to precisely monitor the engine's performance. The sensors will allow the engine management system to run the engine at its most efficient rate, cutting both fuel consumption and emissions (Barrie, 1989a). Similarly, a sensor in the exhaust allows the engine management system to reduce emissions caused by a poorly maintained engine. An adaptive learning system discovers, by itself, what the optimum engine parameters are and adjusts these as the engine becomes older.

The system can control the air-fuel ratio, which is important in achieving complete combustion and optimum operation of a catalytic converter. It is also possible to accurately control the ignition timing for all engine modes (accelerating, cruising, etc).

Ford have also used engine management to control the intake valves in their new engine. It has also been used along with other enhanced features of the Ford engine. Hence, such a system can optimise the engine over all operating modes. Lucas Automotive claim to be at an advanced stage and so are several other companies, particularly Bosch, who are responsible for many contributions to this sort of technology.

One future possibility is a system which extends management of the engine to include control of an advanced low-loss automatic transmission system. The potential for further improvements in fuel consumption, and hence emissions, is said to be considerable (Engineers Digest, May 1989).

Integrated Approach

The integration of the above technologies into an engine design can be expected to make significant contributions over the next five to ten years. Such engine designs are now in prototype form or nearing production.

For example, Ford's new engine, I4, is said to have a fuel economy 10 percent better than its two litre predecessor (Barrie, 1989b). Ford has developed 'jet ports' to allow the air-fuel mixture into the engine without too much turbulence. This is to achieve a thorough combustion. Variable valve controls, run by computer, can close one of the intake valves in each cylinder. This allows one intake port to be designed for torque and the other for efficiency, allowing control of the amount of fuel and its behaviour more precisely.

The engine can run on leaded or unleaded fuel without adjustment, and is designed to use a 3-way catalytic converter. It will run smoothly on mixtures as lean as 19:1 air to fuel. The inlet manifolds have been designed to improve circulation in the combustion chamber. The chamber has a scroll shaped wall which forces the mixture to whirl in the chamber at high speed, helping it to burn thoroughly. The position of the sparking plug is such that a more efficient burn is obtained. Low friction pistons and bearings have cut mechanical losses in the engine by 40 percent. The engine can be equipped with a microprocessor-driven fuel injection system. This has an adaptive learning programme and a memory, so that control matches the needs of each engine.

This is by no means the only example of an integrated approach. Equally effective engines are being developed by many other vehicle manufacturers and such developments are also being applied to diesel engines (Siuru, 1992).

Alternative Engine Types

There are alternatives to the conventional reciprocating piston engine. The Wankel rotary engine, for example, is in limited use today. They can rotate at high speeds and run quietly. However, emissions of CO and HC, from current designs, are higher than conventional engines, while NOx is similar (Watkins, 1991).

Gas turbines are simpler and lighter than piston engines and may, therefore, have advantages over conventional engines. Combustion is continuous and can be controlled to give low rates of emission (Watkins, 1991).

A ceramic gas turbine engine has been demonstrated which has a fuel economy 35 percent better than conventional engines, and gaseous and particulate emissions below current and proposed US federal standards (Harmon, 1992). The turbine is also able to run on alternative fuels. Harmon says that it has competitive initial and life cycle costs, relative to a conventional engine. However, further developments are needed in the areas of cold start, acceleration, deceleration, and the mass production of ceramic turbines for cars.

Alternative Fuels

Alternative fuels have been, and still are being, used around the world. Some of these alternative fuels can be used in conventional engines with little or no modification.

These alternative fuels usually result in lower emissions of some pollutants. Potential alternative fuels include: alcohols; natural gas; and hydrogen (Siuru, 1989; Valenti, 1991; Harmon, 1992).

Alcohols

The two alcohols usually used as a fuel are methanol and ethanol. Generally, methanol emits less pollutants than petrol (Valenti, 1991). Any incomplete combustion results in the emission of the alcohol, and other organic compounds. However, methanol is toxic and associated formaldehyde emissions also need to be regulated (WHO, 1987). Aldehyde emissions from alcohol fuels are approximately three times those from petrol (Watkins, 1991). The alcohol can be used directly as a fuel or as part of a mixture containing conventional fuel (Harmon, 1992; Gabele and Knapp, 1993).

In an attempt to meet ozone limits in Los Angeles, California, one of their strategies is to introduce fleets of methanol and ethanol fuelled automobiles (Science, 1989).

Natural Gas

The burning quality of natural gas is such that it would operate satisfactorily in a high-compression diesel engine. Emissions of carbon dioxide are lower than conventional fuels. As well as occurring in natural deposits, it is also possible to grow plants which will subsequently yield bio-gas.

The Ricardo Group has been awarded a contract by a consortium of five Scandinavian bus companies to convert a Saab-Scania 6-cylinder diesel bus engine to run on natural gas (Barrie, 1989c). The gas is 94 percent methane, to which a mixture of gaseous hydrocarbons are added. The resulting engine is expected to give very low levels of emission. For example, it should meet standards of 2 g/kWh for NOx and 0.1 g/kWh for particulates. This will be achieved using: a 3 way catalytic converter; electronically controlled carburetor to mix the gas and air; software to run carburetor and ignition system; a Nebula combustion chamber design; and exhaust gas recirculation.

A new tank to hold sufficient quantities of natural gas has been developed (Automotive Engineer April/May 1989). A research project which has run for nearly five years at the Royal Military College of Canada is showing promising signs for an eventual breakthrough in vehicle propulsion by natural gas. Gas tanks also exist that are able to survive in a vehicle collision (Valenti, 1991).

Hydrogen Power

Hydrogen burns with oxygen to produce water. Consequently, from an air pollution point of view, it has very desirable combustion characteristics. Siuru (1989) described a hydrogen powered vehicle with a 25 gallon tank and reciprocating engine which was able to travel 300 km on a tank of fuel. It had low emissions of nitric oxide and nitrous oxide.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) offers an effective method for reducing emissions of nitrogen oxides from internal combustion engines. As shown in Chapter 2, NOx is produced from a high temperature reaction between nitrogen and oxygen. Therefore, changing the fuel used in a combustion engine may not reduce NOx emissions.

Small quantities of exhaust gas are introduced into the cylinder to dilute the incoming mixture of fuel and air. This reduces the mixtures oxygen content, combustion power and, hence, the temperature of combustion (Watkins, 1991). As EGR lowers the temperature of combustion, NOx is also reduced. EGR is widely used to meet emission legislation (Siuru, 1992). Although, EGR can increase fuel consumption (CEC, 1983) and increase diesel emissions of HC and particulates (Hollis, 1984), EGR is widely used in diesel vehicles to reduce NOx (Siuru, 1992).

Catalytic Converters

A catalytic converter reduces the pollutants in a vehicle's exhaust. Today there are two types of catalytic converter: oxidation catalyst; and three way catalyst (Watkins, 1991). Oxidation catalysts oxidise carbon monoxide and hydrocarbons to carbon dioxide and water. The three-way catalyst (TWC), also oxidises carbon monoxide and hydrocarbons, but in addition, it reduces nitrogen oxides, primarily to nitrogen and oxygen.

A typical catalytic converter is made from a ceramic honeycomb coated with a paint to increase the microscopic surface area. On the surface is one and a half to two grams of platinum and rhodium - the catalyst. A catalyst encourages, or speeds up, a reaction but does not react itself and hence remains unchanged. If, however, the catalyst's surface becomes covered by another substance, such as lead, its effectiveness deteriorates. Consequently, to use a catalytic converter unleaded petrol must be used, as lead destroys the catalytic properties. The TWC works most efficiently within a fixed air-fuel ratio (Hodgson, 1987), maintained by an engine management system equipped with an oxygen lambda sensor in the exhaust.

A catalytic converter can remove up to 90 percent of the three pollutants mentioned. The exact figure depends on many factors such as catalyst temperature, engine cylinders misfiring, and the age of the catalytic converter. The use of leaded fuel will damage the catalyst.

Typically, there are two ways of operating a catalytic converter: unregulated and regulated. An unregulated catalyst is one in which the content of gas entering the system is uncontrolled. The effect of such a catalyst depends on whether the engine is run lean or rich. The former gives over 60 percent reduction in HCs and CO, and 30 percent less NOx. While the rich setting gives up to 40 percent less HCs and CO but up to 60 percent less NOx.

The second option is to use a controlled catalyst, in which a device (known as the lambda-probe, invented by Bosch in 1973) measures the remaining oxygen content of the exhaust gas flow. The measurement can be fed back to the fuel injection system to ensure the oxygen content is maintained at the optimum level, allowing the catalyst to work at peak efficiency. It represents a relatively complicated setup, typically requiring an engine management system, and is more expensive than an uncontrolled version. However, levels of all three pollutants can be cut by over 90 percent.

It has been said that catalytic converters result in about a 10 percent loss in fuel economy, although this is questionable. This is because the catalyst may require a richer mixture and hence the engine consumes more fuel. Other sources show that catalytic converters have a slight effect or even no effect on fuel consumption. A report (CEC, 1983) shows that a controlled TWC may increase fuel consumption by up to 16 percent, but in other cases may reduce it by up to 5 percent.

American engineers doubt that 3-way catalytic converters will be durable enough in Europe. Here vehicles travel faster than in the US resulting in hotter exhaust gases. The hotter the exhaust gas, the sooner a TWC deteriorates. Climatic differences between Europe and the US are also significant. The colder European climate means that a vehicle's catalyst can take longer to warm up to its 'light-up' temperature at which it operates efficiently. This results in more emissions over the warm up period.

Catalytic converters are known to produce unwanted by-products. The small sulphur content in fuel, mainly diesel, results in sulphur dioxide emissions which are then converted, by the catalyst, to sulphuric acid. This is a corrosive acid and one present in acid rain. A reduction in the fuel's sulphur contents will reduce these emissions. The US plans to reduce the sulphur content of diesel fuel to 0.05 percent, compared with 0.3 percent in the UK. The other by-product nitrous oxide, is known to contribute to the greenhouse effect. However, although the emissions have been shown to be higher than a vehicle without a catalyst (Gould and Gribbin, 1989), no conclusions can yet be drawn because without a catalyst the higher NOx emissions can also react, in the environment, to form nitrous oxide.

Another potential disadvantage concerns the catalyst itself. The actual catalytic material is known to be a danger to health and concern exists over possible emissions of platinum from a large number of vehicle's equipped with catalytic converters (LTT, 1992). There is also concern over the highly toxic hydrogen sulphide gas, produced from catalytic converters. Currently though, it appears that dangerous levels of these substances do not occur and even in the US, where catalytic converters have been widely used for years, there seems to be no serious concern.

Electric Vehicles

Electric vehicles provide an effective solution to the reduction of *urban* air pollution. The electric motor has no emissions, nor does it make much noise. However, electric vehicles typically have limited power and range. The range is limited by the capacity of the vehicle's batteries, and so they need to hold as much charge as possible, whilst being relatively small and light weight.

Although they reduce emissions in urban areas, electric vehicles may increase emissions elsewhere. For example, if the batteries were to be charged up from the electricity mains supply, fossil fuel power stations may emit more pollution, to cater for an increased demand. The electricity supply could, however, be generated by other means which would not contribute to air pollution, such as nuclear and renewable sources of power.

A study of the overall impact from the widespread use of electric vehicles in California predicted that large reductions in CO and HC were possible (Wang, DeLuchi and Sperling, 1990). Emissions of NOx decreased moderately, while sulphur oxides and particulates increased or slightly decreased.

Electric vehicles are possibly a viable alternative for urban travel. They have sufficient speed for most urban travel and need not consume energy when stationary in a queue. Considerable work has been carried out in this area and vehicles suitable for urban travel have been produced (Porter, 1980; Siuru, 1989 and 1991; Harmon, 1992).

Denmark's battery powered minicar, the Mini-el, is produced at the rate of about 30 each month (Mech. Eng, Feb. 1989). These are primarily for use in neighbourhoods where petrol-powered vehicles have been banned. Three 12 volt lead acid batteries supply power for distances from 25 to 45 miles at cruising speeds of 25 mph. The Mini-els are made from a strong but lightweight plastic construction.

Electric vehicles do not necessarily have to use batteries charged from the mains power supply as their source of power. For example, fuel cells generate electricity by a chemical reaction between a hydrogen rich fuel and oxygen. Romano (1989) points out that the theoretical efficiency of a fuel cell is 80 to 85 percent, whereas the internal combustion engine's is only 40 to 50 percent. Methanol would be a suitable fuel for the fuel cell. However, Romano indicates that the size and weight of the fuel cell needs to be reduced. The operation of fuel cells have been demonstrated and developments are taking place (Hirshenhofer, 1989).

Volkswagen's solution is to use an electric hybrid vehicle (Barrie, 1989a). A combustion system is used only when its extra power and torque are needed, relying at lower speeds on an electric motor. The Volkswagen hybrid Golf will use an electric motor up to 50 kph, with a diesel engine for higher speeds. They estimate that in urban traffic the Golf will do 100 kilometres on 2.5 litres of fuel.

Friction

Losses caused by friction are significant and it is worth taking measures to reduce them. One possibility is the introduction of low loss transmission systems, but there are also losses in the engine (Monaghan, 1988). Reducing the friction of a petrol engine by 10 percent would yield a fuel economy improvement of about 5 percent and a similar proportional reduction of the diesel engine's friction would give as much as 7 percent. Truck engines burn about 70 percent of their fuel at full engine load and so reduced friction would give a smaller saving in fuel consumption.

Monaghan states that reduced friction and improved oil formulations will allow engines to be produced which have better efficiency, longer service intervals and better overall durability.

The analytical and experimental tools to achieve worthwhile reductions in friction are essentially available today. Monaghan claims, to achieve those worth-while gains, the study of engine friction needs to be changed from a 'passive' to an 'active' role.

Vehicle Weight

Low weight vehicles provide another way of contributing to FEOS. In urban travel a significant proportion of the time is spent accelerating (Nishimura and Hino, undated). Significant amounts of energy, and hence fuel, are required to accelerate the vehicle up to speed. By reducing the vehicle weight a saving in energy and fuel consumption can be expected. Vehicle body weights could be reduced by the introduction of light alloys, plastics and carbon fibre composites. A car with a weight half that of a conventional car has been demonstrated by General Motors (Ashley, 1992). However, the carbon composite body cost US $13,000. Hence, a significant reduction in material costs would be needed before these materials became viable.

Aerodynamics

Aerodynamic vehicle designs can help save energy, and hence fuel (Vicker, 1983). These savings increase rapidly with speed although at low urban speeds the effects are less significant (Gotz, 1983; Hucho, 1987).

4.3 FUEL AND EMISSION OPTIMISATION STRATEGIES

Fuel and Emission Optimisation Strategies (FEOS) aim to reduce fuel consumption and emissions. They may incorporate many of the technological options described above, in addition to planning philosophies and policy choices. The author envisages that FEOS may make use of many technologies, such as vehicle design, ATT, traffic management, and the planning of roads.

Wide scale traffic restrictions and bans, are generally expected to provide environmentally effective results, because the emission source is reduced or removed. However, such decisions are viewed by many as politically and socially unacceptable. Hence, improved air quality is likely to arise, at least in the short to medium term, from strategies which offer an effective compromise between society's environmental and travel demands. Several options have been considered and these offer varying degrees of air quality protection and restrictions on the public's freedom to travel.

There is a philosophy that a substantial reduction in the total volume of traffic will significantly reduce emissions. This has been demonstrated in Gothenburg, Sweden (Elmberg, 1977). The philosophy applies both nationally and at the local urban level. The types of strategies required to implement such philosophies are, however, likely to be different at national an urban levels. For example, at the national level traffic restrictions cannot be directly applied in a physical sense, with ease. Whereas at the urban level, access to environmentally sensitive areas can be physically restricted, enforcing a total ban or a selective ban based on vehicle types.

At the national level, a reduction in traffic volume and hence emissions may be achieved by the introduction of a 'carbon tax'. This forms part of a 'make the polluter pay' philosophy and involves adding an additional tax which takes into account the environmental damage caused by the use of fuel and its corresponding emissions. By adding this tax to the cost of fuel, it is anticipated that the higher prices will discourage people from making unnecessary journeys. Carbon dioxide emissions from transport in the UK are projected to increase by up to 70 percent in 2020, relative to 1990 levels; total UK emissions are projected to increase by 38 percent (DTp, 1993). The UK has a commitment of returning overall emissions of carbon dioxide in 2020 to 1990 levels (DTp, 1993). Therefore, the application of such a strategy, or a suitable alternative, appears likely if the commitment is to be achieved.

Some strategies to reduce vehicle emissions can be applied at national, or regional, level and within conurbations. For example, traffic volumes can, potentially, be reduced by encouraging several people to make their journey in the same shared car. These High Occupancy Vehicles (HOV) can be given preferential treatment such as access to specific areas and roads, or lanes, on which low occupancy vehicles are banned. This, combined with the will to improve air quality, may encourage its use and reduce the total traffic volume. Taking the concept further, traffic volumes have the potential to be reduced by encouraging people to leave their cars at home and make their journeys by public transport. However, before people are persuaded to switch their mode of transport from private to public, a clean, comfortable, safe, reliable and efficient image for public transport may be necessary.

The use of public transport is seen by many as an important tool in the combat of air pollution. Public transport often operates most effectively within urban areas, and inter-urban travel, but for many commuters in rural or semi-rural habitats private transport still represents the most effective way of reaching an urban dwelling. Even in this case, public transport has something to offer in the form of park-and-ride schemes. This involves driving your car to the periphery of an urban, or inner urban, area and leaving it in a car park, from which you are collected by a bus and driven into the central area. Such schemes can be encouraged by relatively low park-and-ride costs, efficient public transport and effective disincentives such as high car parking costs within the central urban area. While this scheme may not control travel outside an urban area, it can assist in reducing the traffic volume inside an urban area.

Ideally, decision makers would seek a system which offers an effective compromise between society's demands for freedom of travel and protection of the environment. Ideally, such a system would need to be sufficiently flexible to support those demands during changing moods of public opinion and changing levels of air quality. Advanced Transport Telematics (ATT) can provide a flexible infrastructure which may have the potential to reduce vehicle emissions by offering a series of scalable strategies. This offers the potential to introduce a range of strategies from mildly restrictive measures, up to stringent control measures offering a very high degree of environmental protection. Further, such strategies may be automatically implemented only when required, avoiding otherwise poor levels of air quality and applying restrictions only when necessary. ATT can be applied to many areas of traffic management and control; in terms of air quality some of its potential applications are:

- traffic restrictions and the encouragement of inter-modal travel and public transport, potentially reducing the total vehicle-miles travelled, and hence overall emission levels;

- emissions per vehicle-kilometre may be reduced by, for example, maintaining optimum vehicle speeds, reducing the number of speed changes and the time spent queuing;

- high concentrations of pollutants may be preventable, where they will harm people, property, or agriculture, through the implementation of traffic restrictions;
- peak concentrations could potentially be reduced by distributing traffic spatially and temporally;
- through traffic could be rerouted, reducing emission levels in an urban area; and
- emissions could be regulated by restricting access to environmentally sensitive areas, based on a vehicle's emission characteristics.

The author has been actively involved in some of these potential applications, and later chapters of this thesis describe their demonstration and evaluation.

4.4 SUMMARY

This chapter has shown that there are many options available for reducing air pollution. These options have a wide range of costs and are potentially useful for short to medium term solutions. At least some of these options may have to be taken in the near future, given existing pollution levels and traffic growth forecasts.

Although many of the options described in this chapter are concerned with vehicle modifications, the author acknowledges that there are options available which do not necessarily involve vehicle modification. For example, careful road and urban planning may have the potential to reduce air pollution. However, they do not fall directly within the scope of the author's work and so have not been described.

The reduction of fuel consumption and carbon dioxide emissions should also be borne in mind, especially in view of concerns about global warming and the commitment to reduce total emissions in the year 2000 to the 1990 level. Technological options may provide assistance in achieving this goal. However, the potential growth in road traffic needs to be seriously considered; high levels of traffic growth could potentially counteract any savings arising from vehicle modifications.

One of the main objectives of this chapter has been to illustrate that there are many options available to the decision maker and that no one option alone is likely to offer a completely satisfactory solution to the air pollution problem. In addition, the options available and the demands of society are evolving, and as such should be anticipated.

This was recognised by the author at an early stage in his research. Consequently, an approach was adopted that would offer a high degree of flexibility, and incorporate several state-of-the-art technologies and strategic options. It would also provide a framework capable of evolving with the technology and environmental demands of the future.

Chapter 5

MODELLING AND PREDICTION

5.1 INTRODUCTION

A model is a representation of reality. It is usually a simplified and generalised statement of what seem to be the most important characteristics of a real-world situation. The value of a model is that it can be used to improve our understanding of the ways in which a system behaves, in circumstances where it is not possible (for technical, economic, political or social reasons) to construct or experiment with a real-world situation.

Modelling provides an alternative to on-site monitoring, and is typically a more economical approach, assuming input data already exist and no comprehensive data collection exercise is required for model calibration. Given the flexible nature of models, many strategies can be compared in order to determine the most effective and beneficial approach. Such an approach has been used in this research.

This chapter provides a review of modelling and prediction techniques suitable for application to traffic related air pollution studies. In this chapter a brief outline of traffic modelling techniques are given, followed by a review of emission and dispersion prediction methods and models. Finally, this chapter summaries these techniques and assesses their suitability for the modelling of advanced environmentally sensitive control strategies.

5.2 TRAFFIC MODELLING

This section describes some common techniques used to model traffic. The output from traffic models are often used to provide direct, or indirect, input data for environmental modelling. Hence, in studies which are unable to obtain actual traffic data, these models provide an essential component in the pollution modelling process.

Traffic models have a role in planning the urban traffic network, understanding its behaviour and providing predictions for traffic appraisal schemes. The role of models in the planning process has been described by Lee (1973), and the Institution of Highways and Transportation (1987) and provides a comprehensive description of transportation planning tasks and the use of models. It has not been practical to go into such detail in this thesis.

An hierarchy of data collection, prediction and forecasting tasks are necessary for transportation planning. These tasks can be grouped into the following areas:

- urban growth, socio-economic aspects and the demand for travel;
- trip origins and destinations and the demand between them;
- choice of mode of travel;
- transport network capacity and traffic assignment;
- traffic flows and traffic performance (e.g. average speeds, stops, delays, etc.);
- signal coordination; and
- policy selection and feedback.

With the possible exception of the first (Wickstrom, 1991) and last areas, the transportation planner may use one or more models to assist in the prediction or forecasting of these effects. Urban growth and socio-economic aspects involve many factors and are difficult to understand and accurately represent in a model (Edner, 1991; McDowell, 1991). Hence, the demand for travel is also difficult to forecast (Pisarki, 1991; Wachs, 1991). The quality of the forecasts is therefore dependent on the skills of town planners and economists in predicting demographic trends, and national and local economic performance.

Trip Origins and Destinations

Trip origins and destinations can be established by conducting surveys and identifying zones perhaps split by residential, industrial and commercial areas. These surveys provide an indication of the number of trips made from one zone to another and vice versa (Lane, Powell and Smith, 1971). This process establishes the overall demand for travel and the origin and destination of trips (Stopher and Meyburg, 1976).

Travellers have the option of travelling by various modes of transport, such as car, bus, or train for example (TRB, 1993). Based on the modal choice trips are allocated to the various categories, or modes, of transport. This allows the volume of road traffic to be predicted.

Traffic Assignment

The route that traffic will take through a finite capacity network is determined by modelling the assignment of traffic flows to routes which offer the 'best' journey between origin and destination (O-D). The criteria used to define the 'best' journey is usually one, or a combination of, the following:

- minimum journey time;
- minimum journey distance; and
- minimum cost (based on such parameters as time, distance, etc).

Calculation of the best journey based on time, distance or cost is a relatively easy task and represents the methodology employed by most assignment models. In rare cases, the assignment model may also represent modal split, for the routing of different modes of transport (Southworth and Janson, 1980), or just public transport (Lane, Powell and Smith, 1971; Chaplean and DeCea, 1983).

Thomas (1991) describes a range of traffic assignment techniques. The assignment process may simply assign all the traffic between a given origin-destination pair to the same route, and repeat this process for all origin-destination pairs throughout the network. This technique is referred to as all-or-nothing assignment because all the trips, between an O-D pair, are assigned to one route, and none to the others.

An alternative is to assume that all trips between a given origin-destination pair do not use the same route and adopt a stochastic approach. The probability of a trip taking a particular route is assigned for all 'reasonable' routes between origin and destination. Routes are assigned a probability based on their attractiveness (e.g. short travel time). The 'best' route would be assigned the highest probability and other routes ranked according to their attractiveness. The trips between origin and destination are then assigned across all reasonable routes, based on the probabilities. This method of assignment has been widely used (Burrel, 1968; Dial, 1971; and Van Vliet and Dow, 1979).

However, this approach takes no account of changes in journey times as a result of traffic loaded onto the network and the finite link capacities. For example, if all journeys travelled along the same route then it is likely that there may be a faster alternate route unhindered by traffic delays. As the flow increases along a link its average speed falls according to a speed-flow relationship until a critical point is reached at which the flow cannot increase any further. Therefore, as the flow on a link increases the link becomes less attractive due to increased link travel times. The assignment model may take these effects into account and repeat the above assignment process for a preset number of iterations, or until convergence.

Other factors can also be incorporated into the process such as: different delays for turns; over-saturated conditions; interaction of queues; effects of traffic signal settings; delays due to conflicting flows and lane sharing; bus routes; and prohibition of HGVs. Models have been developed to take account of some of these factors: HINET (TPA, 1981); JAM (Wootton Jeffreys and Partners, 1980) and TRIPS (MVA, 1982). Congestion assignment models may use simulation techniques, rather than fixed equations to represent delays. Examples being: SATURN (Van Vliet, 1981), CONTRAM (DTp/TRRL, 1982) and TRAFFIQ (Transpotech Ltd, 1983).

An in-vehicle route guidance system being used in the QUARTET field trials allows the user to select between "short, economy and easy routing modes" (QUARTET Consortium, 1993a). Easy routing is defined by the number of junctions/turnings and preferred type of road. Therefore, it may eventually be necessary to represent these options in assignment models, if such route guidance systems achieve a significant market penetration.

Traffic Models and Signal Coordination

Traffic flows and traffic performance are represented by the traffic model to simulate how flows behave, interact at intersections and to calculate stops, delays and average speed. A traffic model is also likely to form part of a model designed to coordinate signal timings. Using these tools, the traffic engineer can alter signal timings to change, for example, the capacity at junctions. This alters the stops and delay at junctions, and has an associated impact on traffic emissions. The author's research has investigated this impact in detail. The methodology and results are described in later chapters.

Signal coordination improves the efficiency of the road traffic network by coordinating traffic signals that are in the same urban area. This results in significant benefits in terms of total stops and delays compared to uncoordinated traffic signals. Traditionally, a set of fixed-time traffic signal plans are calculated, for various periods throughout the day, that offer the best traffic performance index (minimising stops and delays).

The signal settings in each plan are fixed in that the green periods and offsets do not vary from cycle to cycle. Fixed-time systems control known patterns of traffic, rather than respond to instantaneous demand. Probably the most widely used and proven fixed-time model is TRANSYT, developed and revised by the former Transport and Road Research Laboratory (Robertson, 1969; Vincent, Mitchell and Robertson, 1980).

TRANSYT is a method of determining optimum fixed-time traffic signal settings that enable known flows to pass through a road network with the minimum of stops and delay. It uses a traffic model which allows for flow interaction between successive road intersections, and the dispersion of platoons between them. Traffic flow may be controlled by signals or another (priority) traffic stream which has right of way. Optimum signal settings are achieved by using a procedure that minimises any chosen balance between total delay and the number of stops. Both the signal offsets and the allocation of the green times can be optimised.

This model forms an essential part of the PREDICT model suite, its role has been described in PREDICT Deliverable Two (PREDICT Consortium, 1989a), and in this thesis in Chapters 6 (Model Suite) and 8 (Modelling Methodology).

TRANSYT is a good signal coordination model for producing optimised fixed-time plans, but, as an off-line model, it does have a number of weaknesses (Institution of Highways and Transportation, 1987). These are:

* traffic flows need to be collected throughout the road network, for representative periods of the day, week, etc., and should be kept up to date to achieve maximum benefit from signal coordination (Bell, 1986);

* significant short term traffic fluctuations within the period of a fixed-time plan will not be accounted for; and

* differences between input and actual link flow data on saturated links can give rise to large errors in the prediction of total delay for those links.

Policy Selection and Feedback

Policy selection and feedback represent the final steps in the transportation planning tasks described above. This may form part of the modelling software, and both these steps are important to the transportation management process.

Given the initial predictions from the model suite the 'decision maker' may decide that the existing scenario (as predicted) is not satisfactory. A policy, or strategy, will then be defined to modify the existing scenario in an attempt to make it more satisfactory. For example, it may be decided that link journey times are too long for particular links and that signal timings should be adjusted to resolve this problem. In this case the timings may be adjusted and the modelling process repeated.

The output of a model may be used to adjust the model's input parameters; this is known as feedback. Feedback can be used to give a model stability and provide a more accurate representation of the process being modelled. Alternatively, manual feedback may be introduced with adjustment to some of the model's parameters according to a preferred traffic control strategy or policy.

In addition to traffic criteria, such as journey time, the criteria influencing policy choice and strategy activation may be based on environmental considerations, such as high levels of noise or atmospheric pollution. In this case, the policy decision step is taken after the environmental modelling steps, such as the emission and dispersion modelling techniques described in the following sections of this chapter.

5.3 EMISSIONS MODELLING

Emission modelling techniques vary from relatively simple average speed models to more complex types representing emissions from each driving mode and the effects of different vehicle types and ages.

For mean emission rates based on laboratory simulation of different driving schedules there have been indications that CO and HC from petrol vehicles can be estimated by mathematical models (Watson, 1972; Watson, Milkinks & Bulach, 1976; Evans, 1979; Kent & Mudford, 1979: Potter & Savage, 1983). These account for variations of average traffic speed from area to area or from link to link. However, for NOx complex models must be used because of its sensitivity to vehicle acceleration rates.

Whatever type of model is used, the availability of comprehensive, accurate and up-to-date emissions input data is a fundamental requirement for accurate predictions from an emissions model. In the US, comprehensive guidelines for the preparation of mobile source emission inventories exist (EPA, 1989) and significant efforts have been made to compile such inventories. However, the task is not a trivial one and a number of technical and institutional problems were identified in a study based on existing practises for fifteen urban areas (Suhrbier, Lawton and Moriarty, 1991). Nevertheless, if accurate model predictions are deemed necessary this task must be pursued.

Emission Models

Models to predict air pollutant emissions generally represent speed and/or a driving cycle. Models developed in the US require additional information on factors such as age and condition of vehicles (including their emission control devices) in the fleet.

In the past, methods used in the United Kingdom and the Federal Republic of Germany have been based on a simple emission rate equation. Generally, in the UK, the emission rate was only based on speed (Hickman & Colwill, 1982; Costas Abacoumkin and Associates, 1988). In the Federal Ministry's method, traffic composition was also included (Federal Minister of Transport, 1982). The model also required information for traffic conditions, based on a classification of individual road links used in the Federal Republic of Germany.

MOBILE is widely used in the US, forming the emissions component of several pollution model suites (Schewe and Braverman, 1991; Halcrow Fox, 1993). It is a comprehensive computer model developed by the US EPA (1981) for the calculation of CO, HC and NOx emission rates from highway motor vehicles. It calculates emissions for eight individual vehicle types in three regions of the USA. The program uses the calculation procedures and emission factors presented in the document EPA 460/3-81-005 (EPA, 1981a) and will estimate emission factors for any calendar year between 1970 and 2020. Emissions per unit distance are calculated as a function of trip length and average speed, based on a series of simultaneous equations. A constant rate of emission is assumed over the length of the road. It also makes use of speed values which incorporate the delay at intersections, as opposed to specifically modelling emissions by driving mode.

MOBILE emission estimates depend on various ambient factors, vehicle usage and maintenance, and fleet composition factors. The required percentage of hot-starts is determined based on a document published by the FHWA (Ellis, Camps & Treadway, 1978) and the results of an earlier study (Midurki & Castaline, 1977). The emission rates for all areas except high altitude (greater than 4000 ft) and California are based on dynamometer test results, over-the-road emission sampling (heavy duty trucks only) and emission standards.

An earlier mathematical model, the Modal Analysis Model (MAM) by Kunselman et al (1974) can be used to calculate the amount of CO, HC and NOx emitted by individual vehicles, or groups of vehicles, which are driven over particular driving sequences. Vehicle emission data collected in 1971 from 1020 individual light duty vehicles is the basis of the model. The definition of 37 speed-time profiles (5 steady-state) are used to predict the emission response over a specified driving sequence. Though the model is now rather qualitative, as many years have passed since its data base was collected, no other model in the US exists to provide similar predictions. The model has been used for modelling carbon monoxide hot spots (Zamurs & Piracci, 1982), and consists of part of the EPA Intersection Midblock Model (IMM) (Benesh, 1978) where some care has been taken regarding the update of emission rates used by the model.

The Emission Modal Analysis Model models CO emission rates near isolated signalised junctions, or in conjunction with traffic simulation models (UTC-1 and NETSIM). It distinguishes between emission rates near intersections and those along a link. It is typically used to model on a network wide basis in conjunction with detailed traffic simulation models that follow every vehicle throughout the network and through each of their driving modes (cruise, acceleration, idling and acceleration). The model represents the spatial variation of emissions along the link and at the intersection. However, it only models emissions of carbon monoxide.

The MODEM Emissions Model uses speed-time profiles to express emissions in terms of averages per driving cycle. The calibration data is based on a recent pan-European study of car emissions (Joumard et al, 1992). This involved collecting driver behaviour measurements on 58 vehicles in 6 European towns. The processing of urban speed curves allowed the design of 14 driving cycles representative of urban characteristics and passenger car behaviour. The emissions database is based on laboratory measurements from 150 cars including conventional, catalyst equipped and diesel cars. This resulted in the derivation of emissions and fuel consumption as functions of instantaneous speed, and the product of speed and acceleration. An attempt to validate this model with an in-vehicle emissions sampling system was unsuccessful. It was concluded that the correlation between traffic parameters and emissions were not entirely satisfactory, and that further developments are needed.

Modelling studies which simulate traffic flow and emissions (and dispersion) have been carried out to assess the air quality impact of signalised intersections (Patterson, 1976; Claggett, Shrock & Noll, 1981; Griffin, 1980). Models in this area include the German Federal Ministry of Transport (FMT) which calculates CO and NOx emissions at junctions with or without traffic control and the US IMM (Benesh, 1978), MICRO (Griffin, 1980) and TEXIN (Messina, Bulin, Nelli & Moe, 1982) models. In the same area theoretical studies have been carried out to optimise signal progression using air quality criteria as a measure of effectiveness (Patterson, 1975; Ludwig, Simmon and Moon, 1973; Mahalel & Peled, 1984).

A relatively comprehensive emissions modelling approach has been adopted as part of the UROPOL pollution model suite (Matzoros, 1990). This models emissions from cruise, acceleration, deceleration, idling and creeping. The creeping mode represents the characteristics of vehicles queuing at a priority junction, whereby vehicles gradually move forward towards the junction.

A comprehensive emissions model is being developed in Italy (Negrenti, 1993). The TEE computer model represents vehicle emissions and energy consumption. It aims to be a decision support system for the impact analysis of traffic management strategies, traffic control systems, fleet development, and driver behaviour modifications. It also aims to predict absolute emission estimates for input into atmospheric dispersion models.

TEE has been designed so that it is able to make use of virtually all existing types of vehicle emission data. It is able to represent a mixed fleet containing various vehicular categories. It supports standard vehicular categories, such as those used in CORINAIR studies, and user defined categories. In addition to normal traffic flows, vehicles parking along the street or joining the traffic stream from parking are also represented. It can model on street parking and parking lots. The model also includes a set of correction factors to take into account engine temperature, gradient of the road, altitude above sea level, and other parameters.

There are several kinematic options for representing the driving patterns of each vehicle category. The three main kinematic models are average speed, real speed cycle and the four phase drive cycle. The output of the TEE model can be reported as grams per vehicle and kilometre, grams per vehicle along a particular stretch, and total emission rate in kilograms per hour. Totals and intermediate results can be requested for each vehicular flow or traffic 'mode'.

The model incorporates most of the desirable features of existing emission models around the world. It has been designed in a modular manner, provides menus for the creation of data-sets, and includes predefined data-sets. If the proposed final version of this model achieves all its objectives, it is likely to be an effective research and decision tool for air pollution impact studies.

Emission model performance

The analysis of poor air quality levels, as a result of traffic emissions, has been the subject of many studies in the United States. Not surprisingly therefore, there have been some detailed studies assessing the performance of emission models.

As noted earlier, the availability of comprehensive, accurate and up-to-date emissions input data is a fundamental requirement for accurate predictions from an emissions model. In a European perspective, the apparent absence of relevant literature seems to suggest that these issues are not being actively pursued in great detail. Although the author has identified some pan-European activity, in terms of collecting emission data over a driving cycle (e.g. MODEM and CORINAIR). The author did not find any evidence for the existence of recent UK or pan-European activities aiming to specifically validate emission model performance.

Chapter 3 and this chapter, have shown that there are problems associated with emission models based solely on input data from standard (fixed) driving cycles, such as ECE and the US Federal Test Procedure (FTP). History, has shown that the standard driving cycle has been revised a number of times to incorporate various aspects of modern day driving patterns (e.g. the higher speeds of inter-urban travel). Further revisions may also be required in the future.

Given studies have shown that many factors have a significant influence on vehicle emissions, the availability of emission data for these factors will significantly influence the accuracy of emission model predictions. In the US, it has been shown that their relatively comprehensive emissions database, and to some extent emission model algorithms, are not adequate for accurate model predictions (Bradlow, 1990; Fujita et al, 1992; Cadle et al, 1993). Consequently, more data needs to be collected for emissions as a function of several factors (Cadle et al, 1991 and 1993). Ostria and Lawrence (1994) have also recommended that consideration is given to efforts by the US EPA and the California Air Resources Board (CARB) to develop new motor vehicle emission certification processes.

Studies have concluded that vehicles emit two to four times as much HC and CO emissions as estimated by US emission models (Pierson et al, 1990; National Research Council, 1991). They have suggested many factors may be responsible for these under-predictions. It is also suggested that much of this under-estimation may be related to the driving cycle tests used in: measuring vehicle emissions; the emissions certification process of new vehicles; and the development of existing emission models (Sperling et al, 1992).

The FTP does not allow for various vehicle operating conditions, such as speeds above 57 miles per hour, accelerations greater than 3.3 miles per hour per second, or sharp decelerations. Activities such as these are believed to be significant contributors to instantaneous vehicle emission rates. Indeed, a recent report by the EPA assessing average driver behaviour concluded that actual driving speeds and acceleration rates are much higher than those represented by the current FTP (EPA, 1993). Hence, the FTP may no longer adequately represent emissions under current driving conditions. Recently, the EPA scheduled a set of tests to quantify emissions for those driving patterns that are outside the envelope of the FTP (EPA, 1993a).

5.4 DISPERSION MODELLING

The role of the dispersion model is to predict pollutant concentrations based on pollutant emission rates, meteorological conditions and site geometry. This often represents the last step in the traffic air pollution modelling process. However, dispersion modelling did not form part of the author's research. This section has only been included to give an overview of the overall pollution modelling process.

A dispersion model has a number of input parameters to calculate the pollutant concentration at a point, or receptor. In particular, it needs the spatial separation of the point sources (or line sources), emission rates, meteorological conditions (typically, at least wind speed and direction) and the distance between source(s) and receptor. These represent the minimum input requirements for a dispersion model, more sophisticated models may have additional requirements.

Techniques for Predicting Pollutant Concentrations

Pollutants emitted from moving point sources are diluted by the mechanical turbulence from vehicles. This gives an apparent source that is a long rectangular volume over the paved roadway containing a relatively well mixed pollutant source from which the pollutants are typically dispersed by the wind.

The starting point for modelling pollutant dispersion is typically a differential equation which expresses the rate of change of the pollutant concentration in terms of average wind and turbulent diffusion. The change in concentration is the result of pollutant movement under the influence of wind or turbulence, contribution from sources within the volume and changes because of chemical reactions.

The dispersion process may be represented by a number of methods depending on the way in which the dispersion equation is solved (Linaritakis, 1987). The most complex solution is by numerical integration. Models following this approach are called numerical models.

The second approach assumes that the wind and turbulence functions are independent of time and position. This allows an analytical solution whereby the concentration is expressed as a Gaussian distribution in the vertical and crosswind directions. Such models are called Gaussian Plume models. Generally, Gaussian models have been applied to highway modelling whereas numerical models have been applied to highway and street-canyon cases. Highway situations often don't have significant topological features nearby and the dispersion is primarily related to wind speed and direction. Whereas, canyons typically refer to urban streets which have tall buildings either side of the street. In these cases the wind's speed and direction can be significantly altered leading to high pollutant concentrations. A useful source of information for these studies are experimental observations from wind tunnel and field studies (McCormick and Xintaras, 1962; Georgii et al, 1967; Linaritakis, 1987).

A third type of model has been derived from the idea of the continuity of mass of a volume element. If the volume element is large enough and diffusion can be neglected, the Box Model may be used. This model has been applied to the street-canyon case for the prediction of pollutant concentrations, but its main use has been in urban mesoscale modelling (Tenekes, 1976).

Empirical models have also been developed based on field and wind tunnel observations using regression analysis to correlate pollutant levels and affecting factors. They vary as to the number of explanatory variables they incorporate and the range of traffic, weather and layout characteristics that they can describe.

Dispersion Models

This section describes some models used for predicting short-term traffic pollutant concentrations at the microscale level. These can be classified into two main categories: highway models; and street canyon models.

Highway Models

The major existing dispersion models are of Gaussian Plume type and are empirical or semi-empirical models. Numerical models have not been widely used because they require detailed meterological data which are often not available and they require considerable computing power. Sistla et al (1979) compared four numerical models with four Gaussian models using data collected at a particular highway site. They concluded that the numerical models did no better than the gaussian models. Numerical models yielded good correlations for neutral stability, while Gaussian had good correlations for unstable conditions.

Most of the models describe pollutant dispersion as a function of the wind angle with respect to the roadway. The UK TRRL method (Hickman & Colwill, 1982) and a wide range of US models are Gaussian type models.

The US Environmental Protection Agency's (EPA) HIWAY model is an empirical gaussian model, designed for estimation of dispersion from a highway in a stable atmosphere (Petersen, 1980). Highway emissions are represented as a series of finite line sources. Each traffic lane is modelled as if it were a straight, continuous finite line source with a uniform emission rate.

CALINE-3 (Benson, 1979) is a Gaussian plume line source model developed by the California Department of Transportation. It can be used to predict carbon monoxide concentrations near highways and arterial streets, given traffic emissions, site geometry and meteorology. The model has adjustments for averaging time and surface roughness and can handle up to 20 links and 20 receptors. Individual links are divided into a series of elements from which incremental concentrations are computed and added. The enhanced version, CALINE4/V9-PG (Benson, 1984; Ireson, 1986), can also model CO in street canyons.

The Intersection Midblock Model (IMM) has been developed as an aid to the identification and analysis of carbon monoxide hot spot locations. It calculates hourly carbon monoxide concentrations at specified locations near streets or intersections (Benesh, 1978). IMM uses carbon monoxide emissions from vehicles cruising, accelerating, decelerating and idling by using the EPA Modal Analysis Model (MAM).

After the emissions have been calculated and distributed among the individual lanes of each link, the EPA HIWAY model is called to calculate CO concentrations at each receptor location based upon values of hourly wind speed and direction and atmospheric stability. If the street configuration complies with a criterion suggested by Georgii et al (1967) then a street canyon vortex is likely to be developed and the model will use the street canyon model of the Stanford Research Institute (Johnson et al, 1973) to calculate the concentration of a street orientated receptor.

The computer based TRRL Method (Hickman, Colwill & Hughes, 1979; Hickman & Colwill, 1982; Hickman & Waterfield, 1984) is based on the gaussian dispersion theory with empirical formulation so that it represents the roadside situation. The method uses a simplified version of the Gaussian dispersion equation which assumes that there is no difference in height between source and receptor (two dimensional model). This method forms the basis of the dispersion model used in the PREDICT model suite.

Its inputs have been confined to information readily available to the transportation planner. Pollutant concentrations can be calculated for either a single location or for a grid of receptors. Although the calibration and validation of the composite (emission-dispersion) model has been based on measurements of carbon monoxide, some relationships which use CO levels as a guide to HC, NOx and lead concentrations have also been included in the method.

The model (PREDCO) based on this method used measurements from two highway sites which may not be representative of all situations. A single concentration value is considered implicitly by the model as background concentration but on many occasions this value may prove to be quite different from background levels local to a transportation scheme. Therefore, it has been argued that no estimated concentration should be regarded as an accurate prediction, and that predicted changes between 'before' and 'after' scenarios should be considered. The method is not suitable in situations where large topographical features are present, nor where there is more than one level of traffic.

The Site Monitoring Method is a flexible method which can be used in the air quality impact assessment of a rural (highway) or an urban (street canyon) transportation scheme (Watkins, 1991). The method can be used to assess future pollutant concentrations using specifically developed site models or site calibrated dispersion models. The method usually requires concurrent measurement of pollutant concentrations and traffic and weather data which are analyzed later to determine background variation and/or to develop empirical relationships between pollutant concentrations and different exploratory variables.

As the method is specific to the monitoring site, developed relationships are not necessarily valid for other locations. The accuracy of these relationships varies depending on the pollutant, the number of the explanatory variables, the traffic and weather conditions, and the method of the analysis.

Specially designed dispersion experiments in the US resulted in improved model accuracy. Evaluation of some commonly used American Gaussian and numerical highway models (Chock, 1978; Maldonado & Bullin, 1977; Noll, Miller & Claggett, 1978; Rodden, Green, Messina & Bullin, 1982) using data from different studies showed that:

* numerical models perform no better than gaussian;

* when the entire range of concentrations is considered, gaussian models appear to be more accurate;

* in general, all models seem to give good predictions close to the source, with correlations between predicted and observed levels decreasing as the distance from the source increases;

* the models tend to over-estimate pollutant concentrations much more

as the distance between source and receptor increases;

- the accuracy of model predictions depends on the atmospheric conditions; most of the models perform poorly for wind speeds less than 1.0 m/sec; whereas model accuracy in most cases increases with the angle between wind direction and road alignment (performs best for winds perpendicular to the road); and

- the more accurate models over- or under-predict by a factor of 2 for the majority of the cases (85 per cent of the time).

Street Canyon Models

Complex numerical models may be used to study pollutant concentrations in street canyons. However, such techniques require considerable computer power. There are also difficulties in accounting for variations in street-level dispersion parameters which arise from the air motion induced by counter flowing traffic streams along roadways.

Box models have been used to represent pollutant dispersion in a street canyon. Williams (1982) used a simple box model for long-term (annual average) prediction of CO, NOx and black smoke concentrations based on data collected from a road with high traffic volumes in London. Application of the model to another site allowed him to conclude that the most important factor in determining the accuracy of the simple box model for a street canyon is likely to be the accurate specification of pollutant emission rates.

Nicholson (1975) developed a "scalar budget-box" diffusion model to predict hourly pollutant (CO) concentrations in street canyons. It comprised two equations for wind parallel and perpendicular to the street respectively. For most days at all sites, the predicted values were within 33 percent of the observed. The model appeared to be less reliable in the case of weak winds. The model performed reasonably well as an average street canyon air quality model. However, it appears that the number of wind profile parameters required for its application at each site have resulted in it no longer being used.

A street canyon model developed by the Stanford Research Institute has been used in America (Johnson, Ludwig, Dabberdt & Allen, 1973). This is largely based upon extensive measurements made by Georgii et al (1967) and experimental contributions from other researchers. The input data consists of emission rates, street canyon depth, street width, wind speed at roof-level and the slant distance between receptor and the nearest traffic lane.

A Street-Canyon Model has been developed in the UK (Crompton and Gilbert, 1970). Research concentrated on relating traffic, layout and meteorological factors to pollutant levels at the kerbside of urban roads over short periods of time. The first attempts to quantify air pollution levels (CO) at the kerbside (Crompton and Gilbert, 1972) were based on data measured in Edinburgh, Canterbury, Kingston and Greenwich, representing a wide variety of traffic and layout characteristics. Although they could not explain more than 70 per cent of the variation in the data, Crompton and Gilbert found that by far the most significant variable was the traffic density per unit width of carriageway.

Studies (Richardson, 1982 and Linaritakis, 1983), using data collected from a range of typical urban streets in central London, demonstrated that empirical models based on multiple regression techniques have the potential to produce robust models. Such models describe the situation in urban street canyons in relation to traffic generated air pollution, and can be used for practical transportation planning studies.

Evaluation of Models

Predictions from the TRRL dispersion model have been compared with observations (Hickman and Colwill, 1982). At a tunnel site 86 percent of the predictions were within 50 percent of the observed values. At an urban site 74 percent were within 50 percent of the observed values; and 57 percent were within that range at a rural site. Members of the QUARTET Consortium have used the model in Athens and found plots of model predictions closely followed observed pollutant concentrations (PREDICT Consortium, 1989a; QUARTET Consortium 1992). However, Watkins (1991) points out that the model is based on many assumptions and a simplified dispersion theory. He suggests that it would be unwise to literally interpret the predictions of absolute concentration values. It is better used for the comparison of 'before' and 'after' road traffic scenarios.

An evaluation of eight intersection modelling techniques was conducted by the US Environmental Protection Agency (Schewe and Braverman, 1991). The study measured air quality, traffic and on-site meteorological data at an intersection in suburban Chicago. The topography of the site consisted of flat, level terrain and no street canyon effects were present. Their results indicated that TEXIN2/MOBILE4, CALINE4/MOBILE4 and CAL3QHC/MOBILE4 were the best performing models and, generally, it was concluded that they performed well.

However, difficulties with dispersion modelling are encountered in urban areas with significant topological features. In particular, street canyons have to be treated in a special way (Linaritakis, 1983). The Stanford Research Institute's canyon model has been shown to perform "reasonably well" (Koushki, 1991). The correlation coefficients, for measured versus predicted levels, varied between 0.53 and 0.85. It has also been shown that the model can be applied to European sites (Leisen and Sobottka, 1981; Hamilton, 1984).

Zamurs (1990) has emphasised the importance of a modal emissions approach for intersection modelling, and the need for further developments in dispersion modelling.

As part of the environmental impact statement for a major transport project in New York, an air quality study was undertaken to determine the performance of intersection air quality models and determine which model would be most suitable for the impact analysis (Zamurs and Conway, 1991). The study collected traffic and meteorological data, and monitored carbon monoxide concentrations. The study concluded that model performance was disappointing. The models under-predicted, except for a modal emissions approach, which approached or over-predicted, compared with observed concentrations.

5.5 MODEL SUITES

The previous sections of this chapter have described traffic, emission and dispersion models in isolation. However, when a study team investigates the impact of traffic management and control strategies on air pollution they often make use of a model suite. A model suite is a collection of traffic and pollution models which are used together. A model suite may also include additional software modules to automatically translate the output data of one model into a format suitable for input into the next model.

A good example of a model suite is the Urban Road Pollution Model, called UROPOL (Halcrow Fox, 1993). This model suite comprises the SATURN traffic assignment and simulation model (Van Vliet, 1982; Hall et al, 1980), queuing model, emission model (Matzoros, 1990) and PREDCO dispersion model (Hickman and Colwill, 1982). It is designed to model pollutant emissions and concentrations caused by junction effects and driving modes. Queue lengths at signalised, priority and roundabout intersections are specifically modelled, and predictions include the spatial variability of emissions on such urban roads.

The queuing, emission and dispersion modelling elements of the model suite are described by Matzoros (1990). The model incorporates the following characteristics of an urban road networks and its associated air pollution:

- the formation and dissipation of queues;
- different vehicle operating modes (cruise, deceleration, queuing and acceleration) at different points along a link;
- emission rates by operating mode; and
- the effects of the movement of vehicles on the dispersion of their exhaust gases.

The modelling procedure starts by feeding network and trip matrix details into the traffic model. The output of the traffic model consists of traffic flows, speeds, signal settings, road capacities, and junction types. These data, along with acceleration and deceleration rates, are then used as input to the queuing model. The predicted queue lengths for each link in the network and emission rates for each driving mode are used by the emissions model to predict the spatial distribution of emissions along links. Finally, the dispersion model uses these emissions, along with wind speed and direction, to predict pollutant concentrations. The pollutants modelled are carbon monoxide, hydrocarbons, nitrogen oxides, and lead.

5.6 SUMMARY

This chapter has described the various techniques available for modelling the impact of transport policy and traffic control strategies on air quality. The technique can be broken into two key areas: transport and air pollution. The transport models are used to produce predictions of traffic flows, speeds, and delays. These are used by an emission model to predict pollutant emission rates. These emission rates are input to a dispersion model to predict pollutant concentrations.

An emission model usually predicts pollutant emission rates either over an area or link by link. Emission models typically require, as a minimum, the average speed of the vehicle and emission rate as a function of vehicle speed, for each pollutant. In some cases the emission model makes predictions based on a standard driving cycle which is assumed to be representative of the urban driving pattern. It has been indicated that there are problems with models based upon standard driving cycles.

The standard driving cycle provides a standardised way of certifying emissions of new vehicles, conformity testing in-service vehicles and, to a lesser extent, estimating total emissions over a region. The author recognises such benefits of the standard driving cycle. However, in terms of modelling emissions within an urban area, particularly at street level, predictions based on such driving cycles can have significant problems, as has been indicated in this review. Indeed, the findings of the author's work support this view strongly, due to the complexity and variability of driving patterns and emissions from street to street.

For some studies a more detailed modelling approach that specifically represents all driving modes is preferable. In addition, emission modelling needs to accurately represent the emission characteristics of various types of vehicle.

Emissions can be influenced by many factors, such as vehicle type, vehicle condition and ambient factors. MOBILE represents many of these factors, but lacks the ability to specifically represent emissions by driving mode. Also, the database for this model is specific to vehicles in the US. The emissions model incorporated into UROPOL has several good features, particularly the representation of driving modes and the effects of different junction types.

Pollutant emission rates from an emission model are input to a dispersion model to predict pollutant concentrations for a given network (or link) topology and set of meteorological conditions. Dispersion modelling can be a complex process and often a model will be developed to work in a particular context, such as highways/rural roads or roads in a 'canyon'.

The PREDICT model suite follows a modelling approach similar to that outlined in this chapter. It consists of an assignment model based on the Dial algorithm, the TRANSYT signal optimisation program, a specially developed emission model and the PREDCO dispersion model. The PREDICT model suite is described in more detail in the following chapter.

Chapter 6

MODEL SUITE

6.1 INTRODUCTION

This chapter describes the model suite used in the PREDICT and QUARTET projects, and in the research described in this thesis. At the start of PREDICT, the project consortium decided there was not a suitable model suite for modelling advanced environmentally sensitive traffic control strategies. Consequently, the project consortium enhanced an existing model suite and developed a flexible emissions model able to meet the requirements of PREDICT. Further enhancements were also made to the model suite in the QUARTET project.

This chapter outlines the PREDICT model suite's functionality and the interaction between models. The PREMIT emissions model is described in greater detail than the other models of the suite, for two reasons. Firstly, this represents a new and important component of the model suite, whereas the other models are based on techniques that are widely used throughout the traffic engineering and research community. Secondly, the emissions model is directly related to the author's research, and was developed by the author. Its key features are, a high degree of flexibility, and the representation of driving mode and fleet composition.

Finally, this chapter assesses the suitability of the PREDICT model suite for the PREDICT and QUARTET projects, and the author's research.

6.2 OBJECTIVES

The PREDICT consortium needed a model which could simultaneously and accurately represent all of the changes caused by the introduction of environmentally sensitive traffic control strategies. These strategies would change traffic flows, driving cycles, fleet composition and vehicle emissions. The main objective of the model was to compare the effectiveness of different strategies relative to a base case scenario. The emission model also had to have sufficient flexibility to readily accept new emissions data as they became available. This would allow the emission inventory to be improved over time, and sites other than Athens to be evaluated.

In the QUARTET project, an online real-time capability was required, whereby real traffic data would provide the input to predictions. This would allow a closed-loop traffic control infrastructure to be developed which was capable of responding to potential air pollution threats in real-time.

The objectives of the research described in this thesis were, primarily, to investigate the behaviour of road traffic emissions and their implications for environmentally sensitive traffic control strategies. These objectives were met using a subset of the PREDICT model suite.

6.3 PREDICT MODEL SUITE

The PREDICT model suite consists of four main modules: traffic assignment; signal optimisation model; emission model; and dispersion model (PREDICT Consortium, 1989a and 1989b). Figure 6.1 illustrates the structure of the PREDICT model suite.

Starting with an origin-destination (O-D) trip matrix, and a representation of the road network including link travel times, the assignment model allocates traffic flows to links in the network. These flows then provide the input to the signal optimisation model. This model is typically used to produce signal timings that minimise stops and delay. The resulting estimates of delays, stops and queue lengths are then fed into the emissions model, which determines emissions based on the times spent in each of four driving modes: acceleration; cruise; deceleration; and idling. The emissions model calculates pollutant emission rates for each link. These are used by the dispersion model to predict roadside pollutant concentrations.

The author's research involved using the TRANSYT signal optimisation model and the PREMIT emissions model.

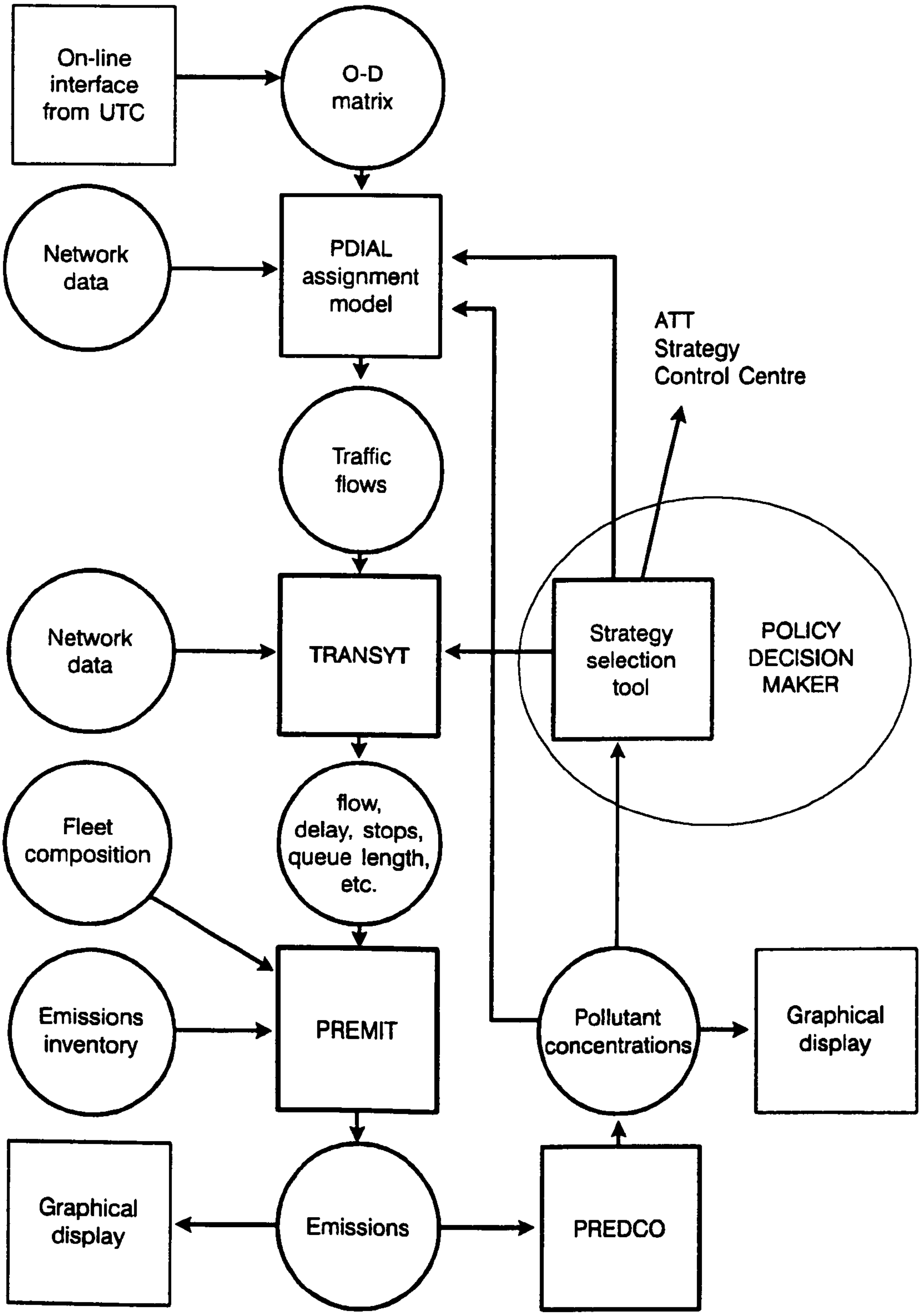

Figure 6.1 PREDICT Model Suite

Assignment Model

The PDIAL assignment model is designed to study cities which have traffic pollution problems. PDIAL distributes trips in such a way that delay (and, potentially, pollution levels) can be optimised over an urban network. The impedance function, used to construct minimum paths through the network, is based on link travel time and, optionally, link pollutant concentration.

The model uses an adaption of Dial's multipath traffic assignment algorithm (Dial, 1971) which distributes flows to all 'reasonable' paths. PDIAL uses capacity-restraint and incremental assignment. The following impedance (cost) function is used to find efficient paths through the network:

$$C = w1 * t + w2 * p$$

where, w1, w2 are user defined weighting factors; t is the link travel time (seconds); and p is the pollutant concentration (ppm). For assignment of traffic based only on conventional factors (i.e. link travel time), the weighting factor w2 is set to zero, removing the pollution component from the assignment.

In its first iteration, PDIAL calculates routes based on given free flow travel times for each link. In subsequent iterations the full cost function is used, whereby link travel times take into account flow and link capacity. To suit the specific needs of PREDICT, the assignment model performs a concurrent two-tier assignment for each and every O-D pair: a minimum path assignment for all route-guided traffic; and a stochastic assignment for non-guided traffic. Composite impedance functions can be defined which convey the strategic routing decisions.

Signal Optimisation Model

Signal coordination is modelled using the TRANSYT 8 program. This was described in the previous chapter and so this section briefly focuses on the weighting factors that were adjusted as part of the author's research.

TRANSYT can find the best fixed-time plan for a signalised network by finding the minimum value of the Performance Index. The Performance Index PI is defined as follows:

$$PI = \sum_{i=1}^{N} (W \, . \, w_i d_i \; + \; \frac{K}{100} \, . \, k_i s_i)$$

where N = number of links

W = overall cost per average pcu-hour of delay

K = overall cost per 100 pcu-stops

w_i = delay weighting on link i

d_i = delay on link i

k_i = stop weighting on link i

s_i = number of stops on link i

The overall cost values for delay and stops, W and K, apply throughout the network. In addition, if for any reason the user sees it appropriate to adjust these values for particular links, the cost scaling factors for those links, w_i and k_i can be adjusted. For example, the author adjusted the cost of stops and delay on links which had high emission rates, in an attempt to reduce emissions on such links.

PREMIT Emissions Model

The PREMIT emissions model has three key features: flexibility and ease of use; modelling of emissions from each driving mode; and representation of different vehicle types in the traffic fleet.

Representation of Driving Modes

Earlier chapters have illustrated how emissions significantly vary as a function of speed and driving mode. Traffic control strategies sometimes significantly alter the proportions of time a vehicle spends in each of these driving modes, both over individual links and the network, or 'driving cycle', as a whole. Therefore, in order to accurately model the impact of traffic control strategies on pollution, the following driving modes were incorporated into the PREMIT emissions model: cruise; acceleration; deceleration; and idling. Within the emissions model, pollutant generation is considered for each element of the driving cycle, as follows.

Cruising is assumed to take place for all the vehicles which are not delayed on a link. For these vehicles, a constant cruise speed is used over the whole length of the link; the emissions from these vehicles being entirely due to their cruise speed. For vehicles that are, at least partly, delayed, the distance over which vehicles cruise is calculated and the corresponding cruise emissions form part of their total emissions; the other emissions coming from the driving modes described below.

Deceleration is assumed to take place as a vehicle arrives within the 'stopping distance' of the back of the queue. The stopping distance is calculated using the vehicle's cruise speed and a specified deceleration rate entered in the parameters file.

Idling is assumed to take place once the vehicle reaches the back of the queue or is held by a red light at the stop line. The output of the signal coordination model (TRANSYT) contains the link delay and it is this value that is used to calculate the total emissions due to idling in any one cycle.

Acceleration from the idling state, for the vehicles which were delayed, is also modelled. The distance over which acceleration takes place is calculated based on the cruise speed and a specified acceleration rate.

The emissions from each of the above driving modes are totalled to produce the overall emission rate for a given link. The emissions model then outputs the total emissions on a segment of road between two nodes; this may include emissions from more than one TRANSYT link. Emissions for selected driving modes can also be reported, providing a breakdown of emissions by driving mode. This feature allows the researcher to determine which driving modes produce significant emissions.

Representation of Vehicle Fleets

PREMIT can model the effects of new vehicle technologies and represent the diverse vehicle fleet encountered within an urban area. The model can represent a wide range of vehicle categories and a range of emission characteristics for each vehicle category.

In strategies where a modal shift or change in vehicle emission characteristics are imposed, the PREMIT can readily represent the new traffic fleet composition and emission characteristics. In particular, two of the most successful strategies in PREDICT were based on changing the emission characteristics of cars, by fitting them with catalytic converters. Consequently, fleet representation was an important requirement for the PREMIT emission model.

The model can incorporate data for a range of vehicle types which are considered to have different emission characteristics. PREMIT can represent a large number of vehicle types, assuming the appropriate emissions data are available. For example, it is possible to represent various combinations of the following vehicle types and vehicle states:

- fuel type: petrol (leaded, unleaded), diesel, alcohol, mixture;
- vehicle type and laden weight;
- engine size and type;
- emission reduction devices: catalytic converter, particulate trap;
- engine and catalyst temperature; and
- vehicle's age and state of maintenance.

For an accurate representation of pollution levels, the emission rates for idling, acceleration, cruise and deceleration are required. The proportion of each individual vehicle type within the overall vehicle population must also be known.

As emission characteristics for different vehicle types can vary significantly, this feature allows a more thorough representation of the vehicle fleet. The accuracy of the model depends largely on the accuracy of the emission rates entered into the model. Where such detailed data are not available, the emissions model can work with a small number of vehicle types, or just one vehicle type if necessary, i.e. treat the whole fleet as one vehicle type.

This flexibility allows the model to make maximum use of all available data and, potentially, provides a more realistic representation of the traffic fleet. In addition, the model can be easily updated to reflect new vehicle emission characteristics. PREMIT can represent advanced vehicle types with much lower emissions, whether they be based on better engine designs, emission reduction systems or alternative fuels, for example. In summary, the emission model provides a high degree of flexibility, ease of use and a detailed representation of the mechanisms involved in pollutant emissions.

Input Data

The PREMIT emissions model receives input data from three areas: vehicle emission database; traffic performance data from TRANSYT; and a miscellaneous traffic parameters file. All these data sources are standard ASCII text files. These are described below.

Emissions Input Data

The emission rates for each pollutant over a range of cruise speeds, and for idling, acceleration and deceleration, are held within a text file. Having specified the name of the pollutant, all emissions data input refer to this pollutant until the next pollutant is specified. For each pollutant, one or more vehicle types may be identified.

For each vehicle type modelled, the percentage it makes up of the entire fleet is specified. For example, the traffic fleet may consist of cars with and without catalytic converters, petrol and diesel engines, buses and heavy goods vehicles. For each vehicle type emission rates for cruise, acceleration, deceleration and idling must be specified.

For the cruise driving mode, speed is specified in units of kilometres per hour (km/h) and emissions in grams/km. The emissions for acceleration correspond to the average emission rate over the period taken for a vehicle to accelerate from rest to the final cruise speed. Similarly, the emissions for deceleration correspond to the average emission rate over the period taken for a vehicle to decelerate from the initial cruise speed to rest. The emission rates for acceleration, deceleration and idling are specified in units of grams/minute.

For each pollutant in the emissions input file, the data points for each vehicle type are used to make a 'graph' in which linear interpolation is used between adjacent points in the input file. When a graph has been obtained for each vehicle type they are combined into one graph, based on the average values from each vehicle type graph weighted by its traffic composition percentage. The result is, that for each pollutant, there will be one graph for each of the following driving modes:

- cruise emissions as a function of speed;
- acceleration emissions as a function of cruise speed; and
- deceleration emissions as a function of cruise speed.

In addition, for each pollutant there will be one value representing the idling emissions.

Traffic Input Data

The emissions model extracts relevant data from the TRANSYT output file, these are: link numbers; cruise speed; link length; flow; stops; queue length; stop-line saturation flow; and total link delay. PCU delay (the average delay per PCU) is also read from the TRANSYT output file to report average link speeds in the output listing. This, along with other output data, may be used by the assignment model, on the next iteration of the model suite, to reroute traffic through the network as described earlier.

Miscellaneous Parameters

This file holds values of the following network parameters:-

- **Vehicle spacing** is the average length occupied by a vehicle in a queue i.e. queue length divided by the number of vehicles in the queue. This is used to determine the length of a queue.
- **Acceleration rate** is the average rate at which vehicles accelerate in the network, and **deceleration rate** is the average rate at which vehicles decelerate. These two values are used to calculate the time and distance over which vehicles accelerate and decelerate for each link.
- **Maximum lane flow** is used to calculate how many lanes there are on a given link.

Emissions Algorithm

Pollutant emissions are calculated based on the above input data and the algorithm described below. A simplified version of the algorithm, which ignores the scaling factors needed to account for the input data being in different units, has been presented. The key input parameters are described in Table 6.1.

The number of vehicles which are delayed, N_D, in one cycle (c) of the traffic signals is calculated for a given link:

$$N_D = f\,c\,z \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

For vehicles which are not delayed, their free flow cruise emissions are calculated:

$$E_{free} = (f\,c - N_D)\,l\,E_c(v) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

For vehicles that are delayed, emissions from all driving modes need to be calculated. The queue length, q_l, is calculated based on the number of vehicles in the queue and

Parameter notation	*Parameter description*
a	acceleration rate
d	deceleration rate
s	vehicle spacing when queuing
l	link length
f	link flow
D	total link delay
z	number of stops on link (as a fraction of flow)
q	maximum number of PCUs in queue
v	link cruise speed
$E_c(v)$	cruise emission (function of speed) per unit distance
$E_a(v)$	acceleration emission (function of final speed) per unit time
$E_d(v)$	deceleration emission (function of initial speed) per unit time
E_{idle}	idling emission per unit time

Table 6.1 Input parameters used by PREMIT

the average spacing between vehicles when queuing:

$$q_l = q\ s \quad \text{.............................} \quad (3)$$

The queue length, and the distance that vehicles cover while decelerating and accelerating, are subtracted from the link length to give the average distance available for cruising, l_c:

$$l_c = l - (q_l / 2) - (v^2 / 2a) - (v^2 / 2d) \quad \text{..............} \quad (4)$$

Given the distance available for cruising (4), to vehicles that are delayed, cruise emissions, E_{delay}, from delayed vehicles are calculated:

$$E_{delay} = N_D\, l_c\, E_c(v) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Emissions resulting from the deceleration, E_d, and acceleration, E_a, of delayed vehicles are calculated, as shown in equations (6) and (7).

$$E_d = N_D\, E_d(v)\ v / d \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$E_a = N_D\, E_a(v)\ v / a \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Finally, idling emissions, E_i, are calculated based on total link delay, provided by TRANSYT, and the idling emission rate:

$$E_i = D\, E_{idle} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

To obtain the total link emission rate, the above emissions are totalled, but the emissions from cruise, deceleration and acceleration are first converted to an emission rate per unit time, as opposed to emissions over the duration of one cycle, c. Idling emissions do not need this conversion and, using equations (2), (5), (6), (7) and (8), the total link emission rate, E, can be calculated:

$$E = (E_{free} + E_{delay} + E_d + E_a) / c + E_i$$

The above process is repeated for each pollutant. As the algorithm calculates emissions from each driving mode, the emissions model is able to report the emissions produced by each driving mode.

Output Data

The results of the emission calculations for each link are recorded in an output file. Figure 6.2 illustrates the format of a PREMIT output file. Each line of data corresponds to a road segment carrying traffic between nodes A and B. Total delay, number of vehicles in the queue, mean stops and average speed are based on the output of TRANSYT.

```
PREMIT EMISSIONS MODEL  Version 3.07
Copyright (C) Castle Rock Consultants 1993.  All rights reserved.

Run time: 19 Jul 93 20:56
Emissions based on:
ATHENS * CENTRAL ARTERIES * Optimisation ON
BASECASE.ctl ** BASE CASE ** using Greek parameters
Modes modelled are: cruising acceleration deceleration idling

 A     B     total    number of    mean     average   Carbon      Hydrocarbons  Nitrogen
node  node  delay    vehicles in   stops    speed     Monoxide    (THC)         Oxides
                     the queue    per PCU             (CO)                      (NOx)
          (PCU-h/h)   (PCU)        (%)      (km/h)    (g/min)     (g/min)       (g/min)

 151   187    0.9        2          72        11      15.76        1.68          0.71
 160   189    1.0        2         104         8      13.05        1.38          0.47
 171   185    4.5       12          80        10      76.62        7.95          3.10


Total pollution emission rates for this network (g/min) :

          Carbon Monoxide (CO) :              7772.1
          Hydrocarbons (THC) :                 889.8
          Nitrogen Oxides (NOx) :              404.7
```

Figure 6.2 Example of a PREMIT output file

The units for the emission rate are grams per minute (g/min), or grams per metre per hour (g/m/h). The former units readily allow the comparison of emission control strategies as the total emission rate for a network, or part of a network, can easily be totalled from the link emission rates. When output is generated in units of g/min the model automatically provides the total network emission rate for each pollutant. The latter units (g/m/h) can be used as input to the PREDICT dispersion model.

Dispersion Model

The dispersion model used in the PREDICT model suite is based on the PREDCO model. The model is primarily used to compare the effectiveness of different traffic control strategies, as opposed to the prediction of absolute values for pollutant concentrations. It also allows the identification of links which are likely to have significant pollution problems. To make this task easier, a graphical display indicates pollutant concentrations by colour coding each link of the traffic network.

Although the dispersion algorithm was initially developed to predict concentrations of CO, it can also be used to predict concentrations of other gaseous pollutants (PREDICT Consortium, 1989a). Assuming different pollutants disperse at the same rate leads to the following relationship:

$$P = C * R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where, P and C are the concentrations of the pollutant under study and CO from the same source, and R is the ratio of the emission rate of pollutant P to that of CO.

Concentrations for oxides of nitrogen may be the result of emissions from traffic, industry and other sources. Therefore, it may be necessary to use a modification of equation (1) to represent the contribution from sources other than traffic:

$$P = a * C * R + b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where, a and b are empirically estimated parameters that account for the contribution from non-traffic related sources. These parameters have to be calibrated for the particular study site.

In Athens traffic was the major contributor to the roadside pollutant concentrations of NOx and other sources were practically negligible. Consequently, the validation of the dispersion model found that the value for parameter a was approximately one and parameter b was approximately zero (PREDICT Consortium, 1989a). This meant that equation (1) could be used for the prediction of roadside NOx in Athens.

6.4 ASSESSMENT OF MODEL SUITE

Although, the PREDICT and QUARTET project teams have made, or intend to make, full use of all the components of the PREDICT model suite, the author's research focuses specifically on the impact that various traffic control strategies have on traffic emissions. Therefore, the performance of the dispersion model is not directly relevant to the work described in this thesis. Similarly, most of the strategies investigated in this thesis have not involved the use of the assignment model. Nevertheless, for the sake of completeness, an overview of all the PREDICT models has been included.

Comparison of Conventional and Enhanced Techniques

The model suite is based mainly around conventional and proven techniques. In addition, it makes use of state-of-the-art modelling techniques, especially in the case of the emissions model. The traffic assignment and signal coordination modules are based on widely known algorithms. The dispersion model is based on the proven technique adopted in PREDCO and has also been calibrated and validated in Athens (QUARTET, 1992). Given that much of the model suite is based on traditional, proven modelling techniques which are widely understood, the author has chosen to focus the assessment on the PREMIT emissions model.

The main advantage of the PREMIT emission model over most other emission models is that it has been specifically designed to represent the impact of ATT traffic control strategies. In particular, it represents driving modes on each link of a traffic network, and has a flexible representation of different vehicle types. These aspects have been shown to be very important in earlier chapters of this thesis.

The ability of PREMIT to output pollutant emissions by driving mode, also provides a powerful research tool for the quantitative analysis and understanding of traffic emissions. These benefits are clearly illustrated in the author's research, which is described in later chapters of this thesis.

Models based on hard-coded data, prevent the user from updating that data; only the designer of the model can update the data, resulting in a clumsy rigid system unable to adapt to strategies based on evolving vehicle emission characteristics and fleet composition. The PREDICT emissions model scores highly in this area, offering maximum flexibility to the user, allowing all input data and configuration parameters to be easily updated. For example, as new or more detailed emissions data become available the PREMIT emissions inventory can be easily updated.

PREMIT's degree of flexibility also allows the transferability of these concepts and strategies to other European cities, where emission characteristics may be different. Potentially, this flexibility can also be used to model changing traffic compositions and emission characteristics throughout the day, providing a more realistic representation of the urban environment and a useful tool for modelling in real-time. For example, the ratio of cold to hot vehicles could be represented. This flexibility is also extremely important to the modelling of strategies which directly force a change in the traffic composition and vehicle emission characteristics. This was used to model the impact of the environmental area licensing strategy described in the following chapter.

Finally, in support of the above, it is worth mentioning that an independent review of traffic pollution modelling techniques illustrated PREMIT's abundance of features for modelling the impact of ATT strategies on emissions (Halcrow Fox, 1993).

Context of the Modelling

An assessment of the context in which a model is to be used is useful for determining requirements and establishing a model's suitability. The Department of Transport (1988) summarises the overall requirements of a model as follows. No model, or set of data, can be expected to represent reality other than within known ranges of tolerance. For complex models involving human choice or meteorological phenomena, these tolerance limits are normally wide. In most cases, it is not necessary to attempt to reduce the error limits by seeking greater precision. What is important is to ensure:

* that the degree of accuracy is adequate for the decisions which need to be taken;

* that the decision makers understand the quality of the information with which they are working; and

* that they take the inherent uncertainties into account in reaching decisions.

Therefore, the quality of a model's predictions should not be judged merely in terms of their proximity to actual values. They should be judged in terms of the ultimate objective; in the case of PREDICT model suite that is, the effectiveness of the control strategies that it evaluates. The degree of accuracy needs to be such that different control strategies can be compared and the most effective identified.

The decision makers, in this case, are experienced in the use of the PREDICT model and fully understand the quality of the information with which they are working. It is realised that the model's predictions have significant uncertainties and these are taken in account when making decisions.

Model Accuracy

To conclusively determine model accuracy a validation study is necessary. This involves the collection of relevant real-time traffic and environmental data. Collected data are then input to the model and its predictions are compared with measured pollutant concentrations. However, such a validation study was not funded in either the PREDICT or QUARTET projects. Therefore, it is not possible to scientifically discuss the quantitative accuracy of the entire PREDICT model suite.

Instead, a semi-quantitative assessment of model accuracy is described in this section, based on a literature review and limited validation studies. This takes into account accuracy of the input data, algorithm and model sensitivity.

Assignment Model

Thomas (1991) describes traffic assignment models and their behaviour. He noted that it is generally accepted that assignment models typically have errors of up to 30 percent of the observed link flows. Typically, the errors in estimated flows, based on a traditionally derived O-D matrix, are of the order of 25 percent.

Janson et al (1986) validated a recently-developed traffic assignment model and found that its estimates of link volumes differed from the observed link counts, on average, by 16 to 28 percent.

Choraffa and Ferreira (1983) demonstrated that the O-D matrix being used by an assignment model could be updated by using observed traffic flows. In this case, the resulting estimates of traffic flows from the assignment model were in better agreement with observed flows. The on-line version of the PREDICT model suite now includes such a technique, using an interface to an urban traffic control centre and a set of inductive loops (QUARTET Consortium, 1993a).

Path spreading, in PDIAL, is kept to low levels: it has been found not to exceed 4 to 5 percent of total kilometres for the range of different rerouting strategies examined.

In QUARTET, assignment modelling results will not represent the only source of traffic information. Traffic counts will be used as an alternative source of basic information. The model suite will link-up with the UTC system to utilise accurate traffic information. Hence, the uncertainty in predictions is expected to be less than a conventional modelling scenario, because of the availability of real traffic data.

Signal Optimisation Model

It has been shown that TRANSYT gives accurate delay/stop predictions (Robertson, 1969). Estimates of delay over the network have been within 2 to 4 percent of those directly measured on the streets (Hillier and Lott, 1966). Though larger discrepancies can arise on individual links. For example, a 10 percent variation between measured and modelled delay would be a reasonable estimate for a typical link.

Sensitivity tests indicate that larger errors can be anticipated in total delay on links operating near to capacity, because of the non-linear random plus over-saturation component. According to Vincent et al (1980), this sensitivity reflects actual traffic behaviour. Presumably then, any model will, potentially, be subject to significant errors on over-saturated links.

A study by Bell (1986) showed the effect of forecasting errors associated with the "ageing" of data. The extra network delay may be 3 percent for each year's discrepancy, so for example an 'optimised' network based on 3 year old traffic data may incur an additional 9 percent delay, compared to the same network optimised with up to date data. In PREDICT, these modelling errors had to be accepted, as they are in other traffic engineering studies. However, in QUARTET, the model can use up to date data from a traffic control centre. This is expected to reduce the uncertainty in predictions.

Emissions

The sensitivity of the emissions model has been illustrated and its implications analyzed (QUARTET Consortium, 1992). The predicted emissions are sensitive to a number of input parameters. However, the number of critical parameters is low. This is because some of the parameters can be accurately measured, or, more commonly, because their variation is insignificant from strategy to strategy. The greatest degree of uncertainty affecting comparisons between strategies was found to result from uncertainty in TRANSYT output parameters. In particular, delay has a significant impact on the emissions. Because delay is very sensitive to traffic flow on links that are operating at or near saturation, higher levels of uncertainty are expected on such links. Hence, this fact has to be borne in mind by the decision-makers who use this tool. In some cases, this problem can be overcome by the automatic measurement of actual traffic flows, especially on critical links.

Overall emissions calculated by the model are also significantly affected by errors in the input data emission rates for cruise, acceleration and idling modes. Deceleration emissions have little or no significant effect. Re-routing strategy evaluations are not greatly influenced by these errors, since the rates do not change for these strategies.

For scenarios involving clean vehicles or environmental area licensing, the uncertainty in the emissions inventory may be more important. These strategies substantially reduce emissions rates, due to the much lower emission levels experienced with catalytic converters. Where substantial uncertainty exists in the emissions inventory, it will be possible to over- or under-estimate the total magnitude of the potential benefits of such strategies. However, the overall magnitude of the emissions reduction resulting from catalytic converters is substantially larger than the range of uncertainty expected in the base emissions data. Thus, while the precise magnitude of the benefits to be gained is subject to error, the overall worthiness of the policy (in producing major reductions in pollution) is not itself in question.

A number of fundamental questions relevant to the assessment can now be asked and answered.

Is the degree of accuracy of the forecasts adequate for the decisions which have to be taken?

> The degree of accuracy of the policy variables (pollutant emissions) has been thoroughly examined. Despite significant limitations in both the projected traffic data, in an off-line modelling scenario, and the available emissions inventories, the emissions model meets the UK Department of Transport's major criterion for model selection: that is, the degree of accuracy is adequate for the decisions which need to be taken.

Are simpler, or more complex models available which would give more cost-effective guidance to decision-makers?

> There exist both simpler and more complex models of vehicle emissions. Simpler models were used for previous traffic planning studies, but these were not sensitive to changes in traffic management measures. Therefore, they cannot evaluate the effects of ATT. Similarly, models based on fixed representations of the urban driving cycle are incapable of reflecting the consequences of ATT policy choices. More complex microscopic models have the potential to model ATT, but the detailed emission data that they require are not generally available.

Dispersion Model

The validation of PREDCO was described in the previous chapter. Note, however, that the dispersion model was not actually used by the author. This was because his research focused on pollutant emissions, rather than pollutant concentrations.

6.5 SUMMARY

This chapter has highlighted the objectives of the model suite used in the author's research, and in the projects PREDICT and QUARTET. The model suite's structure and functionality have been described and its suitability assessed.

The PREDICT model suite offers an effective combination of conventional and enhanced modelling techniques. Indeed, the PREDICT model suite is the only model suite which is currently able to satisfy all of the requirements of the QUARTET project. The traffic modelling is based on conventional techniques. The PREMIT emissions model is based on state-of-the-art techniques, in particular, the representation of emissions by driving mode and traffic fleet composition.

In terms of its functionality, the PREDICT model suite satisfies all its objectives and works well in its operational context. In terms of accuracy, its actual performance is unknown. This is because there has not been an opportunity to validate the PREDICT model in its entirety. Although it should be noted that the TRANSYT and PREDCO models have already been independently validated. However, most components of the PREDICT model suite use techniques comparable to, and in some cases better than, those described in the previous chapter. Therefore, it seems reasonable to suppose that the PREDICT model suit would at least perform reasonably, compared with other pollution modelling approaches.

In terms of the author's research, the TRANSYT and PREMIT models are assumed to be more than adequate for illustrating the characteristics of traffic pollution as reported in this thesis, and demonstrating the importance of representing emissions by driving mode.

Chapter 7
CONTROL STRATEGIES

7.1 INTRODUCTION

In the PREDICT project, following the development of the model suite, four environmentally sensitive traffic control strategies were designed and modelled. The objectives of these strategies were to:

- reduce traffic emissions and improve urban air quality levels; and
- maintain transport efficiency.

Each PREDICT control strategy was developed with particular environmental objectives in mind. These objectives aimed to reduce pollution levels over a wide area, within an environmentally sensitive area, and at particular "hot spots". Each of these aimed to address the concern over urban air pollution, and assist in achieving the mandate of air quality standards. These policy objectives have an adjunct that traffic efficiency on the network should not suffer significant adverse effects as a result of an environmental control strategy.

These strategies aim to provide short to medium term improvements in urban air quality. It was also envisaged that some of these concepts could be revised in the future, reflecting developments in vehicle technology, and changes in emission and air quality legislation. In these cases, the advanced transport telematics (ATT) infrastructure needed for strategy implementation could be adapted to complement transport planning policies aimed at long term improvements in air quality.

Four strategies were designed to meet the above objectives (PREDICT Consortium, 1990). They were evaluated using the PREDICT model suite and central Athens as the case study area. The strategies modelled were:

1) environmental optimisation of traffic signal timings;

2) pollution sensitive traffic rerouting;

3a) the introduction of clean vehicles; and

3b) environmental area licensing.

These strategies are based on varying degrees of technological innovation in urban traffic control, monitoring systems, and vehicle emission reduction devices. For example, at the most basic level, strategy one aims to improve air quality using existing traffic control systems and vehicle designs. While strategy 3b makes use of a combination of state-of-the-art advanced transport telematics and vehicle designs which have lower emissions. These strategies are described in the following sections.

7.2 OPTIMISATION OF TRAFFIC SIGNAL TIMINGS

The first PREDICT strategy involves the adjustment of traffic signal timings to reduce air pollutant emissions. This strategy is divided into two sub-strategies with objectives to minimise:

* pollution over an urban area (strategy 1a); and

* pollution at links and intersections with high emissions (strategy 1b).

These are achieved by the strategic implementation of environmentally optimised traffic signal plans, developed using the TRANSYT model in conjunction with the PREMIT emissions model. These objectives aim to reduce air pollution levels, without significantly reducing a traffic network's efficiency.

TRANSYT 8 does not include any direct measure of emissions within its traffic performance index. Effects on pollutant emission levels therefore need to be taken into account by running TRANSYT in tandem with the PREMIT emissions model.

Environmentally optimised signal plans may then be derived through an iterative process involving adjustments to traffic signal timings.

Network-wide Pollution Reduction - Strategy 1a

The concept of this strategy is to adjust traffic signal timings in such a way that total network emissions, of one or more pollutants, are reduced whilst maintaining an adequate degree of efficiency in the traffic network. The specific reductions to be achieved would probably be set by the decision maker(s) responsible for transport and air pollution policy. Thresholds are likely to be different for each pollutant and the methodology used to determine such values may be specific to the decision maker and particular air pollution problems. For example, a city aiming to achieve a reduction in the severity and number of air pollution episodes involving photochemical smog may wish to establish a total network emission threshold for nitrogen oxides and hydrocarbons.

The strategy aims to reduce emissions by making significant adjustments to urban driving patterns. This is implemented by making adjustments to traffic signal timings.

Conventional thinking is based on the hypothesis that optimisation of the traffic network to reduce congestion (stops and delays) will also reduce pollutant emissions. Strategy 1a incorporates this philosophy and additional concepts. Evaluation of this strategy explored the validity of such concepts and the potential benefits and disadvantages to traffic efficiency and network emissions.

In practical terms, implementation of this strategy at a network-wide level, could be accomplished using either off-line or on-line automatic selection of environmentally optimised signal plans. Off-line selection of fixed time signal plans may involve several changes of plan during a normal weekday.

With on-line automated plan selection, information received from on-street detectors at critical intersections would be used to select the most appropriate signal plan from a pre-determined library. Although this method provides a degree of self-adjustment to prevailing traffic conditions, it requires preparation of signal plans off-line.

The process of developing environmentally optimised signal plans could be improved if a measure of air pollutant emissions was built into TRANSYT's traffic performance index. This would incorporate a feedback loop directly from the PREMIT emissions model. Implementation of environmentally optimised signal settings calculated in real-time would also be conceptually feasible if adaptive systems, such as the SCOOT system, were linked into a suitably adapted emissions model.

Pollution Reduction at Hot Spots - Strategy 1b

Within an urban area, pollutant emissions and concentrations are unlikely to be uniformly distributed across the network. High pollution levels may occur on links with high traffic flows, and at busy intersections. These locations are often referred to as pollution "hot spots".

This strategy involves adjusting signal settings at pollution hot spots in order to reduce pollution levels at those particular locations. Critical links are given favourable signal settings, even if this results in a slight degradation to other parts of the road network.

In a practical context, this involves intervention in the signal plan development. Hot spots on the road network are identified based on an initial run of the PREDICT model suite. Intervention is then required to reduce pollution levels at these points. For example, within TRANSYT weighting values for delay and stops can be adjusted for particular links. The theory was that by reducing congestion, reductions in pollutant emissions may result. The validity of this theory was tested in the author's research.

7.3 POLLUTION-SENSITIVE TRAFFIC REROUTING

This strategy is based on pollution-sensitive rerouting of traffic around a congested central area. High traffic flows and congestion are responsible for high levels of pollutants for a number of reasons:

- the more vehicles there are, the more contributors there are to the pollutant emissions;
- slow moving traffic is responsible for high emission rates of carbon monoxide and hydrocarbons - slow speeds result in the highest emissions (in terms of quantity per unit distance) of these pollutants when cruising; and
- idling vehicles in congested networks contribute substantial additional emissions of carbon monoxide and hydrocarbons.

On the basis of these factors, this strategy is aimed at reducing congestion levels and, hence, pollution levels within a defined area. The strategy is activated during, or in advance of, an air pollution episode. Advanced strategy activation is based on forecasts from PREDICT model predictions.

It also aims to achieve these reductions without significant detrimental impacts to traffic and air quality on links around the periphery of the defined area. Specific aspects for ensuring this may include increased road capacity for particular peripheral routes; and the use of in-vehicle route guidance systems and Variable Message Signs (VMS) supplied with optimum rerouting information from a traffic control centre.

This strategy is dependent on real-time monitoring of pollution levels and short-term prediction of future trends. It utilises a monitoring system of the type discussed in the PREDICT project (PREDICT consortium, 1989d), in conjunction with the PREDICT model suite. When pollutant concentrations are predicted to reach unacceptable levels due to prevailing traffic and meteorological conditions, the re-routing strategy would be activated.

In practical terms, the strategy is based on a network of VMS around the environmentally sensitive area. During strategy activation, these advise drivers of optimum diversions around the sensitive area.

The VMS may act as an advisory tool encouraging drivers to reroute around polluted areas. Alternatively, the strategy could be enforced by a system of flexible traffic cells to prevent through traffic passing through the sensitive area.

VMS would be positioned at all main access points between these cells, with minor access roads physically blocked to vehicular traffic. During periods when the strategy is in use, these variable message signs would display a "no entry" message, forbidding vehicle access between adjacent cells and thus preventing traffic from passing straight through the sensitive area.

Enforcement of the re-routing strategy would concentrate primarily on preventing the access between cells. Although this could be accomplished by routine police surveillance, a more effective system would use ATT enforcement technologies such as automated cameras, video capture systems or licence plate readers. Licence plate readers would offer a highly automated solution, avoiding the need for manual examination of photographs.

Alternatively, the enforcement system could be replaced by physical restrictions between traffic cells. For example, the main access points between cells could be equipped with automatic barriers, linked to the traffic control centre. When the strategy is activated the barriers would block the road, prevent vehicles passing between cells.

Vehicles authorised to pass between cells would be equipped with automatic vehicle identification (AVI) transponders. Roadside AVI readers would be used to detect the presence of such vehicles, then open the barrier and allow the vehicle to pass.

7.4 INTRODUCTION OF CLEAN VEHICLES

The objective of Strategy 3a is to produce a network-wide decrease in air pollution levels. This is based on a policy which specifies that all new vehicles must be "clean"; for example, all new vehicles should have emission reduction devices, such as catalytic converters and/or lean burn engines.

This would probably require appropriate legislation at national or pan-European level. Indeed, such legislation is now effective in the form of European Community Directives regulating emissions from new vehicle types. PREDICT modelled the impact of an evolving traffic fleet, which had an increasing proportion of vehicles fitted with catalytic converters.

7.5 ENVIRONMENTAL AREA LICENSING

Assuming that there is a gradual penetration of low emission ("clean") vehicles, area-wide emissions will gradually reduce, until offset by increasing traffic growth (Holman et al, undated; LTT, 1990). However, the rate at which a vehicle fleet is replaced may be relatively slow, taking several years. Hence, although the impact of Strategy 3a may be effective, it does not necessarily offer a rapid solution to existing air pollution problems.

Therefore, Strategy 3b imposes a restriction that all vehicles entering a defined environmentally sensitive area must be low emission vehicles. This offers an interim measure in European cities with severe air pollution problems, prior to achieving a complete fleet of low emission vehicles.

The strategy's system architecture is also sufficiently flexible to provide benefits beyond this interim period, by allowing stricter emission standards and strategies to be adopted. For example, later strategies may restrict areas to very low or zero emission vehicles.

In practical terms, "clean" vehicles wishing to enter the central area need to be fitted with AVI transponders. AVI readers, strategically placed around the environmentally sensitive area, ensure that only authorised vehicles are allowed access. Visitors who only make the occasional trip into the restricted area would be able to go to a hire booth and hire an AVI transponder for the duration they were in the restricted area, provided they could supply certification that their vehicle is clean.

Enforcement of the restriction involves using an automated camera, video surveillance or licence plate reading system. Vehicles that do not have clean status would be advised to reroute around the sensitive area by variable message signs. This aspect is implemented using the same approach as that of the traffic rerouting strategy.

The transponder, or a central computer database, would indicate that the vehicle has a valid clean status. However, a catalytic converter's performance is likely to deteriorate with time. A vehicle's "clean" status therefore needs to be reviewed periodically by approved inspection centres. This involves testing the vehicle's in-service emissions. Hence, to indicate the validity of a vehicle's clean status it is also necessary to include an expiry date, upon which the vehicle must be inspected. The expiry date would either be held in the transponder, or in a central computer database.

In order to support future environmental demands, later strategies may be based on very low or zero emission vehicles. Therefore, the transponder, or central database, would have to reflect the category of the vehicle (e.g. low, very low, or zero emission), as opposed to just a "clean" flag.

7.6 QUARTET FIELD TRIALS

Following the model based evaluation of the PREDICT strategies a demonstration plan was designed to test the strategies in a real-world environment (PREDICT consortium, 1990c and 1992). This led to the evaluation of strategies 2 and 3b in a real-world environment as part of the QUARTET field trials.

The ATT system architecture requirements, technology used in the demonstration, operational aspects, and evaluation methodology are described in detail in the project's reports (QUARTET consortium, 1992b, 1993a, and 1993b). This section outlines the APOLLON system architecture that was used for the environmentally sensitive traffic control strategies in QUARTET. The Athens APOLLON system design consisted of the following components:

* traffic data collection;

* meteorological data collection;

* environmental monitoring;

* central prediction and control systems;

* variable message signs (VMS);

* radio data system (RDS);

* in-vehicle route guidance;

* automatic vehicle identification (AVI) system; and

* a network integrating these sub-systems.

Many of the above sub-systems are common to both strategies being demonstrated. The data collection and monitoring sub-systems provide input to the central prediction and control systems. From this, short-term forecasts are derived and a suitable strategy is recommended. Based on these forecasts and recommendations, the system operator determines if an environmentally sensitive traffic control strategy needs to be activated, and if so which one.

The environmental area licensing restricts access to the environmentally sensitive area, allowing only clean vehicles to enter. Consequently, vehicles which are not clean, and would normally take a route through the sensitive area to reach their destination, are rerouted around this area. Hence, the environmental area licensing strategy makes use of a selective (for vehicles which are not clean) rerouting strategy, using the ATT infrastructure of the traffic rerouting strategy.

In a full scale implementation, the actual strategy approach to be adopted may be influenced by one or more of the following factors:

* the predicted severity of air quality deterioration resulting from a do-

nothing scenario (based on forecast traffic and meteorological conditions);

- the relative effectiveness, cost, and administration of the two strategies;
- and the political/social acceptability of each strategy.

Indeed, it is feasible to select both strategies for full scale implementation in a given urban environment. A particular strategy, or combination of strategies, would then be activated during periods of unfavourable traffic and environmental conditions.

Rerouting Strategy

The rerouting strategy incorporates all of the ATT infrastructure described above except the AVI system. A recommended strategy is selected by a strategy selection tool, but the system operator must make the decision to activate either the recommended strategy or an alternative strategy. A strategy will be activated in advance of a predicted air pollution episode, or when an air pollution episode is actually in progress.

When the strategy becomes active, variable message signs show traffic to rerouting details and optimum routes. RDS broadcasts transmit specific rerouting information for all trips that would otherwise have passed through the environmentally sensitive area. Vehicles equipped with route guidance systems are able to use this information to automatically provide the driver with an efficient alternative route.

Environmental Area Licensing

The environmental area licensing strategy uses all components of the APOLLON system. The criteria for strategy activation and operation is similar to that described for the traffic rerouting strategy. In a full-scale implementation an AVI system would be used to enforce access to the environmentally sensitive area, as described earlier.

7.7 SUMMARY

In PREDICT, four strategies were designed with the aim of improving urban air quality whilst maintaining the efficiency of the traffic network.

Strategy 1 aimed to improve air quality levels by developing traffic signal plans which take into account both traffic performance and pollutant emissions. This is a relatively low cost approach because in many cities a traffic signal network will already exist, and the strategy does not require vehicle modifications.

Reductions in traffic levels may give a significant reduction in pollutant emissions and this forms the philosophy of Strategy 2: traffic rerouting. When an air pollution episode is predicted to occur, through traffic will be rerouted around an environmentally sensitive area. This strategy uses variable message signs and RDS broadcasts, coupled with in-vehicle route guidance, to advise drivers to reroute.

A significant reduction in emissions may be achieved by developments in vehicle technology. This formed the basis for the introduction of clean vehicles (Strategy 3a); and environmental area licensing (Strategy 3b). Strategy 3a reflects national or pan-European legislation and a gradual introduction of low emission vehicles to the traffic fleet.

Strategy 3b defines an environmentally sensitive area in which only low emission vehicles are allowed. In the short to medium term, this may mean restricting access to vehicles which have a catalytic converter and/or lean burn engine. In the long term, the strategy could be modified to restrict access to very low and zero emission vehicles. This strategy uses the same technology as Strategy 2 plus an AVI system. Permitted low emission vehicles are fitted with AVI transponders to indicate their emissions status. Unauthorised, vehicles attempting to enter the area will be photographed by the AVI enforcement system.

The work of PREDICT led to the demonstration of strategies 2 and 3b in a real-world environment as part of the QUARTET Athens APOLLON field trial.

Chapter 8

MODELLING METHODOLOGY

8.1 INTRODUCTION

This chapter describes the methodology used by the author to model the impact of environmentally sensitive traffic control strategies. This includes general implementation aspects of the TRANSYT and PREMIT models, representation of the base case scenario, the specific methodology used for each strategy, and the data analysis methodology.

8.2 MODEL IMPLEMENTATION

The modelling was carried out using part of the PREDICT model suite: version 8 of the TRANSYT signal optimisation program; and version 3.07 of the PREMIT emissions model.

The software was run on an IBM PC AT compatible with 486DX processor running at 33MHz. A TRANSYT run with green time and offset optimisation enabled took of the order of ten minutes to run (whereas, in the initial PREDICT modelling the old PCs took about an hour!). The improved performance of the new PC, and the disk space available, allowed the author to investigate more options and conduct a more detailed investigation than was feasible at the time of the PREDICT project.

Many options were investigated by the author, much more than reported. For example, many TRANSYT runs were made with different stop and delay weights in order to find values which provided the most beneficial reduction in emissions, whilst having a reasonable impact on network efficiency. Of these, the most interesting options were presented in the results chapter.

The TRANSYT program was run directly from the DOS command prompt. PREMIT was run via a batch file. The batch file recorded comments for each run, recorded the input parameters used, and ran PREMIT several times to generate output files for total emissions from all driving modes (default output) and emissions from individual driving modes. The emissions output data by individual driving mode was very useful for assisting in the formulation and testing of hypotheses.

In some cases the batch file was also used to capture the detailed emissions data produced by PREMIT in its verbose mode. This additional information provided valuable evidence for formulating and testing hypotheses which aimed to explain the complex behaviour observed in traffic emissions. For example, in verbose mode, for each link of the network, PREMIT separates cruise emissions into those arising from vehicles which are delayed on the link, and those arising from vehicles that are not delayed. It also provides the average cruise distance available, to vehicles that are delayed.

8.3 BASE CASE

This section describes the base case scenario and the modelling aspects of this scenario. The base case represented existing conditions in the Athens study area. It provided a reference, against which the model predictions for various strategies could be compared.

Base Case Scenario

The base case represented the existing conditions within the defined study area. The study area contains a large number of signalized intersections, with signal timings coordinated using the TRANSYT model. It is also subject to vehicle restrictions, as it lies within the Daktylios controlled area of Athens.

The Athens Daktylios restriction operates in the central area defined by a ring road on its periphery. The scheme was introduced in September 1982 and has undergone a number of extensions since then, though the basic principle is the same. Vehicle entry is permitted on a given day according to the last digit of the number plate of the vehicle, such that each vehicle is banned on alternate days, Monday to Friday.

The current version of the scheme is based on an odd/even differentiation, with the permitted plate matching the date. The scheme operates from 07.00 to 20.00 and includes taxis as well as cars and lorries. Motorcycles and buses are the only general classes of vehicle that are exempt. However, there are some exemptions for specific individuals (doctors, journalists, tourists). The ban also applies to the cars of residents living inside the area, but it only affects moving traffic, so prohibited vehicles may be left parked on the street during restricted hours.

The authorities were initially prompted to introduce the scheme because of a deterioration in environmental conditions, with the objective of reducing car traffic by 50 percent. Although early monitoring studies did find significant reductions in traffic, these were not as great as anticipated. Nevertheless, vehicle-kilometres decreased by around 15 percent and vehicle-hours dropped by 22 percent, showing worthwhile reductions. Reductions in some types of pollutant were also recorded in the first year.

However, a substantial growth has occurred in traffic in the area since 1983. This is thought to be related to a general growth in car ownership in the Athens region. Nevertheless, traffic levels are lower than they would have been in the absence of the scheme. There is no information on the type of adaptations that people have made in response to the scheme (eg. re-routing, re-timing, or mode switching).

Original TRANSYT input files representing this scenario were supplied in 1989 by Dr Stathopoulos of the National Technical University of Athens, as were miscellaneous network parameters (average lane capacities, vehicle spacing in queues and acceleration and deceleration rates). Files were supplied for each area of the Athens study network. These areas were: North, West, Centre, South and Ring (the ring road).

Modelling Aspect

Although the work in PREDICT modelled all areas of the Athens study network, the author's results presented in this thesis have been confined to the central area. This consisted of approximately 100 TRANSYT links and provides a conveniently sized network for research purposes and analysis of the emissions data. This area is shown in the maps of Appendix A.

The flows in the TRANSYT input file represent morning peak flows for this area. The TRANSYT model is run with flow and speed scaling factors set to unity and the optimisation is set to full optimisation (offsets and green times). This provides the 'optimum' signal timings for this network, such that the performance index is minimised. The weights assigned to delay and stops were 55 and 50 respectively.

The results of the TRANSYT run were processed by the PREMIT emissions model. The Greek traffic emissions data and miscellaneous traffic parameters were used for this scenario (and all following scenarios, with the exception of Strategy Three).

The output of this run represented the base case data set for TRANSYT statistics, and link and total network emissions. All emissions output data produced by PREMIT were expressed in units of grams per minute (g/min).

Emissions Input Data

The emissions input data came from several sources. The primary sources of emission input data were as follows. The emissions for the petrol engine cars were obtained from an existing emissions inventory, modified with data supplied by the Aristole University of Thessaloniki (Pattas and Samaras, 1987). These data were based on work carried out under a contract with the Commission of the European Communities DG XI programme (NTUA, 1988). A graphical representation of data used has also been reported by Stathopoulos (1989). The emissions for taxis and buses were based on a German study by the Institut Fuer Stadtbauwesen (1985).

Emissions from petrol engine cars equipped with catalytic converters were obtained directly from the Saab car manufacturer, in June 1990. General purpose studies were unsuitable for this type of emission data as their results were provided as emissions over an entire driving cycle or for an average cruise speed only, as opposed to specific emission rates for each driving mode. Hence, the need to approach the manufacturer directly.

Supplementary data sources were also used to provide emission rates for ranges or driving modes not covered by the above sources. These data sources were also used to provide comparative and sensitivity tests (QUARTET consortium, 1992).

The PREDICT study team had great difficulty obtaining vehicle emission data for all driving modes and vehicle types. In particular, acceleration and deceleration emission data were only available for petrol engine cars. Therefore, these data were also used to represent diesel vehicles. Whilst not being ideal, there were three justifications to support this decision. Firstly, while emissions from diesel powered cars are lower than those from petrol cars, the larger exhaust volume from buses offsets this and overall diesel emissions are comparable to petrol. This assumption has been used by others (Watkins, 1991). Secondly, the proportion of petrol engine cars in the Athens fleet was the dominant factor. The fleet composition was: 57 percent petrol engine cars; 31 percent diesel engine cars; and 12 percent diesel engine buses. Finally, the proportion of total emissions arising from these two driving modes was, in general, less than those arising from cruise and idling.

Details of emission data sources, variations by vehicle category and state of maintenance, and sensitivity to driving mode and speed have been discussed in QUARTET Deliverable 2 (QUARTET consortium, 1992).

8.4 ENVIRONMENTAL SIGNAL OPTIMISATION

The modelling methodology used for Strategy 1 is described in two parts: signal optimisation for reducing total network emissions; and signal optimisation for reducing emissions on links which have the highest emissions, these were named hot links.

Network Emissions

Several sensitivity tests were carried out to investigate how total network emissions varied as a result of the following scenarios:

- an unoptimised network;
- flow scaling;
- cruise time (speed) scaling;
- delay to stop weight ratios; and
- different cycle times.

Systematic changes were made to the base case TRANSYT input file to represent the above scenarios. PREMIT was run with the corresponding TRANSYT output data, whilst keeping all other input parameters constant.

To model the impact of an unoptimised network on emissions, TRANSYT's optimisation and 'equisat' options were disabled. This meant that signal timings specified on the TRANSYT input cards were used, as opposed to TRANSYT automatically adjusting signal timings to give optimum settings which minimise the performance index.

Flow scaling was modelled by running TRANSYT with flow scaling factors of 50, 75, 80, 90, 110 and 120 percent. This causes TRANSYT to scale the input flows by the specified factor and then optimise the network based on the scaled flows. Of course, a flow scaling factor of 100 percent represented the base case scenario.

Cruise time scaling alters the free flow link cruise times, and allowed the sensitivity of emissions to cruise speed to be investigated. Model runs were made for cruise time scaling factors of 50, 75, 150 and 200 percent.

The delay to stop weight ratios were varied by changing the network cost values for stops and delay. Ratios of 0.01, 0.1, 1, 10 and 100 were used. This tested the effect of reducing network delay, as opposed to reducing the number of vehicles stopped, and vice-a-versa.

Finally, the impact of different cycle times were tested. The cycle times tested were 90 (base case), 100, 120, 140, 150, 160, 170, 180 and 200 seconds. The 180 second cycle time corresponded to the value chosen by TRANSYT, when its automatic optimum cycle time and double node cycling option was enabled.

Hot Links

Links were sorted by carbon monoxide emission rate and the top twenty links were arbitrarily defined as hot CO links. A similar process was used to determine the hot NOx links. Hot HC links were not specifically identified because HC emissions follow a similar pattern to CO emissions. Therefore, hot CO links were also expected, in general, to correspond to hot HC links.

These links were highlighted on maps of the central Athens area to obtain a clear picture of where the hot links were and where hot links would be competing for green time with other hot links.

A set of hypotheses were developed and used to test different strategies that aimed to reduce emissions of CO and NOx, on hot CO and NOx links respectively. Many tests were performed but only those that represented effective and practical scenarios were described in detail in the results chapter.

The analysis had indicated that CO (and HC) emissions were very sensitive to delay, especially for links near saturation. Consequently, strategies that aimed to reduce the delay on hot links were tested. This involved assigning higher delay and stop weights to hot CO links by setting the delay and stop weight scaling factors on the TRANSYT input 'cards' corresponding to the hot links. Various combinations of delay and stop weight scaling factors from the maximum of 9999 to 200 were tried.

A similar approach was adopted with hot NOx links. However, the mechanisms behind NOx emissions showed a behaviour different to that for CO and HC emissions. This behaviour was harder to understand and eventually a strategy aimed at increasing the number of stops on hot NOx links was investigated.

8.5 ENVIRONMENTAL AREA LICENSING

This strategy results in an environmentally sensitive area where all petrol engine cars are fitted with a catalytic converter. Therefore modelling of this strategy involved modifying a copy of the emissions input file to include emissions from petrol engine cars with catalytic converters. The emissions from non-catalyst petrol engine cars were removed by changing its fleet composition percentage from 57 percent to 0 percent. The composition value for catalyst petrol cars was set to 57 percent.

The base case TRANSYT output file is used along with the modified emissions file to run the PREMIT emissions model and establish the emissions as a result of the environmental area licensing strategy.

8.6 DATA ANALYSIS

The above sections have described how the emission output files were generated for each strategy; this section describes how they were analyzed. This analysis was mainly based around the use of Lotus 123 spreadsheets.

In order to import the data (text files) into a 123 spreadsheet the emissions output files had to be converted into a formatted text file suitable for 123. The author created a program to automate the conversion from the PREMIT output format to the 123 import format. This program was run for each PREMIT output file to be analyzed using 123.

A number of spreadsheets were set up for the different sensitivity tests, strategies and options within strategies. Data were sorted using 123 by CO emissions and NOx emissions respectively. Graphs were plotted of link emissions to establish the distribution of link emissions and the relationships between pollutants. Graphs were plotted of network emissions against 'sensitivity' parameter (e.g. flow and speed scaling). As were changes from base case and emissions for each driving mode.

Ratios between network emissions of CO:NOx, HC:NOx and CO:HC as a function of flow scaling factor were tabulated and plotted.

In order to try and assist the author postulate some hypotheses a number of correlations between network emissions and network traffic parameters (TRANSYT summary totals) were tested, as were correlations at the link level. However, many of these proved unsuitable in terms of the limited amount of data given the number of 'independent' variables. In cases where a correlation may have been feasible, between link traffic and emission data, the correlations were often poor and/or inconsistent from strategy to strategy. The link correlations also required the conversion of the output section of the TRANSYT output file to the 123 import format, followed by manual editing in the spreadsheet to take care of unusual field values, reduced output flows and link totals (where several TRANSYT links exist between a given pair of nodes). This manual process was awkward and very time consuming. For these reasons, it was decided not to use such correlation factors in the data analysis methodology.

The whole analysis process required considerable manual intervention and was extremely time consuming given the number of modelling runs done and the vast amount of data generated. As the author's research was of an innovative nature part of the methodology, and analysis procedure, had to be modified throughout the course of the work. For example, it was not initially obvious which factors were significant, and which may or may not be correlated with other factors. Therefore, by the very nature of this research, the process could not be automated as it was unknown what the analysis would involve. Further, as the author's research progressed from strategy to strategy the important factors requiring analysis changed to some extent.

The results of the modelling and data analysis are presented and discussed in the results chapter.

Chapter 9
RESULTS

9.1 INTRODUCTION

This chapter presents the results of the author's modelling work, based on the PREMIT emissions model and the methodology described in the previous chapter. The results include sensitivity tests, signal timings to reduce network and hot link emissions, and the impact of the environmental area licensing strategy. These results are discussed in the final section of this chapter.

The TRANSYT and PREMIT output data corresponding to these results are included in Appendices B and C respectively. The translation between TRANSYT link numbers and the node numbers used in the PREMIT output was achieved using the link-node translation table included in Appendix D. The modelling work for the pollution sensitive traffic rerouting strategy was not carried out by the author, but for the sake of completeness it has been included as Appendix E.

9.2 BASE CASE

The base case, as described in the previous chapter, represented the existing Athens scenario for the central area. This scenario was used as a reference by which the effectiveness of various strategies could be assessed.

The traffic network values, produced by TRANSYT, for this scenario were:

total time spent (pcu-h/h)	1125.6
mean journey speed (km/h)	11.8
total uniform delay (pcu-h/h)	267.6
total random + over-saturation delay (pcu-h/h)	234.3

The TRANSYT output file representing the base case scenario had four saturated[1] links and seven links were flagged as having excessive queue lengths[2]. The total pollution emission rates, expressed in grams per minute, for this network were:

carbon monoxide (CO)	7772
hydrocarbons (HC)	890
nitrogen oxides (NOx)	405

The approach used by the PREMIT emissions model is more detailed than that used by an average speed emissions model. Therefore, it is interesting to plot the PREMIT predictions against average speed, to see if emissions appear to correlate with average speed. The average speed corresponds to the link length over total link journey time, which includes delay.

Figure 9.1 shows the PREMIT predictions for emissions per pcu (passenger car unit) against average link speed. These emissions were determined by dividing link emissions by link flow.

For CO and HC, at low average speeds there is clearly a wide spread in emission rates. Overall though, there is an underlying trend showing relatively high emissions at low average speeds and a reduction in emissions with increasing average speed. Emissions of HC show a similar trend to that of CO. Whereas, emissions of NOx do not follow these trends. Indeed, the plot of NOx emissions illustrates that an algorithm based on average speed would not be suitable for predicting NOx emissions.

9.3 NO OPTIMISATION SCENARIO

This section describes the worst case scenario that the author modelled. This involved running TRANSYT with the base case input data, but with optimisation disabled so

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[1] The author has used the term saturated to refer to links which have a degree of saturation equal to, or greater than, 95 percent.

[2] Taken from the average excess queue column of the TRANSYT output. Excessive queue lengths are indicated by a '+' in this field.

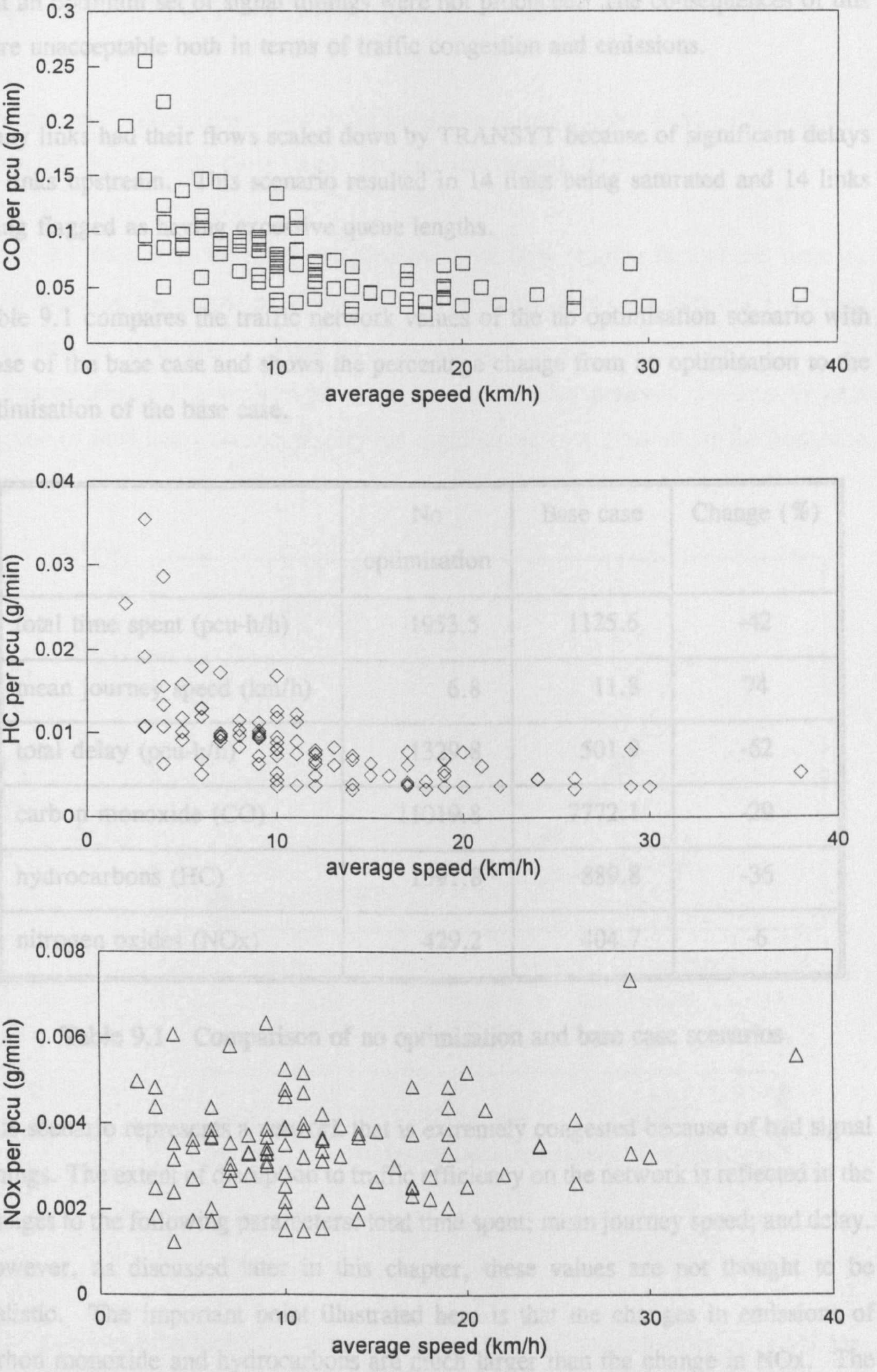

Figure 9.1 Link emissions against average link speed

that an optimum set of signal timings were not produced. The consequences of this were unacceptable both in terms of traffic congestion and emissions.

Many links had their flows scaled down by TRANSYT because of significant delays on links upstream. This scenario resulted in 14 links being saturated and 14 links being flagged as having excessive queue lengths.

Table 9.1 compares the traffic network values of the no optimisation scenario with those of the base case and shows the percentage change from no optimisation to the optimisation of the base case.

	No optimisation	Base case	Change (%)
total time spent (pcu-h/h)	1953.5	1125.6	-42
mean journey speed (km/h)	6.8	11.8	74
total delay (pcu-h/h)	1329.8	501.9	-62
carbon monoxide (CO)	11019.8	7772.1	-29
hydrocarbons (HC)	1391.8	889.8	-36
nitrogen oxides (NOx)	429.2	404.7	-6

Table 9.1 Comparison of no optimisation and base case scenarios

This scenario represents a network that is extremely congested because of bad signal timings. The extent of disruption to traffic efficiency on the network is reflected in the changes to the following parameters: total time spent; mean journey speed; and delay. However, as discussed later in this chapter, these values are not thought to be realistic. The important point illustrated here is that the changes in emissions of carbon monoxide and hydrocarbons are much larger than the change in NOx. The reason for this behaviour will become apparent later on in this chapter, where more detailed investigations of link emissions have been carried out.

9.4 SENSITIVITY TO FLOW

This section illustrates the sensitivity of emissions to traffic flow. Flow scaling factors of 50, 75, 80, 90, 100 (base case), 110 and 120 percent were used.

Figure 9.2 illustrates the relationship between the flow (scaling factor) and network delay based on the output of TRANSYT. The figure shows the network's uniform delay and its total delay. Total delay is the sum of uniform, random and over-saturation delay. The random plus over-saturation delay behaves non-linearly as a function of flow and increases rapidly for slight increases in flow above the base case level.

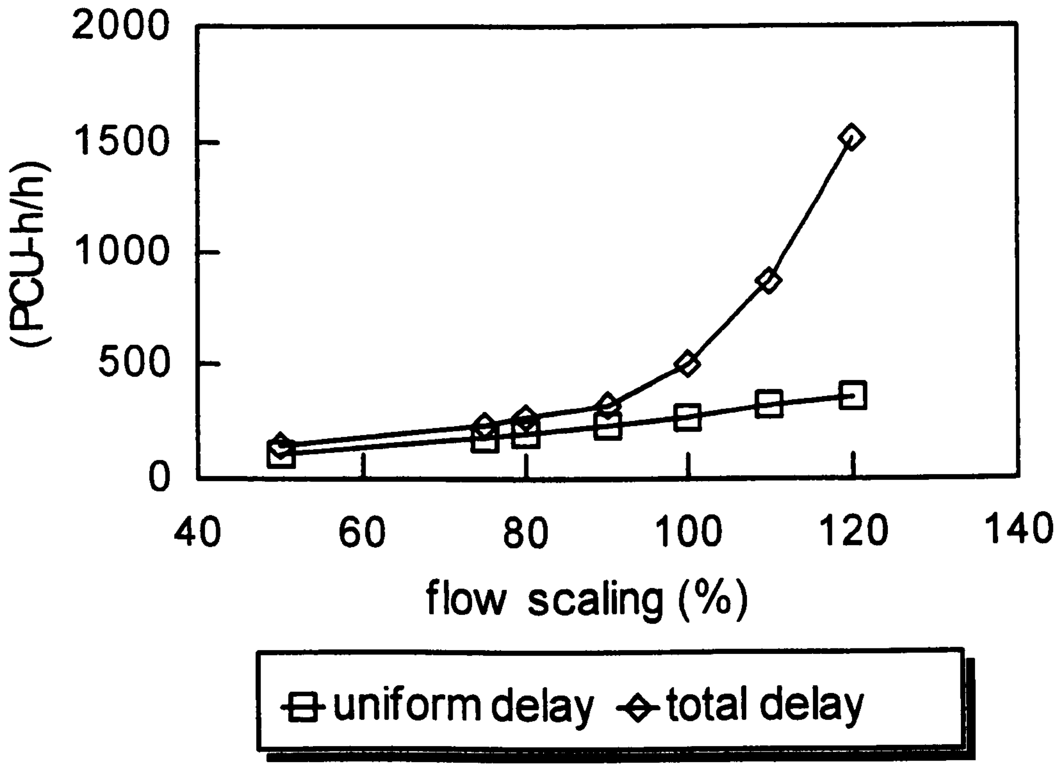

Figure 9.2 Network delay as a function of flow

This figure has been included because delay has a significant influence on emissions. In particular, idling emissions are directly proportional to delay and therefore idling emissions as a function of flow have a similar relationship to that of delay.

Total Network Emissions

Figure 9.3 illustrates the relationship between total network emissions and flow, for each of the pollutants CO, HC and NOx. A number of important relationships are illustrated in this figure. The pollutants CO and HC behave in a similar non-linear manner to each other, whilst NOx behaves in a linear manner.

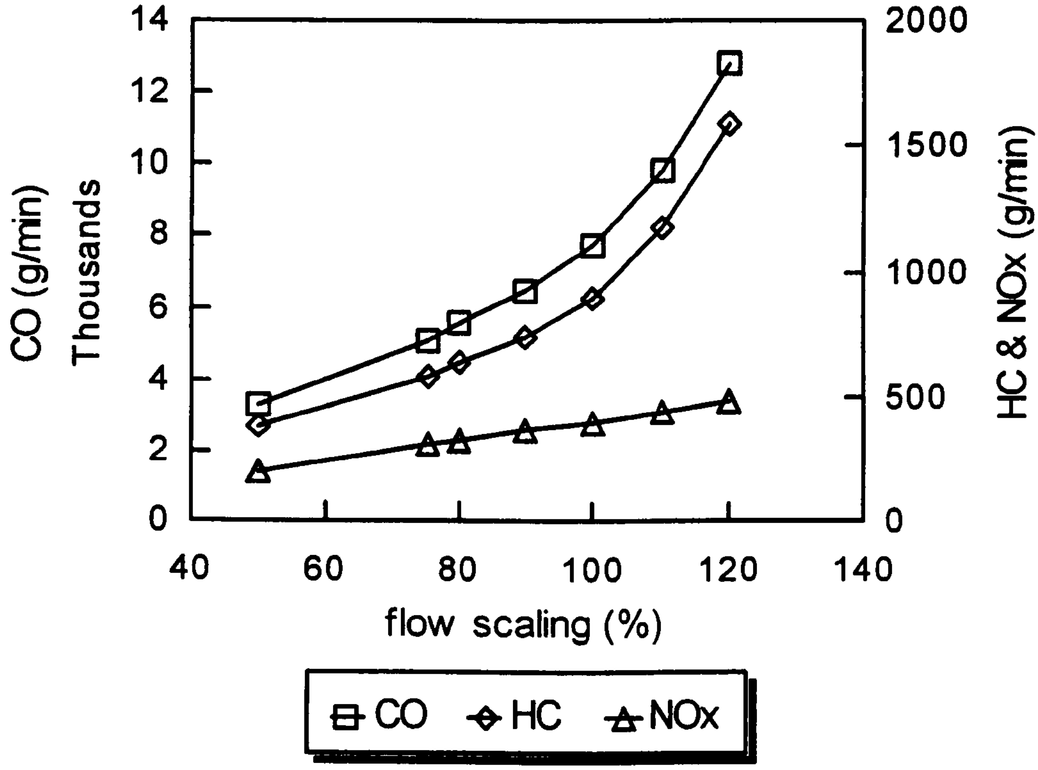

Figure 9.3 Network emissions as a function of flow

The percentage change in emissions, relative to the base case, is shown in Figure 9.4. This shows that the percentage changes are relatively similar for each pollutant for flows below the base case level. However, because of the non-linear relationship of CO and HC to flow, the changes in CO and HC above the base case flow level are much larger than those for NOx.

When the flow was reduced to 50 percent of the base case level, the emissions fell from the base case by 58, 57 and 48 percent for CO, HC and NOx respectively. While an increase in flow to 120 percent of the base case caused emissions to rise by 65, 79 and 22 percent for CO, HC and NOx respectively.

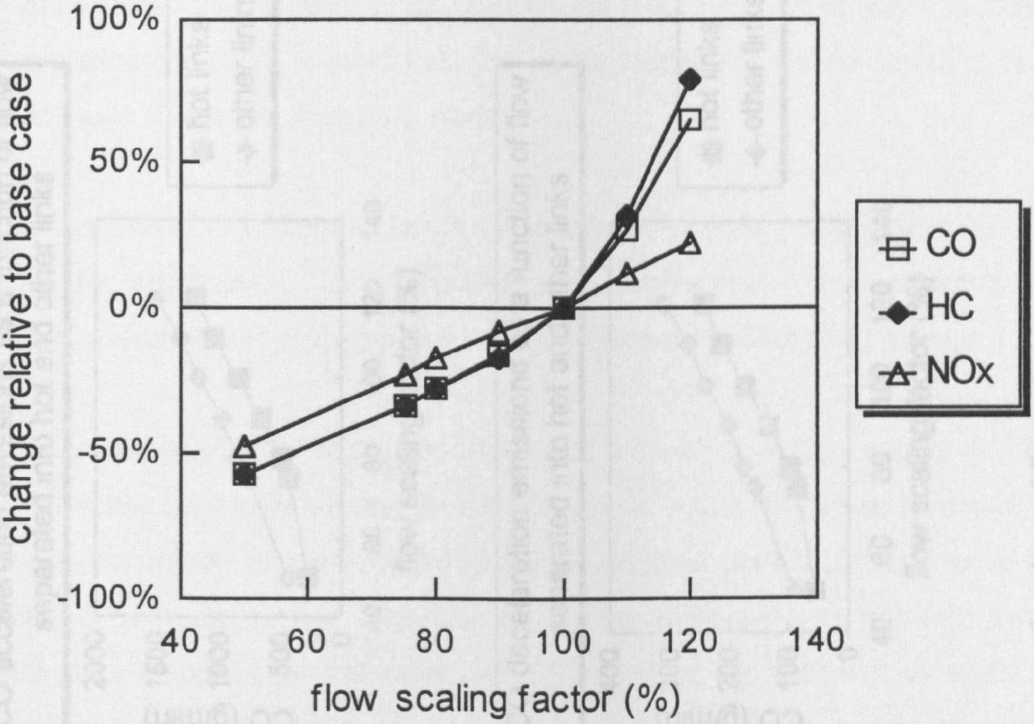

Figure 9.4 Percentage change in emissions as a function of flow

Emissions by Driving Mode

The emissions of CO by driving mode are illustrated in Figure 9.5. The emissions have also been split into two parts: the total emissions from the top 20 links with the highest emission rate (hot links); and the total emissions from the remaining links. This illustrates a number of important points about the emissions from each driving mode.

Cruise emissions of CO initially increase as the flow on the network increases. This is because the number of vehicles cruising, and the vehicle-kilometres travelled during cruising, initially increases with flow. However, as the flow continues to increase, the degree of saturation, stops and queue length on links within the network begins to increase. Hence the proportion of time spent by vehicles cruising begins to decrease as the proportion of time spent decelerating, idling and accelerating increases. Also, the larger queue lengths result in the distance available for cruising being shorter. This is reflected by the cruise emissions reaching a maximum and then

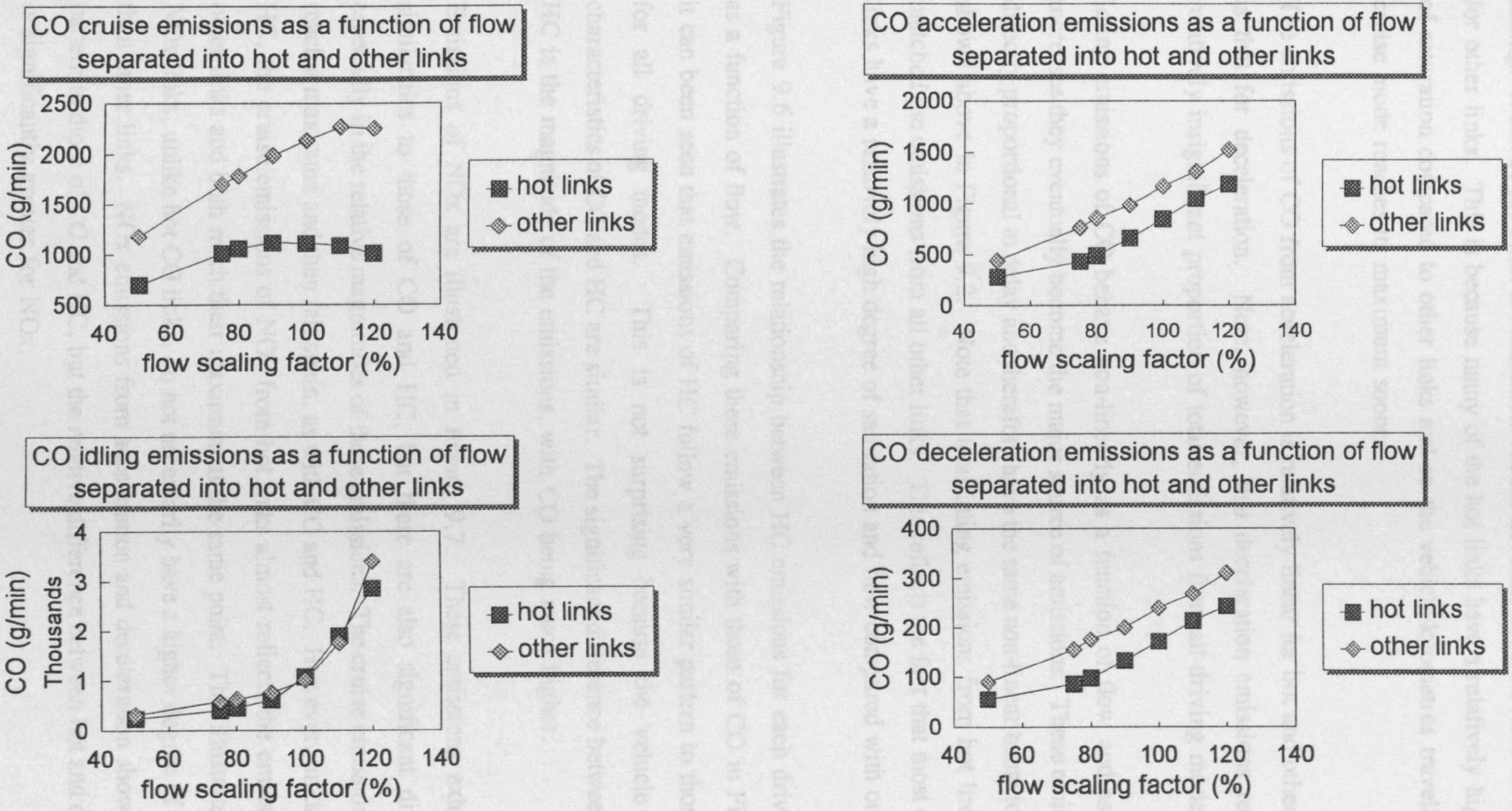

Figure 9.5 CO emissions by driving mode as a function of flow

falling. It can be seen that the maximum for the hot links occurs before the maximum for other links. This is because many of the hot links have a relatively high degree of saturation compared to other links and so the vehicle-kilometres travelled in the cruise mode reaches its maximum sooner.

The emissions of CO from acceleration is relatively linear for hot and other links, as is that for deceleration. Note, however, that deceleration emissions represent a relatively insignificant proportion of total emissions from all driving modes.

Idling emissions of CO behave non-linearly as a function of flow and as the flow increases they eventually become the major source of emissions. These emissions are directly proportional to delay and therefore have the same non-linear behaviour as that shown above in Figure 9.2. Note that total idling emissions from hot links almost matched the emissions from all other links. This reflects the fact that most of the hot links have a relatively high degree of saturation and flow compared with other links.

Figure 9.6 illustrates the relationship between HC emissions for each driving mode as a function of flow. Comparing these emissions with those of CO in Figure 9.5, it can been seen that emissions of HC follow a very similar pattern to those of CO, for all driving modes. This is not surprising because the vehicle emission characteristics of CO and HC are similar. The significant difference between CO and HC is the magnitude of the emissions, with CO being much higher.

Emissions of NOx are illustrated in Figure 9.7. These emissions exhibit some similarities to those of CO and HC, but there are also significant differences, especially in the relative magnitudes of these emissions. The cruise emissions of NOx reach a maximum and then fall again, as with CO and HC. However, unlike CO and HC, the cruise emissions of NOx from hot links almost reflects the emissions from other links and both reach their maximum at the same point. This illustrates that hot NOx links, unlike hot CO links, do not necessarily have a higher degree of saturation than other links. NOx emissions from acceleration and deceleration show a similar pattern to those of CO and HC, but the relative difference between hot and other links is significantly greater for NOx.

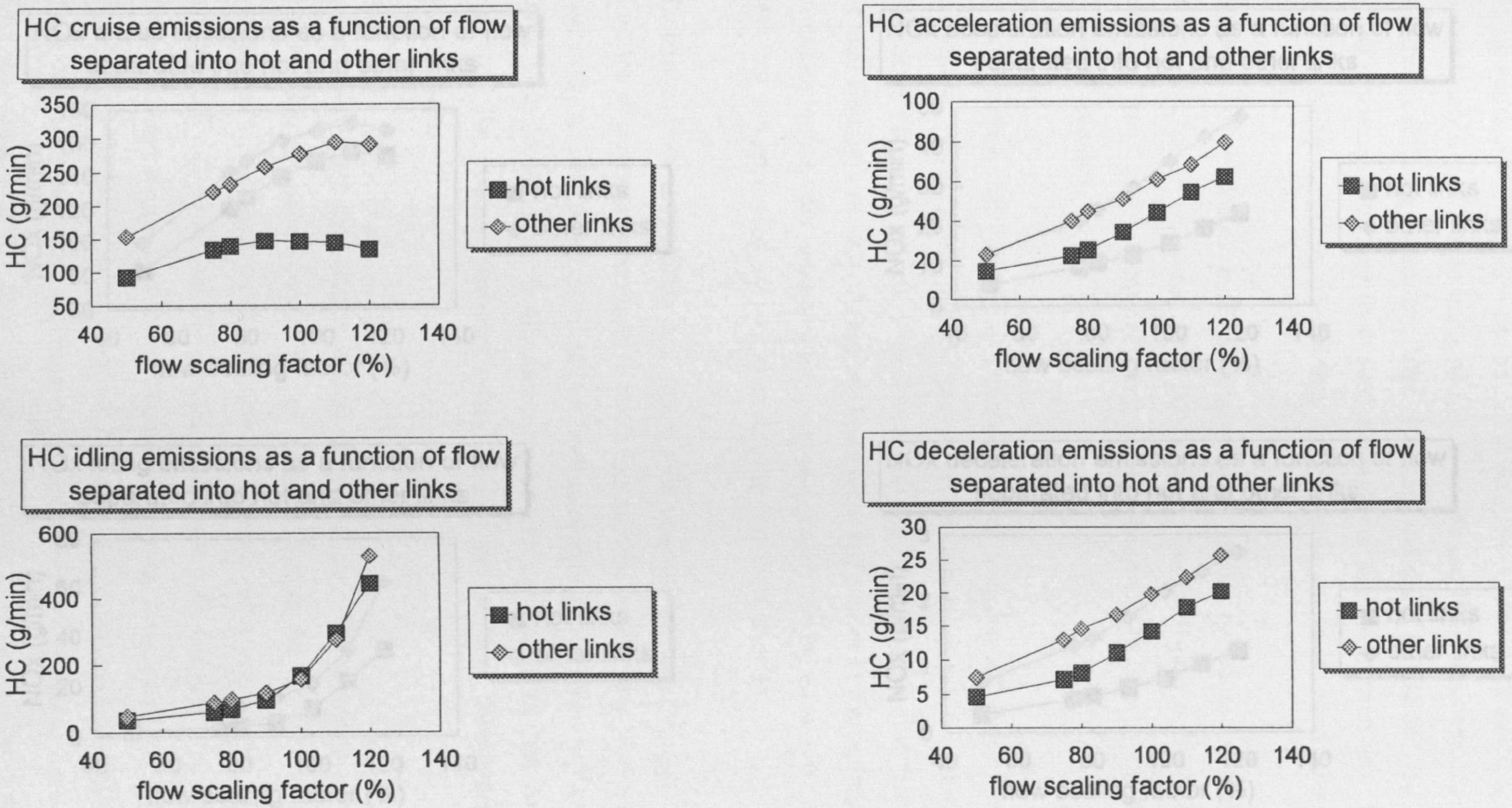

Figure 9.6 HC emissions by driving mode as a function of flow

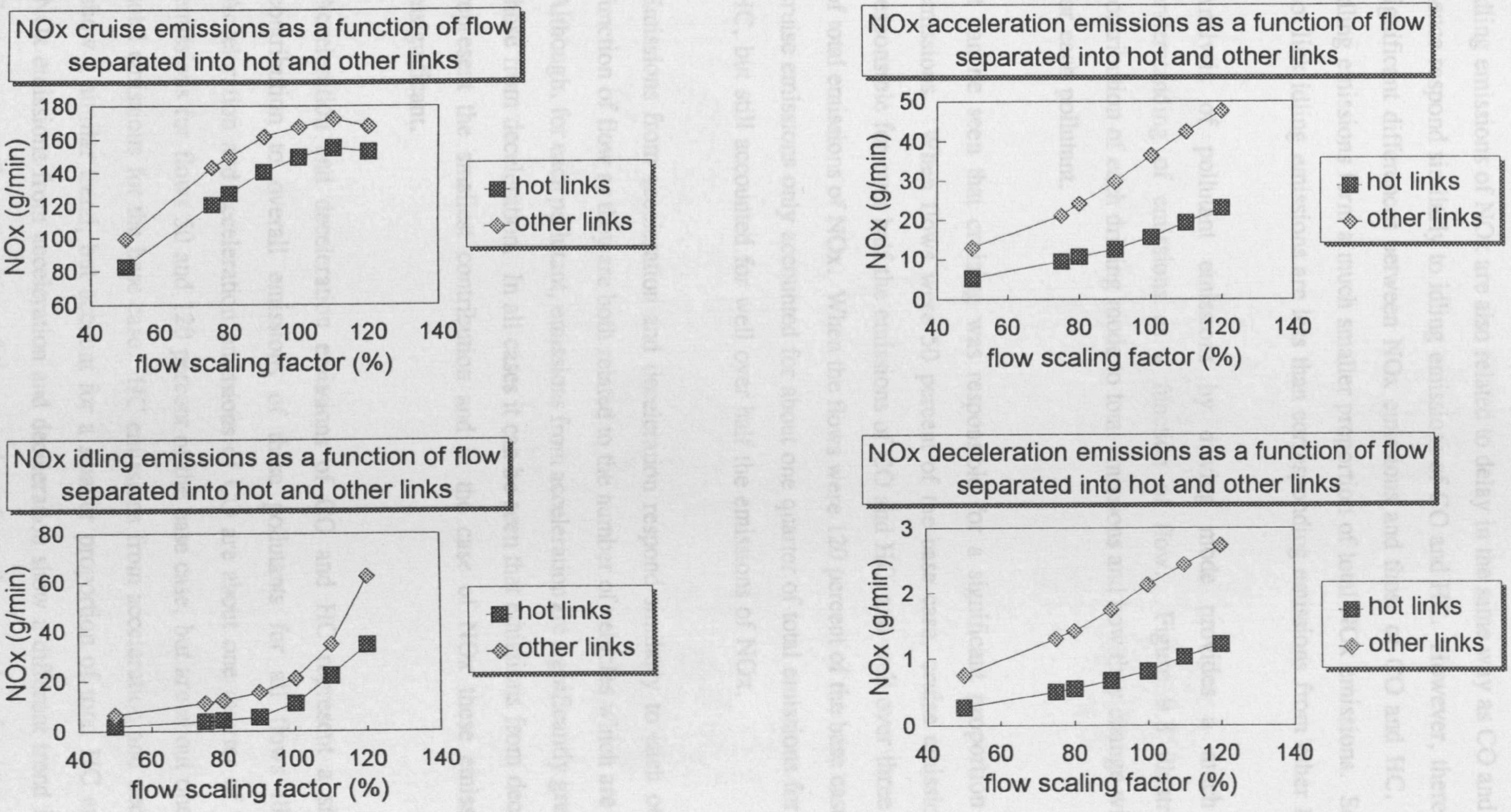

Figure 9.7 NOx emissions by driving mode as a function of flow

Idling emissions of NOx are also related to delay in the same way as CO and HC and hence respond similarly to idling emissions of CO and HC. However, there are two significant differences between NOx emissions and those of CO and HC. Firstly, idling emissions form a much smaller proportion of total NOx emissions. Secondly, hot link idling emissions are less than corresponding emissions from other links.

Analysis of pollutant emissions by driving mode provides a much clearer understanding of emissions as a function of flow. Figure 9.8 illustrates the contribution of each driving mode to total emissions and how they change with flow, for each pollutant.

It can be seen that cruising was responsible for a significant proportion of total emissions. When flows were 50 percent of the base case, cruise emissions were responsible for over half the emissions of CO and HC, and well over three quarters of total emissions of NOx. When the flows were 120 percent of the base case values, cruise emissions only accounted for about one quarter of total emissions for CO and HC, but still accounted for well over half the emissions of NOx.

Emissions from acceleration and deceleration respond similarly to each other as a function of flow as they are both related to the number of vehicles which are stopped. Although, for each pollutant, emissions from acceleration are significantly greater than those from deceleration. In all cases it can be seen that emissions from deceleration represent the smallest contribution and in the case of NOx these emissions are insignificant.

Acceleration and deceleration emissions of CO and HC represent a significant contribution to overall emissions of these pollutants for all flows illustrated. Acceleration and deceleration emissions of CO are about one quarter of total CO emissions for flows 50 and 120 percent of the base case, but are about one third of total emissions for the base case. HC emissions from acceleration and deceleration show a similar trend, but account for a smaller proportion of total HC emissions. NOx emissions from acceleration and deceleration show a different trend in that as flow increases the proportion of the emissions from these modes also increases.

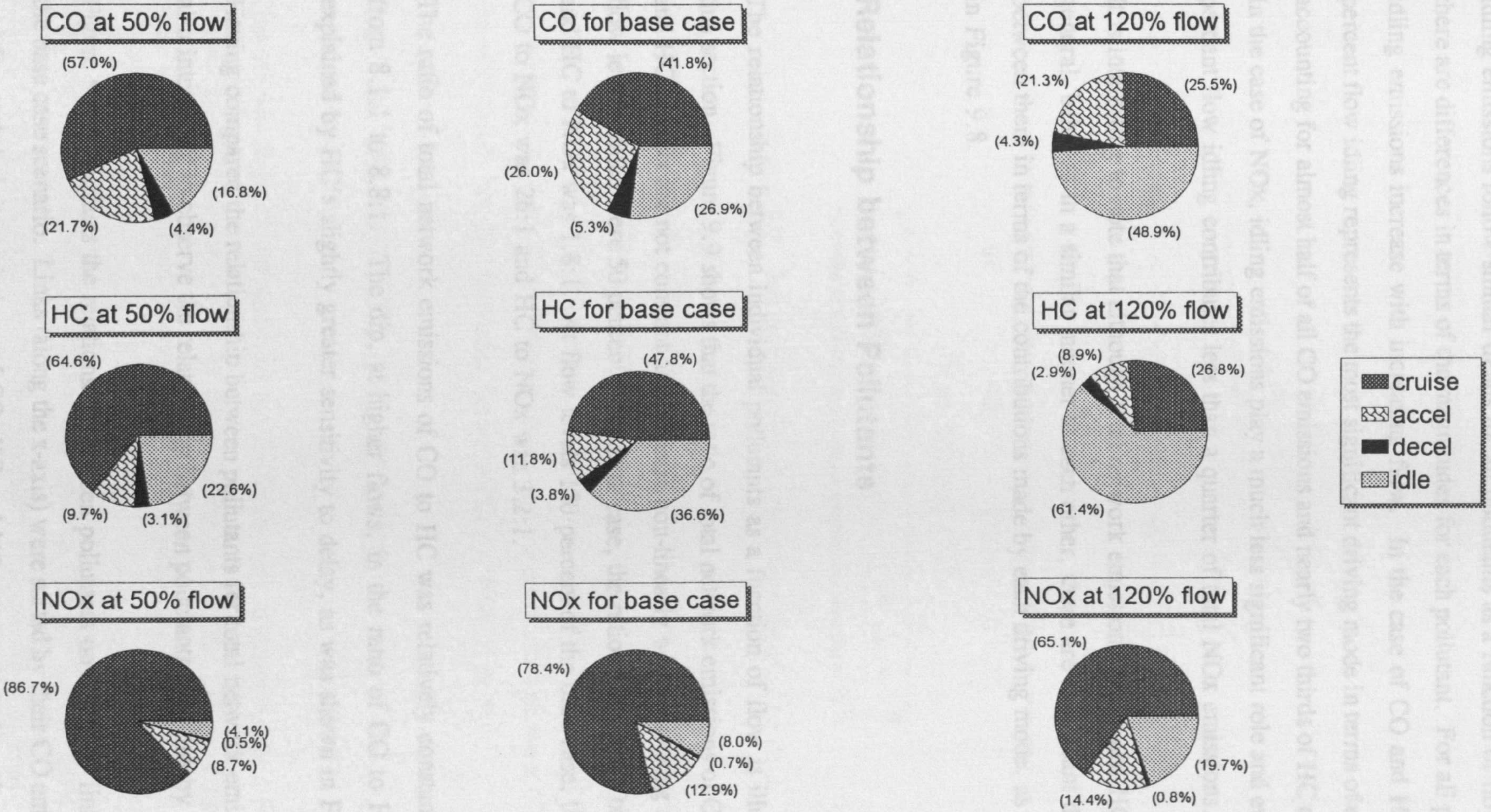

Figure 9.8 Breakdown of emissions by driving mode as a function of flow

Idling emissions follow similar trends for all pollutants as a function of flow, though there are differences in terms of the magnitudes for each pollutant. For all pollutants, idling emissions increase with increasing flow. In the case of CO and HC, at 120 percent flow idling represents the most significant driving mode in terms of emissions, accounting for almost half of all CO emissions and nearly two thirds of HC emissions. In the case of NOx, idling emissions play a much less significant role and even at 120 percent flow idling contributes less than a quarter of total NOx emissions.

It is interesting to note that although total network emissions of CO and HC have, in general, behaved in a similar manner to each other, there are significant differences between them in terms of the contributions made by each driving mode, as illustrated in Figure 9.8.

Relationship between Pollutants

The relationship between individual pollutants as a function of flow is illustrated in this section. Figure 9.9 shows that the ratio of total network emissions of CO to NOx and HC to NOx are not constant and increase non-linearly with increasing flow. For flow levels which were 50 percent of the base case, the ratio of CO to NOx was 16:1 and HC to NOx was 1.8:1. At flow levels 120 percent of the base case, the ratio of CO to NOx was 26:1 and HC to NOx was 3.2:1.

The ratio of total network emissions of CO to HC was relatively constant, ranging from 8.1:1 to 8.8:1. The dip, at higher flows, in the ratio of CO to HC can be explained by HC's slightly greater sensitivity to delay, as was shown in Figure 9.8.

Having compared the relationship between pollutants for total network emissions it is also interesting to observe the relationship between pollutants on a link by link basis.

Figure 9.10 illustrates the relationship between pollutants on a link by link basis for the base case scenario. Links (along the x-axis) were sorted by their CO emission rate and for each link its emissions of CO, HC and NOx were plotted on the y-axis. It shows that there was a relatively good correlation between emissions of CO and HC.

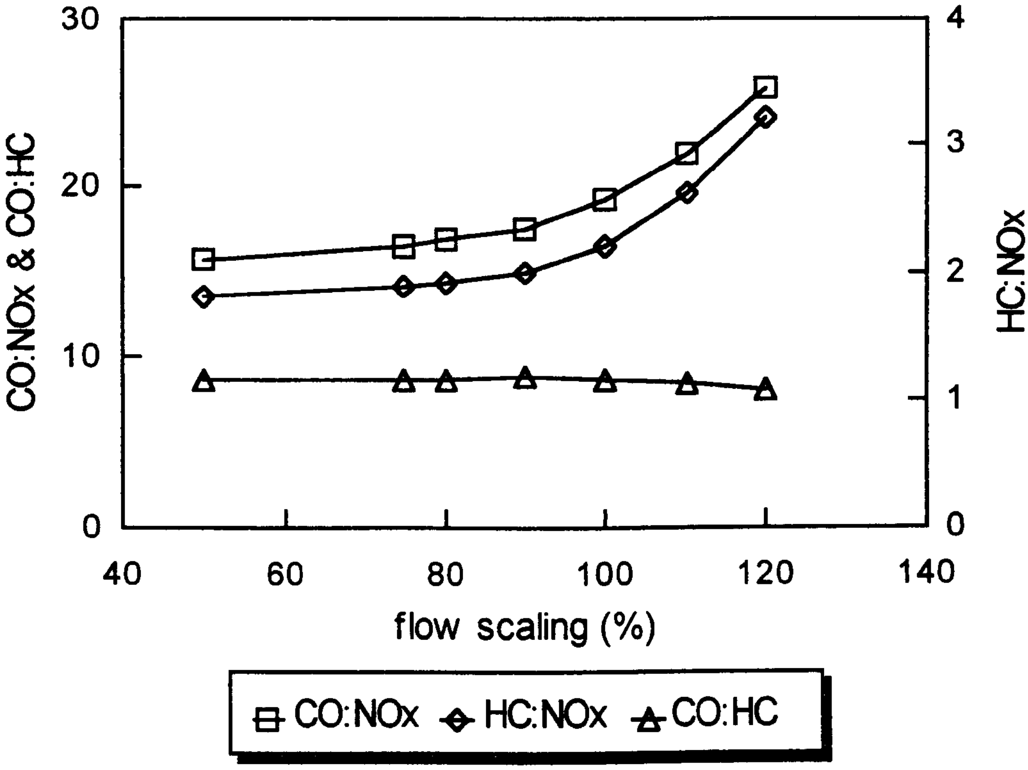

Figure 9.9 Ratios between pollutants as a function of flow

However, emissions of NOx correlated poorly with CO and HC. The correlations between pollutants were determined for the base case and at flows corresponding to 50 and 120 percent of the base case. The correlation coefficients for these scenarios are presented in Table 9.2. This confirmed that the correlation between CO and HC was very good, but the correlation between CO and NOx is poor.

9.5 SENSITIVITY TO CRUISE SPEED

This section presents the results of the sensitivity test of emissions as a function of cruise speed. This was performed by adjusting the TRANSYT cruise time scaling factor over a range of values between 50 to 200 percent.

Although a cruise time scaling factor was used in TRANSYT and plotted on the x-axis, the text in this section refers to the scaling of cruise speed as cruise speed can be easily related to emissions.

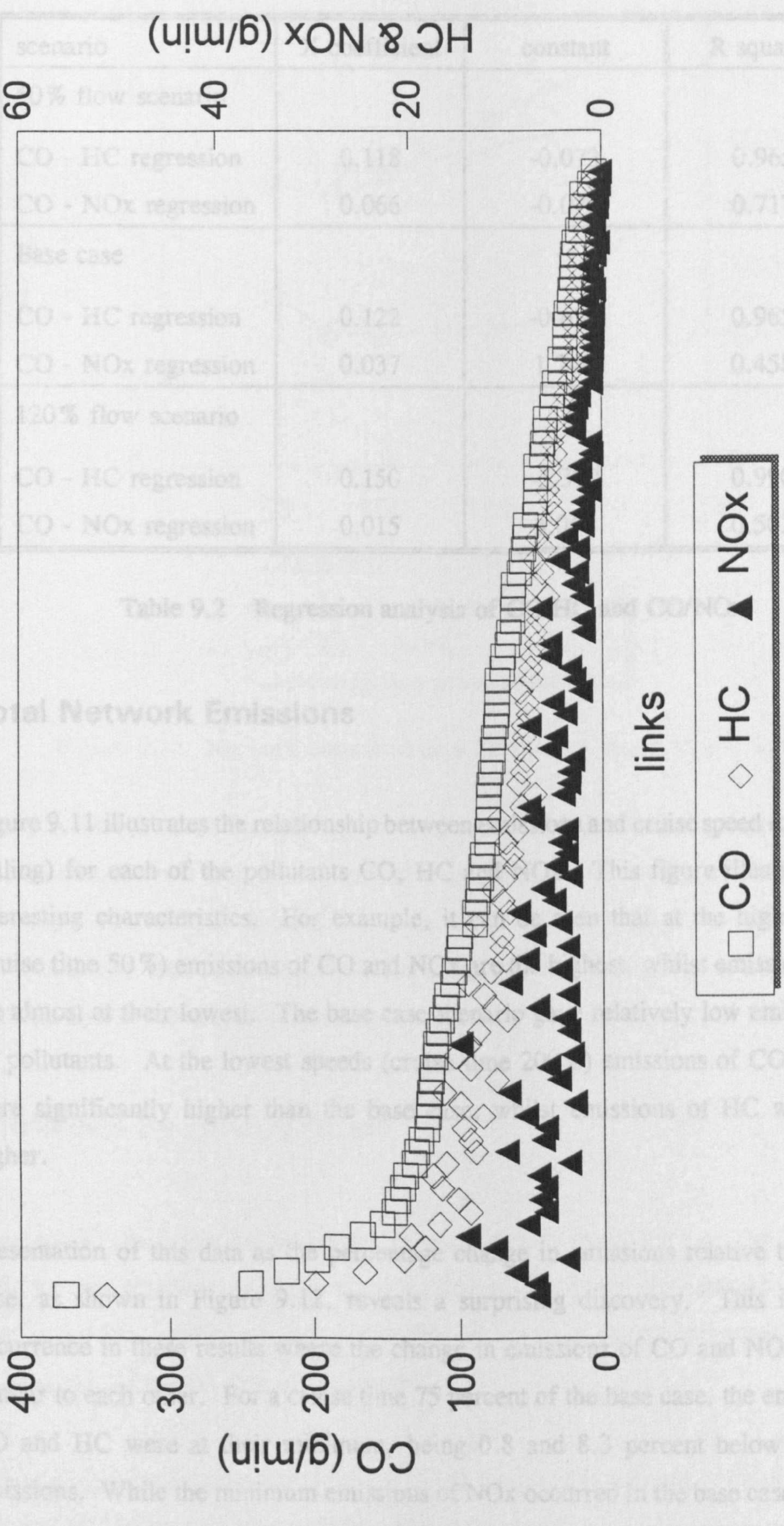

Figure 9.10 Base case link emissions of CO, HC and NOx

scenario	X coefficient	constant	R squared
50% flow scenario			
CO - HC regression	0.118	-0.073	0.965
CO - NOx regression	0.066	-0.070	0.717
Base case			
CO - HC regression	0.122	-0.652	0.965
CO - NOx regression	0.037	1.241	0.458
120% flow scenario			
CO - HC regression	0.150	-3.399	0.990
CO - NOx regression	0.015	3.063	0.503

Table 9.2 Regression analysis of CO/HC and CO/NOx

Total Network Emissions

Figure 9.11 illustrates the relationship between emissions and cruise speed (cruise time scaling) for each of the pollutants CO, HC and NOx. This figure illustrates some interesting characteristics. For example, it can be seen that at the highest speeds (cruise time 50%) emissions of CO and NOx are the highest, whilst emissions of HC are almost at their lowest. The base case scenario gave relatively low emissions for all pollutants. At the lowest speeds (cruise time 200%) emissions of CO and NOx were significantly higher than the base case, whilst emissions of HC were much higher.

Presentation of this data as the percentage change in emissions relative to the base case, as shown in Figure 9.12, reveals a surprising discovery. This is the first occurrence in these results where the change in emissions of CO and NOx are very similar to each other. For a cruise time 75 percent of the base case, the emissions of CO and HC were at their minimum, being 0.8 and 8.3 percent below base case emissions. While the minimum emissions of NOx occurred in the base case scenario. For a cruise time 50 percent of the base case, the emissions of CO and NOx were at

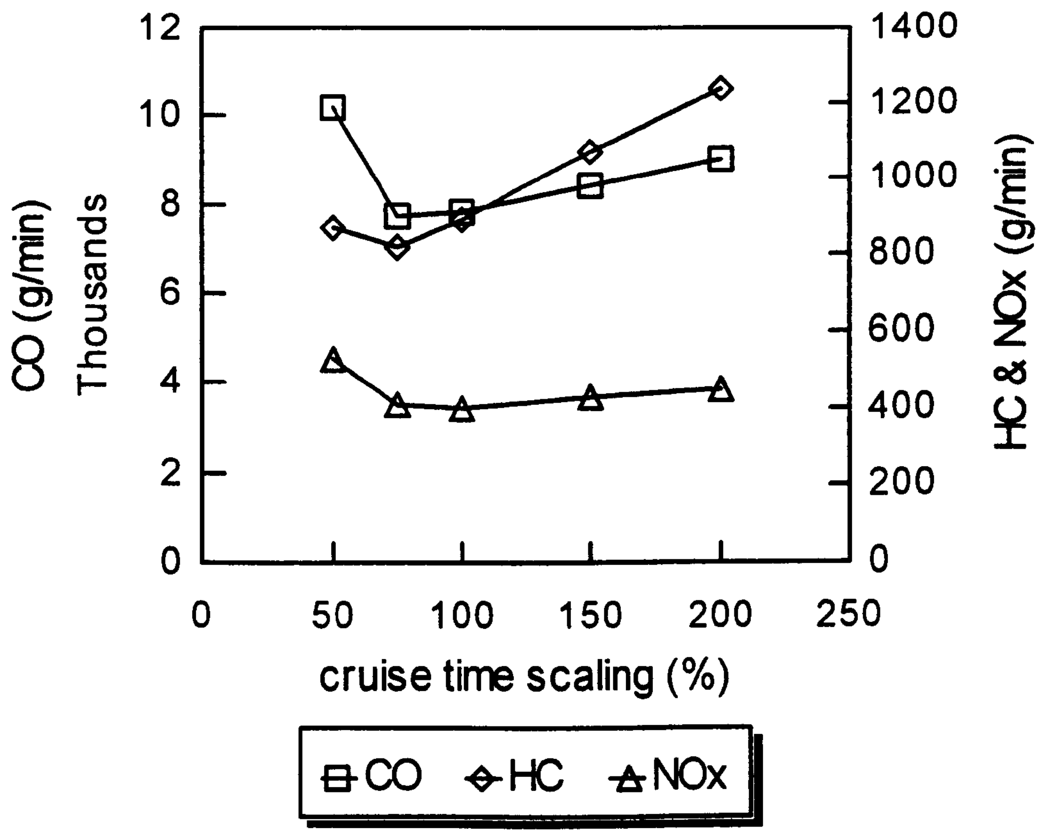

Figure 9.11 Network emissions as a function of speed (cruise time)

their maximum, both being 31 percent above their base case emissions. While maximum emissions of HC occurred for a cruise time 200 percent of the base case, with emissions being 39 percent above the base case. To understand the reasons for the similarities and differences between these pollutant emissions a more detailed analysis by driving mode is required.

Emissions by Driving Mode

Figure 9.13 illustrates the sensitivity of emissions to speed for each driving mode. Note that the acceleration graph has an additional line which has been labelled stops. This is the total cost of stops on the traffic network; its values correspond to the y-axis on the right hand side of the graph.

Cruise emissions for all pollutants increase as the speed is reduced, with emissions of CO and HC increasing substantially. It can be clearly seen that cruise emissions of

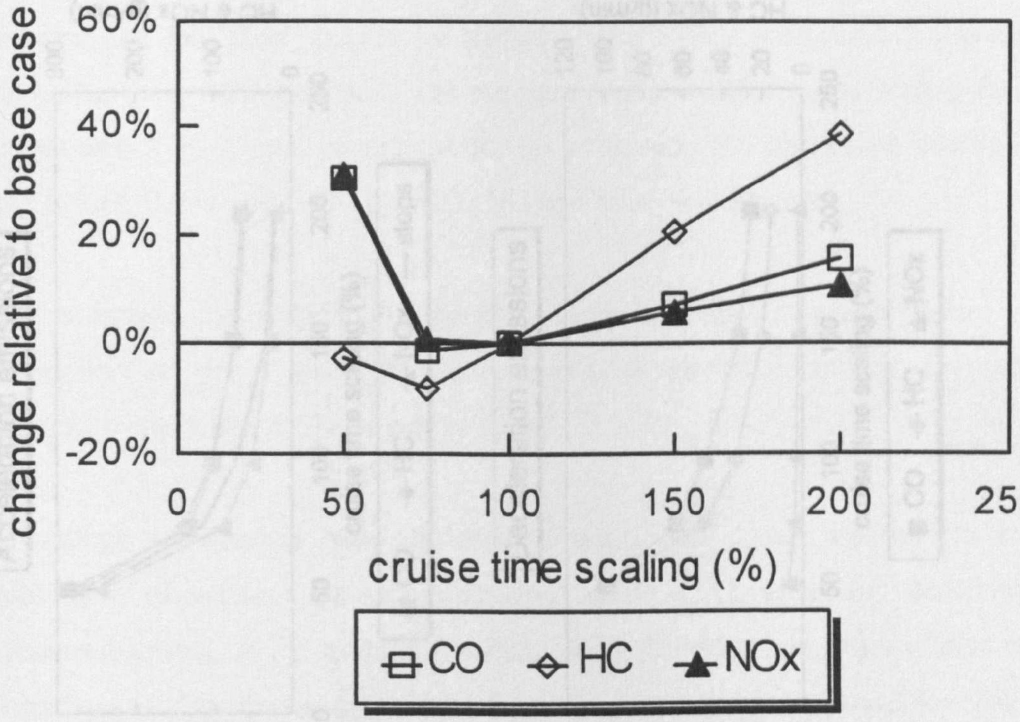

Figure 9.12 Percentage change in emissions as a function of speed

CO and HC are very sensitive to changes in cruise speed, while NOx is much less sensitive. An inspection of PREMIT's verbose output listings for these scenarios showed that cruise emissions reduced with increasing speed for two reasons. Firstly, higher cruise speeds corresponded to lower vehicle emission rates. Secondly, and more significantly, as speeds increased the proportion of a link's length available for cruising became smaller. This was because more of a link's length was occupied by vehicles accelerating and decelerating. Indeed, at the highest speed tested, for most links (73 links) there were no cruise emissions from vehicles that had to stop.

Acceleration emissions of all pollutants are very sensitive to cruise speed. At high speeds, as the speed is reduced these emissions fall rapidly, while at lower speeds a reduction in speed results in a relatively smaller reduction in emissions. Deceleration emissions behaved in a similar way, but NOx emissions were very small. The sensitivity of these emissions was due to the increased distance travelled, in the acceleration and deceleration modes, with increased speed. For a linear acceleration rate, the distance travelled from rest to the final cruise speed is proportional to the square of the cruise speed. These emissions follow the cost of stops plot on the same graph. TRANSYT calculates the cost of stops using a kinetic energy adjustment

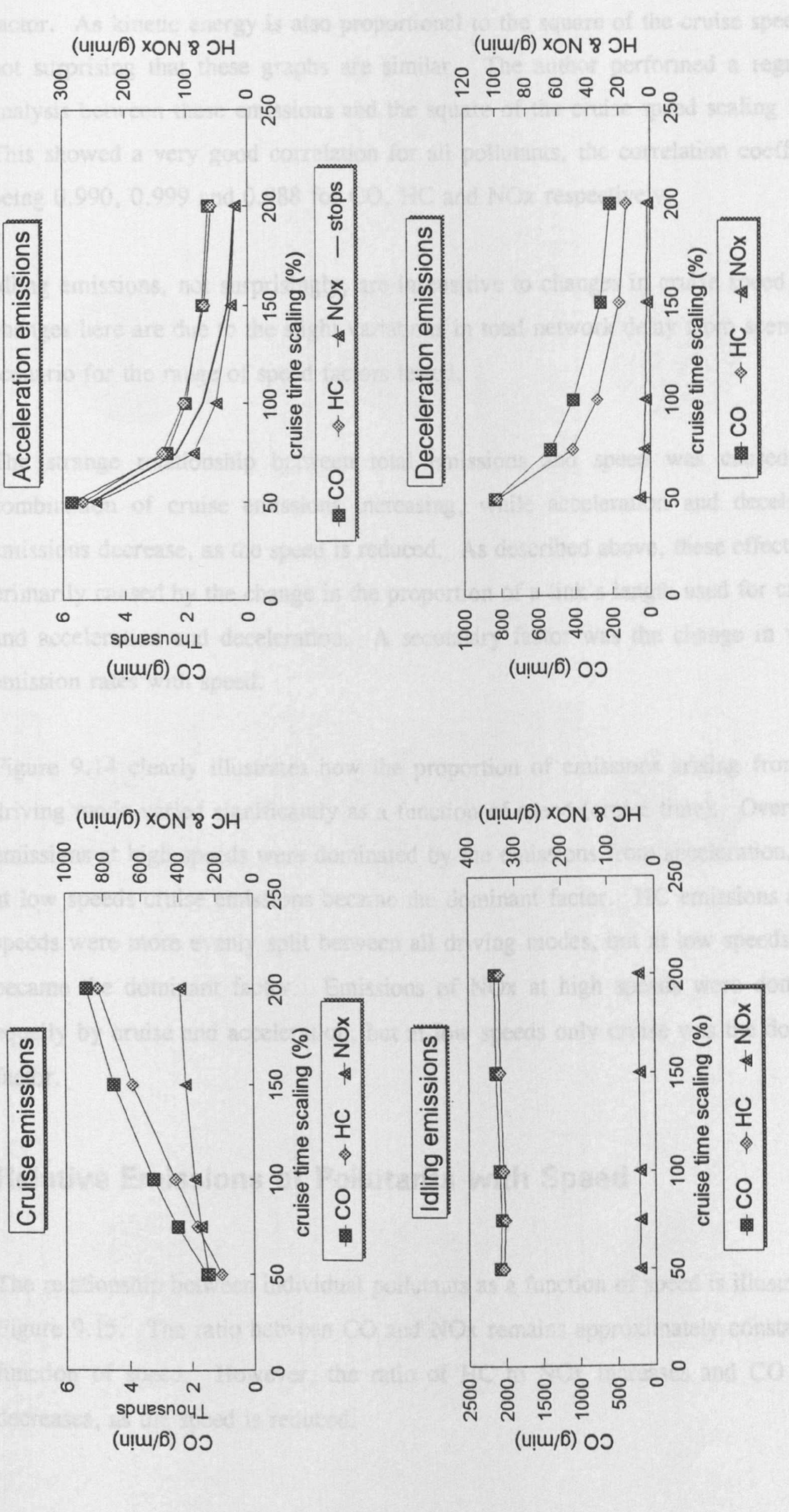

Figure 9.13 Emissions by driving mode as a function of speed (cruise time)

factor. As kinetic energy is also proportional to the square of the cruise speed it is not surprising that these graphs are similar. The author performed a regression analysis between these emissions and the square of the cruise speed scaling factor. This showed a very good correlation for all pollutants, the correlation coefficients being 0.990, 0.999 and 0.988 for CO, HC and NOx respectively.

Idling emissions, not surprisingly, are insensitive to changes in cruise speed. Any changes here are due to the slight variations in total network delay from scenario to scenario for the range of speed factors tested.

The strange relationship between total emissions and speed was caused by a combination of cruise emissions increasing, while acceleration and deceleration emissions decrease, as the speed is reduced. As described above, these effects were primarily caused by the change in the proportion of a link's length used for cruising and acceleration and deceleration. A secondary factor was the change in vehicle emission rates with speed.

Figure 9.14 clearly illustrates how the proportion of emissions arising from each driving mode varied significantly as a function of speed (cruise time). Overall CO emissions at high speeds were dominated by the emissions from acceleration, while at low speeds cruise emissions became the dominant factor. HC emissions at high speeds were more evenly split between all driving modes, but at low speeds cruise became the dominant factor. Emissions of NOx at high speeds were dominated equally by cruise and acceleration, but at low speeds only cruise was the dominant factor.

Relative Emissions of Pollutants with Speed

The relationship between individual pollutants as a function of speed is illustrated in Figure 9.15. The ratio between CO and NOx remains approximately constant as a function of speed. However, the ratio of HC to NOx increases and CO to HC decreases, as the speed is reduced.

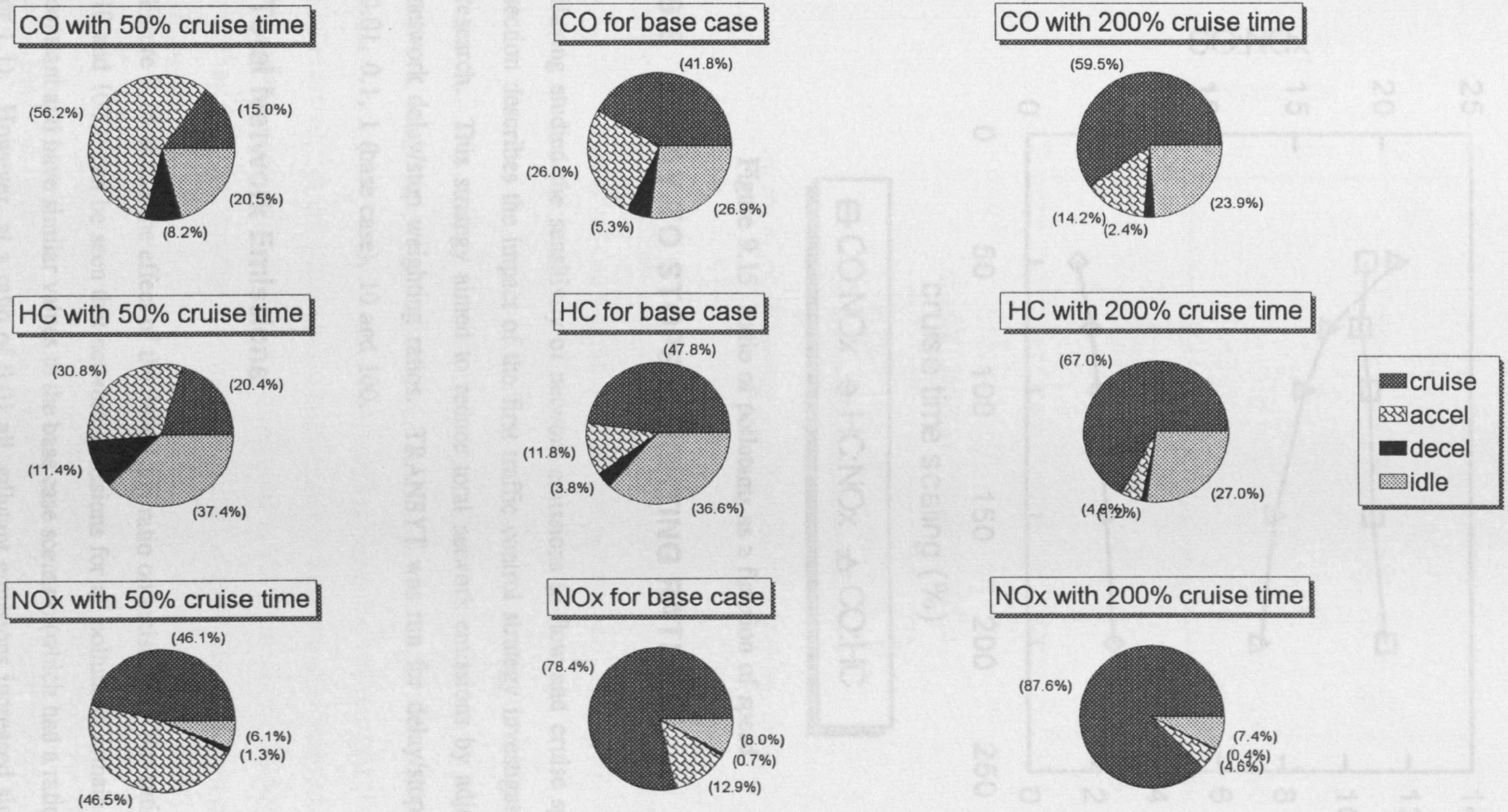

Figure 9.14 Breakdown of emissions by driving mode as a function of speed

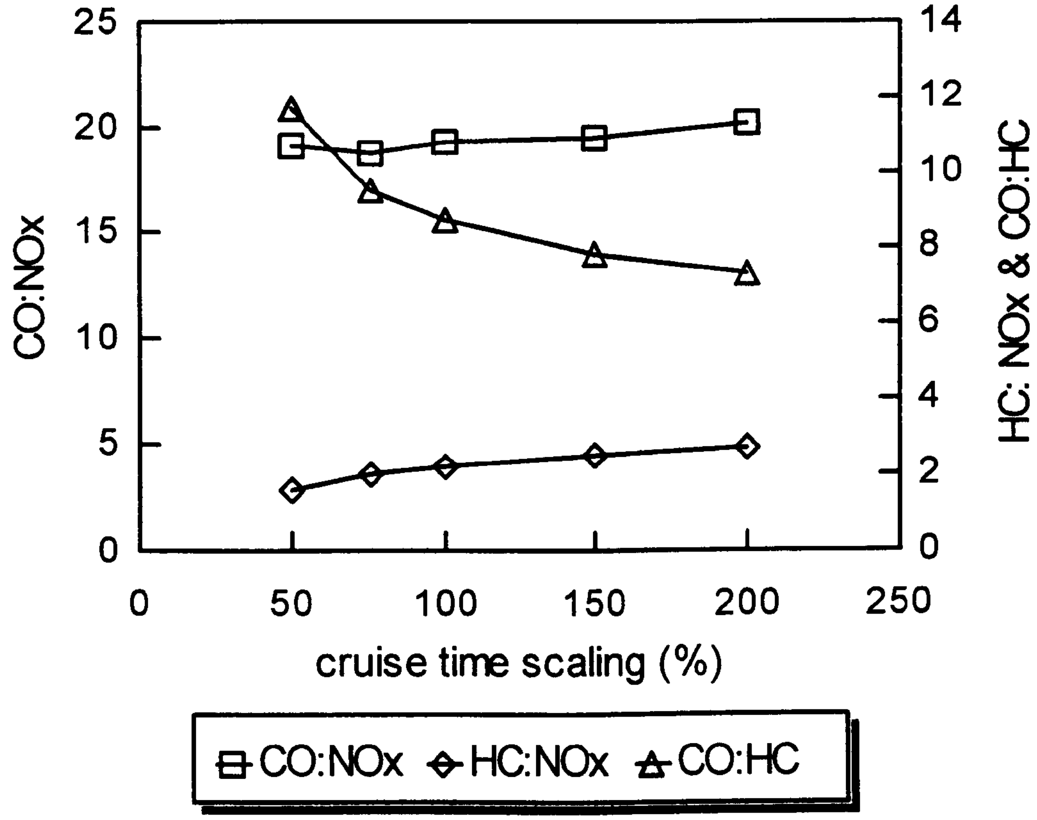

Figure 9.15 Ratio of pollutants as a function of speed

9.6 DELAY TO STOPS WEIGHTING RATIO

Having studied the sensitivity of network emissions to flow and cruise speed, this section describes the impact of the first traffic control strategy investigated in this research. This strategy aimed to reduce total network emissions by adjusting the network delay/stop weighting ratios. TRANSYT was run for delay/stop ratios of 0.01, 0.1, 1 (base case), 10 and 100.

Total Network Emissions

Figure 9.16 shows the effect of the delay/stop ratio on emissions. For ratios of 0.1, 10 and 100 it can be seen that network emissions for all pollutants remain relatively constant and have similar values to the base case scenario (which had a ratio of 55:50 or 1.1). However, at a ratio of 0.01 all pollutant emissions increased significantly relative to the base case.

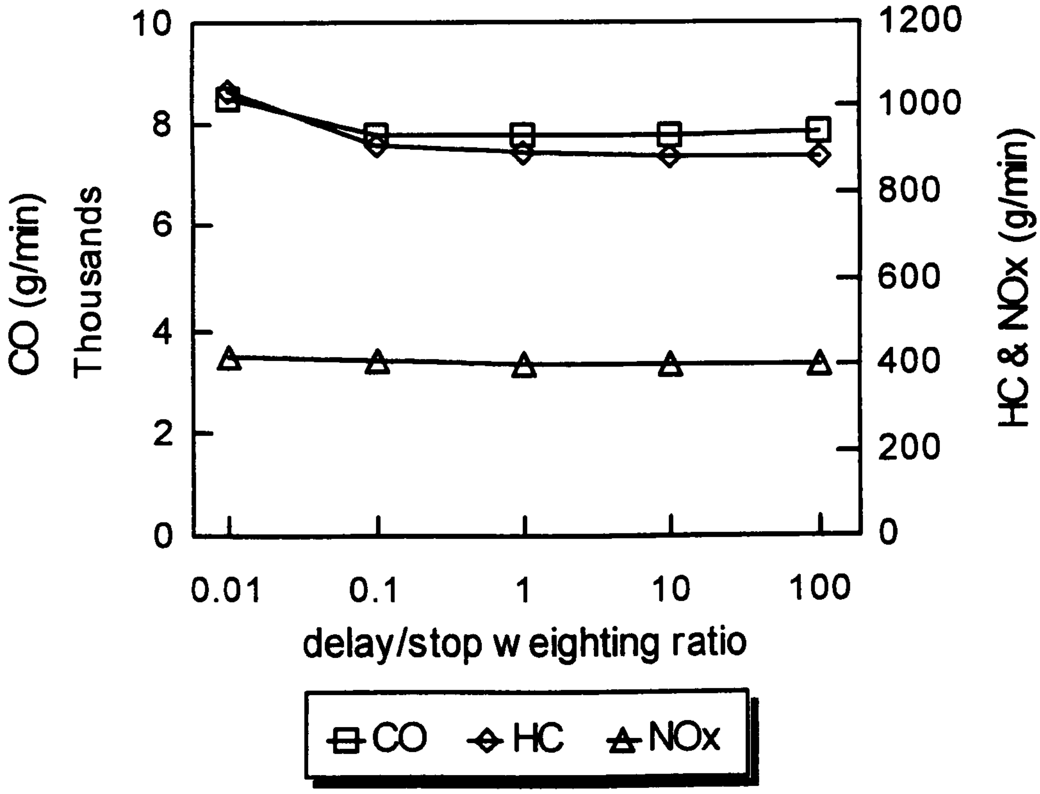

Figure 9.16 Emissions as a function of delay/stop ratio

Figure 9.17 shows the percentage change in emissions, relative to the base case, as a function of the delay/stop weighting ratio. For ratios of 0.1, 10 and 100 the change relative to the base case is less than 3 percent for each pollutant.

For a ratio of 0.01 there were significant increases of 9.8, 16.5 and 3.5 percent for CO, HC and NOx respectively. It can be seen that the trend in emissions closely follows that of total delay. However, a detailed inspection of the TRANSYT output data revealed that three links had unrealistically excessive queue lengths and delay. These links were responsible for a large increase in idling emissions. TRANSYT also predicted that a third of the links in the network had their flows reduced, because of congestion upstream.

The best reductions in emissions were relatively small. Emissions of CO were lowest in the base case. The lowest emissions of HC and NOx occurred at a delay/stop ratio of 100, at which the reductions were -0.4 and -0.9 percent respectively.

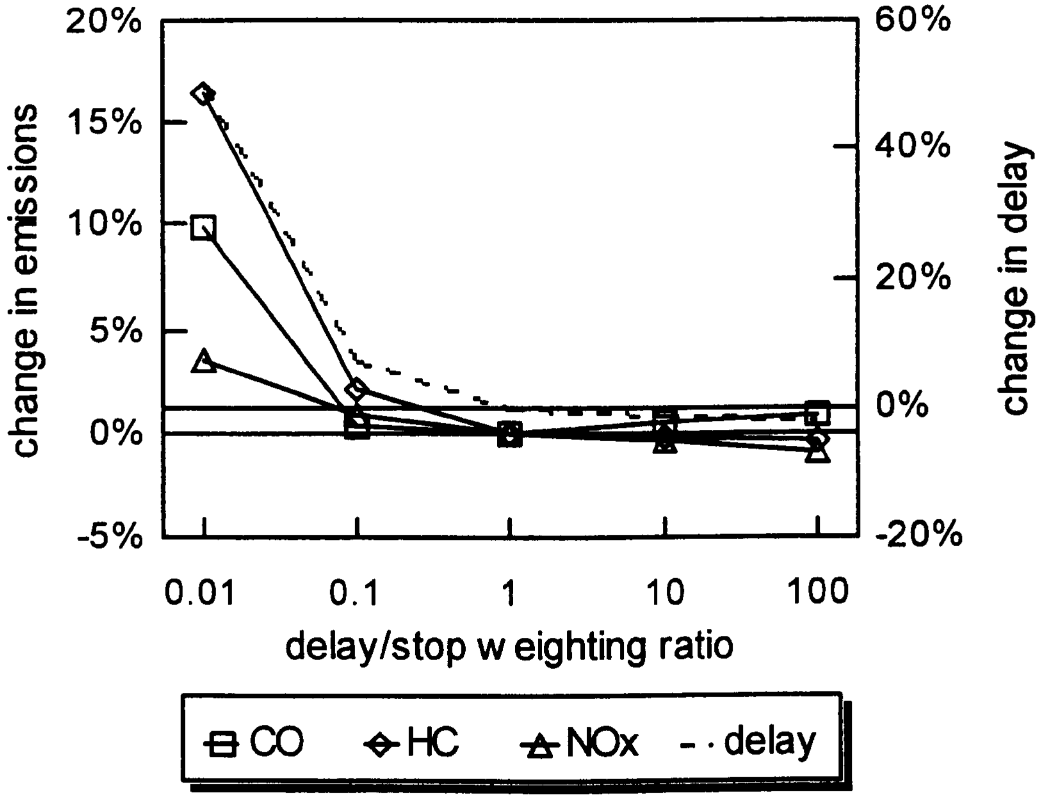

Figure 9.17 Percentage change in emissions and delay as a function of delay/stop weighting ratio

Emissions by Driving Mode

Analysis of these emissions by driving mode, as illustrated in Figure 9.18, reveals that the significant increase of emissions for a delay/stop ratio of 0.01 is due to an unrealistic increase in idling emissions, as discussed above. It can be seen that cruise emissions decrease slightly, while emissions from acceleration and deceleration increase with increasing values of the delay/stop ratio. This was because, at higher delay/stop ratios, TRANSYT optimised the network to reduce delay rather than stops, and this led to many links having increased queue lengths. Increased stops resulted in more vehicles having to decelerate and then accelerate, with a corresponding increase in their emissions. For links with increased queue lengths, the distance available for cruising became shorter, resulting in reduced cruise emissions.

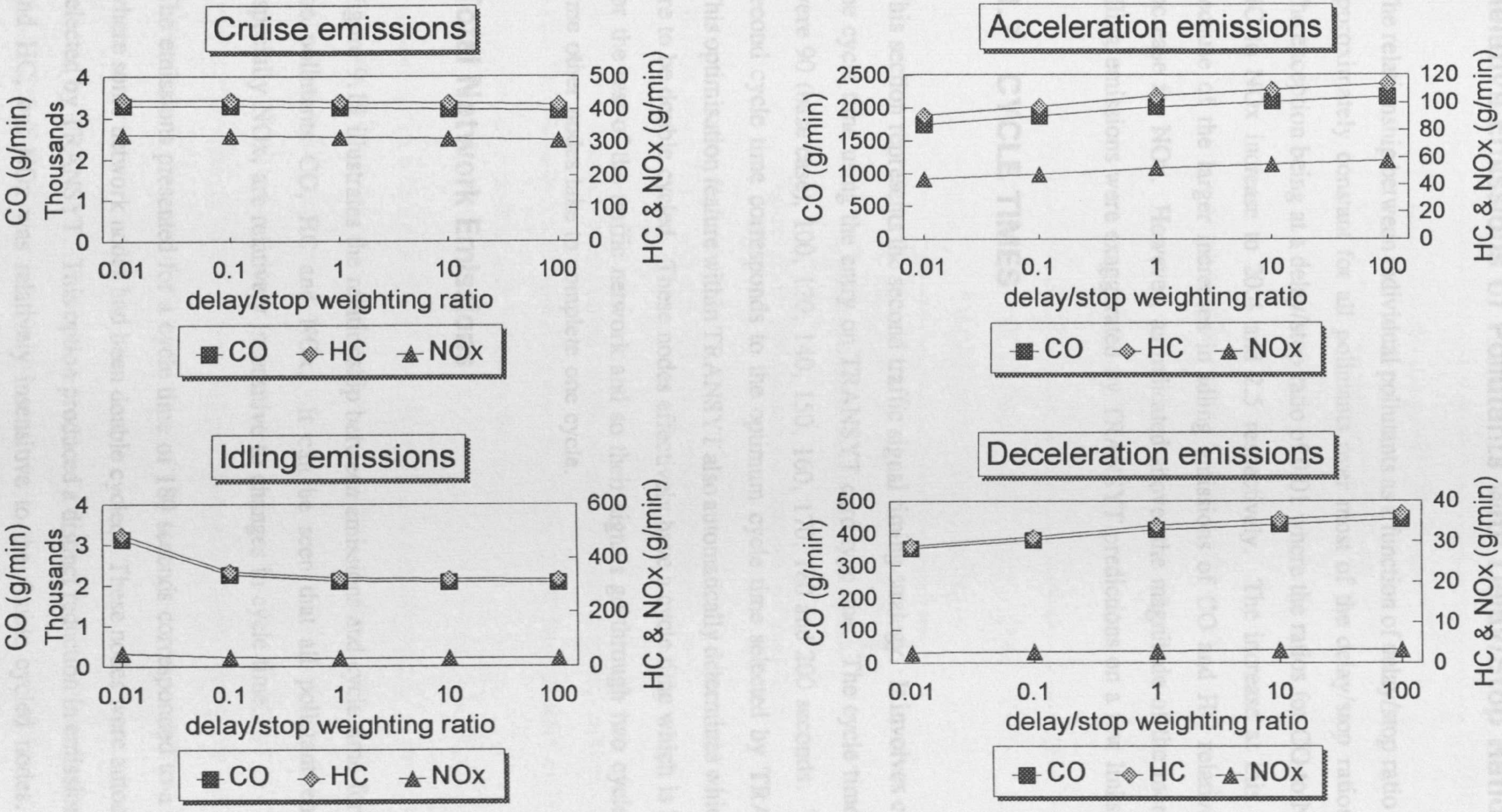

Figure 9.18 Emissions by driving mode as a function of delay/stop ratio

Relative Emissions of Pollutants with Delay/Stop Ratio

The relationship between individual pollutants as a function of delay/stop ratio remains approximately constant for all pollutants over most of the delay/stop ratios tested. The exception being at a delay/stop ratio of 0.01 where the ratios for CO to NOx and HC to NOx increase to 20.4 and 2.5 respectively. The increase at this value is because of the larger increases in idling emissions of CO and HC relative to the increase for NOx. However, as indicated above, the magnitude of the increases in idling emissions were exaggerated by TRANSYT predictions on a few links.

9.7 CYCLE TIMES

This section represents the second traffic signal timing strategy. It involves changing the cycle time using the entry on TRANSYT card type one. The cycle times tested were 90 (base case), 100, 120, 140, 150, 160, 170, 180 and 200 seconds. The 180 second cycle time corresponds to the optimum cycle time selected by TRANSYT. This optimisation feature within TRANSYT also automatically determines which nodes are to be double cycled. These nodes effectively have a cycle time which is half that for the rest of the traffic network and so their signals go through two cycles in the time other nodes take to complete one cycle.

Total Network Emissions

Figure 9.19 illustrates the relationship between emissions and cycle time for each of the pollutants CO, HC and NOx. It can be seen that all pollutant emissions, especially NOx, are relatively insensitive to changes in cycle time.

The emissions presented for a cycle time of 180 seconds corresponded to a scenario where some network nodes had been double cycled. These nodes were automatically selected by TRANSYT. This option produced a distinct reduction in emissions of CO and HC, but NOx was relatively insensitive to the double cycled nodes. In the absence of double cycled nodes, at a cycle time of 180 seconds, emissions of CO, HC

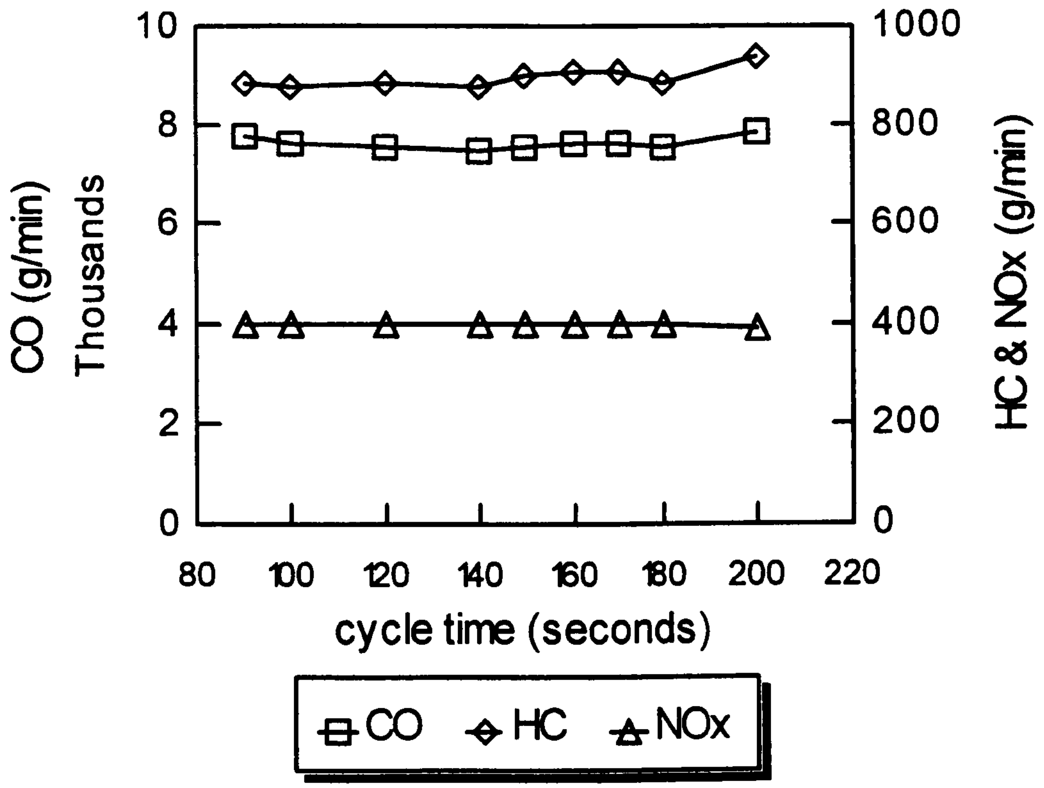

Figure 9.19 Emissions as a function of cycle time

and NOx were 7777, 930 and 401 g/min respectively.

The relative changes in emissions compared with the base case is illustrated in Figure 9.20. The changes follow relatively complex patterns and the minimum emissions for each pollutant occurs at a different cycle time.

The change in emissions of CO and HC follow a similar pattern to each other, for most of the cycle times that were modelled. However, the level of HC is displaced above that of CO such that for some cycle times emissions of CO are below the base case value whilst emissions of HC are above the base case. It can be seen that, in general, the changes in HC closely follow changes in delay. For some cycle times, changes in CO also correspond with changes in delay, but to a lesser extent.

For short cycle times, changes in emissions of NOx show a similar pattern to those of CO, but at the longer cycle times changes in NOx do not follow changes in CO. The changes in NOx do not correspond with changes in delay. This is not surprising

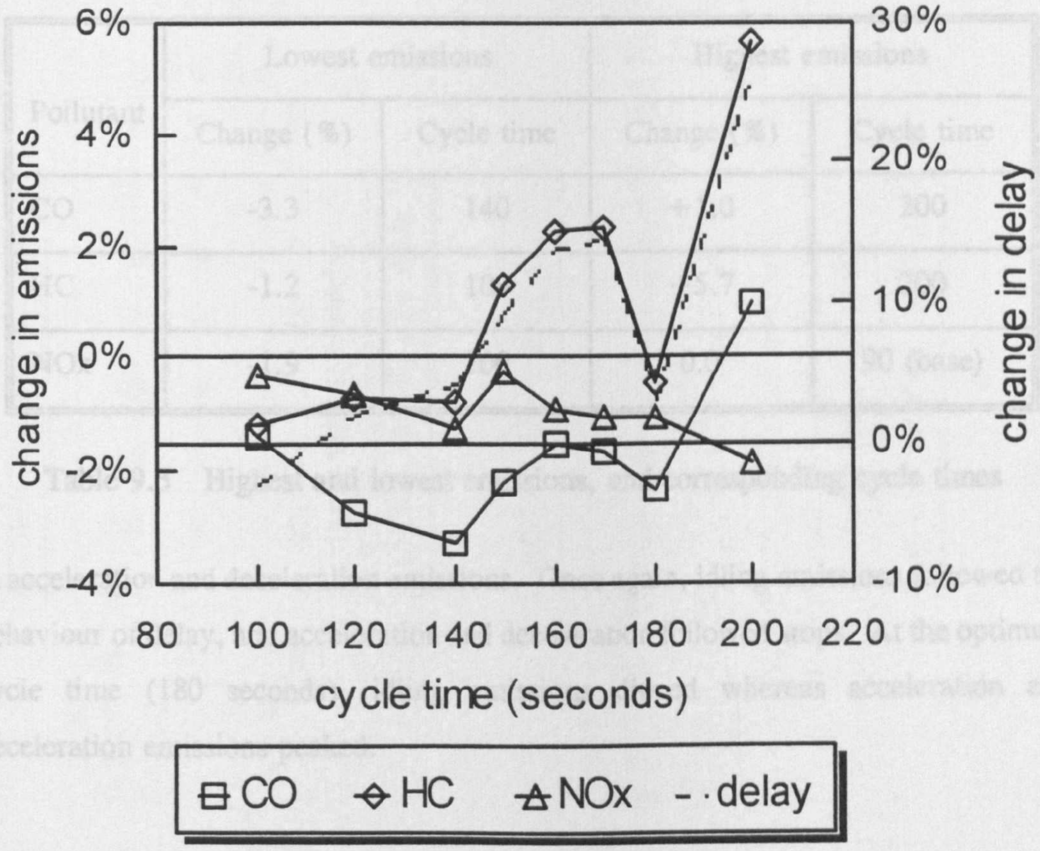

Figure 9.20 Percentage change in emissions and delay as a function of cycle time

because, as illustrated earlier, emissions from idling are only responsible for a small proportion of total NOx emissions.

Table 9.3 shows the highest and lowest emissions for each pollutant over the range of cycle times tested. Note that all cycle times gave emissions of NOx that were lower than those of the base case.

Emissions by Driving Mode

Analysis of emissions by driving mode, as illustrated in Figure 9.21, revealed that cruise emissions were relatively insensitive to cycle time, whereas emissions from acceleration, deceleration and idling were sensitive to cycle time.

The trend of changes in idling emissions were approximately the inverse of changes

Pollutant	Lowest emissions		Highest emissions	
	Change (%)	Cycle time	Change (%)	Cycle time
CO	-3.3	140	+1.0	200
HC	-1.2	100	+5.7	200
NOx	-1.9	200	0.0	90 (base)

Table 9.3 **Highest and lowest emissions, and corresponding cycle times**

in acceleration and deceleration emissions. Once again, idling emissions followed the behaviour of delay, and acceleration and deceleration followed stops. At the optimum cycle time (180 seconds), idling emissions dipped whereas acceleration and deceleration emissions peaked.

9.8 OPTIMISATION OF HOT LINKS

This section presents the results of environmentally sensitive traffic control strategies that aimed to reduce link emissions for links which had the highest emissions in the network. The top 20 links with the highest emissions were termed hot links and were selected for optimisation. There were 20 hot CO links and 20 hot NOx links, of these 11 were both hot CO and NOx links. The study network had a total of 86 links. The term link is used here to refer to an actual unidirectional stretch of road between two intersections; some of these include more than one TRANSYT "link".

Hot CO Links

Based on the results described earlier in this chapter it was possible to formulate an hypothesis that emissions of CO, and HC, were very sensitive to delay, especially on links with a high degree of saturation. Therefore, the strategy to reduce hot link emissions of CO was based on reducing the delay on hot CO links.

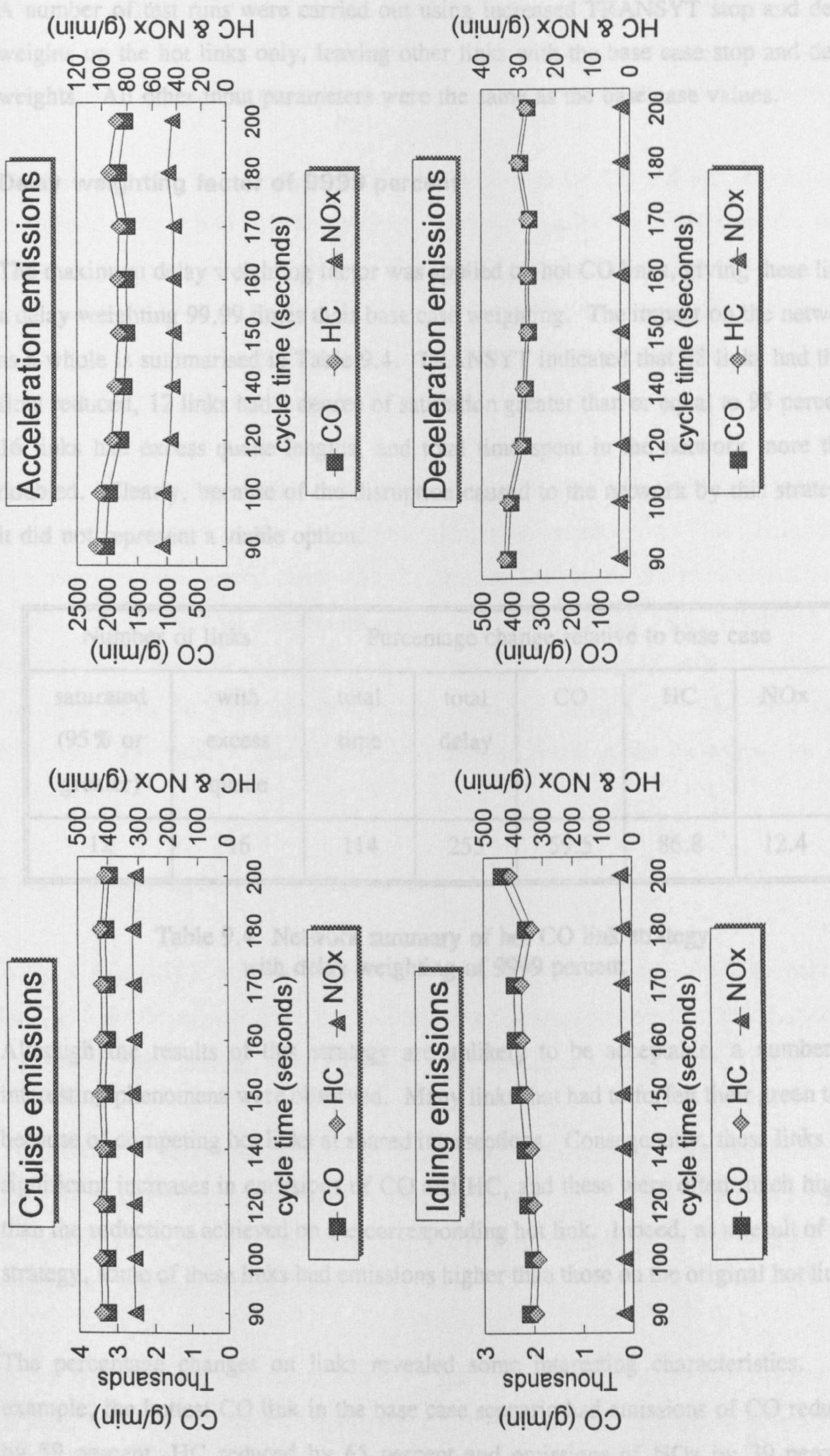

Figure 9.21 Emissions by driving mode as a function of cycle time

A number of test runs were carried out using increased TRANSYT stop and delay weights on the hot links only, leaving other links with the base case stop and delay weights. All other input parameters were the same as the base case values.

Delay weighting factor of 9999 percent

The maximum delay weighting factor was applied on hot CO links, giving these links a delay weighting 99.99 times their base case weighting. The impact on the network as a whole is summarised in Table 9.4. TRANSYT indicated that 68 links had their flow reduced, 12 links had a degree of saturation greater than or equal to 95 percent, 16 links had excess queue lengths, and total time spent in the network more than doubled. Clearly, because of the disruption caused to the network by this strategy, it did not represent a viable option.

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
12	16	114	255	59.5	86.8	12.4

Table 9.4 Network summary of hot CO link strategy with delay weighting of 9999 percent

Although the results of this strategy are unlikely to be acceptable, a number of interesting phenomena were observed. Many links that had to forfeit their green time because of competing hot links at shared intersections. Consequently, these links had significant increases in emissions of CO and HC, and these were often much higher than the reductions achieved on the corresponding hot link. Indeed, as a result of this strategy, some of these links had emissions higher than those on the original hot links.

The percentage changes on links revealed some interesting characteristics. For example, the hottest CO link in the base case scenario had emissions of CO reduced by 59 percent, HC reduced by 65 percent and emissions of NOx by 39 percent.

Whereas the second hottest link had emissions reduced by 16, 17 and 7 percent for CO, HC and NOx respectively. Note that in this case the percentage reduction in NOx emissions was less than half the percentage reduction in CO and HC emissions.

The third hot link had increases of 22 and 24 percent for CO and HC respectively, because of competition with hotter links. However, emissions of NOx for the same link actually decreased by 3 percent. This lack of correlation between changes in CO and changes in NOx is also illustrated on the fourth hot link, on which emissions of CO and HC fell by 63 and 58 percent respectively. Whereas emissions of NOx for the same link actually increased by 43 percent!

Because the impact of these signal timings was so disruptive to the traffic network, many drivers may, in reality, respond by taking an alternate route. This would result in a different set of traffic flows. So if a detailed analysis of this particular strategy were to be pursued an assignment model would have to be used. Although the magnitude of the changes reported above are not expected to reflect reality, the concepts, particularly the lack of correlation between changes in CO and changes in NOx, are still valid. This is illustrated and analyzed in the following hot link strategies.

Delay weighting factor of 500 percent

When a TRANSYT run was made with a delay weighting factor of 500 percent for hot CO links the disruption to the network was considerably less than that caused by a factor of 9999 percent. The impact on the network is summarised in Table 9.5.

The number of saturated links remained the same as the base case and the number of links with excess queues increased by one. However, 21 links had their flow reduced compared with only 4 in the base case. The total time spent in the network was slightly higher than the base case value.

In the base case, the CO emission rate for hot link number 20 was 118. The hot link strategy resulted in only 16 links being at or above this hot link threshold emission rate for CO. Six of the original hot links had their emissions reduced below this

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
4	8	3.1	7.0	1.4	2.3	-0.1

Table 9.5 Network summary of hot CO link strategy with delay weighting of 500 percent

threshold value, and two links became new hot links. Hence, the strategy had the net effect of removing four links from the hot link category.

The impact that this strategy had on hot links is shown in Table 9.6. The table lists the link number for each hot link. These numbers correspond to the ranking of the hot link in the base case scenario, based on its emission rate of CO. Links are sorted in the table by their emission rate of CO in the hot link strategy. The greatest increases and decreases in hot link emissions are underlined.

The worst percentage increase, for the hot links, in emissions of CO and HC occurred on hot link two for which the increases were 56 and 73 percent respectively. The worst percentage increase in emissions of NOx occurred on hot link four, on which emissions increased by 30 percent.

The best percentage decrease in hot link emissions of CO occurred on hot link nineteen, on which emissions of CO fell by 41 percent. Hot link one had the best percentage decrease in emissions of HC and NOx which fell by 37 and 27 percent respectively.

Of the 20 hot CO links, emissions were reduced on 14, 13 and 7 links for CO, HC and NOx respectively. Note that most hot CO links had their emissions of CO and HC reduced, but had their emissions of NOx increased. The changes in link emissions of CO and HC behaved differently to those for NOx. Of the 20 hot CO

Hot link number and nodes		Network emissions			Change in emissions (%)		
		CO	HC	NOx	CO	HC	NOx
2	227 226	380.73	51.62	8.38	56.1	72.8	15.7
1	225 226	247.12	32.33	5.14	-33.2	-37.1	-27.0
3	491 226	215.68	24.44	9.34	-1.6	-1.5	0.1
5	216 217	196.66	19.73	11.52	6.3	6.1	0.2
8	213 214	176.31	15.07	6.01	21.3	8.0	-2.4
15	259 216	162.86	19.02	5.38	33.1	30.5	-10.8
6	226 207	148.45	19.08	14.28	-11.2	-5.0	0.3
7	228 227	148.38	16.68	8.24	-3.3	-2.5	1.7
10	206 227	143.75	17.61	6.25	3.2	4.6	1.3
9	198 199	142.42	14.91	6.63	-0.5	-1.4	-0.7
11	218 219	132.62	17.69	7.2	-3.2	0.1	4.7
4	195 196	129.29	13.87	5.07	-34.8	-33.3	30.0
18	219 220	120.89	16.57	9.94	0.5	0.0	-0.1
13	207 208	120.23	12.2	9.94	-7.0	-8.6	-2.0
14	217 218	114.65	11.93	6.16	-9.5	-14.0	-3.4
16	196 197	113.19	11.81	8.12	-6.9	-6.0	0.1
17	262 261	112.25	13.81	3.1	-7.2	-7.3	4.0
20	199 212	112.14	13.17	5.83	-5.3	-4.9	0.9
12	331 216	108.68	13.7	3.89	-17.2	-16.1	6.9
19	212 213	70.11	7.61	4.89	-41.1	-31.6	5.2

Table 9.6 Impact of 500 percent delay weighting on hot CO links

links, 13 links had changes in CO which were in the opposite direction to changes in NOx. This illustrates that changes in NOx do not correlate well with changes in CO, or HC.

Analysis of opposite behaviour between changes in CO and NOx

The irregular behaviour of changes in emissions of NOx relative to changes in CO represents an interesting and important feature of traffic emissions. It is important to understand the reason for such behaviour.

The link between nodes 195 and 196 was the fourth hottest link and its emissions changed by -35, -33 and +30 percent relative to the base case for CO, HC and NOx respectively. This link, therefore, represents an excellent example of the opposite behaviour in the changes of CO and NOx. This behaviour can be explained by analysing the link's emissions by driving mode. The analysis separated cruise emissions into two parts: cruise emissions from vehicles which are not delayed on a link (free flow); and cruise emissions from vehicles which are delayed.

Emissions of CO significantly decreased on this link after optimisation, as illustrated in Figure 9.22. This was because emissions from idling and acceleration reduced substantially and exceeded the increase in cruise emissions. Emissions of HC behaved similarly to those of CO.

Unlike CO and HC, Figure 9.23 illustrates how NOx emissions increased on this link after 'optimisation'. This was because the proportion of vehicles on this link which experienced free flow conditions increased after 'optimisation'. In fact, a detailed analysis of this link revealed that in the base case there were no vehicles which experienced free flow - all vehicles were delayed. After optimisation of this link over 1200 vehicles per hour were able to travel down this link without being stopped. This resulted in a substantial increase of free flow cruise emissions.

A secondary factor for the increase in cruise emissions was the increase in cruise emissions from vehicles that are delayed, although this increase was not as significant as the increase in free flow cruise emissions. This increase was because the queue length reduced, allowing a longer distance for vehicles to cruise over before joining the back of the queue. Hence, although the number of delayed vehicles fell with optimisation, the increase in cruise distance resulted in a net increase of these emissions.

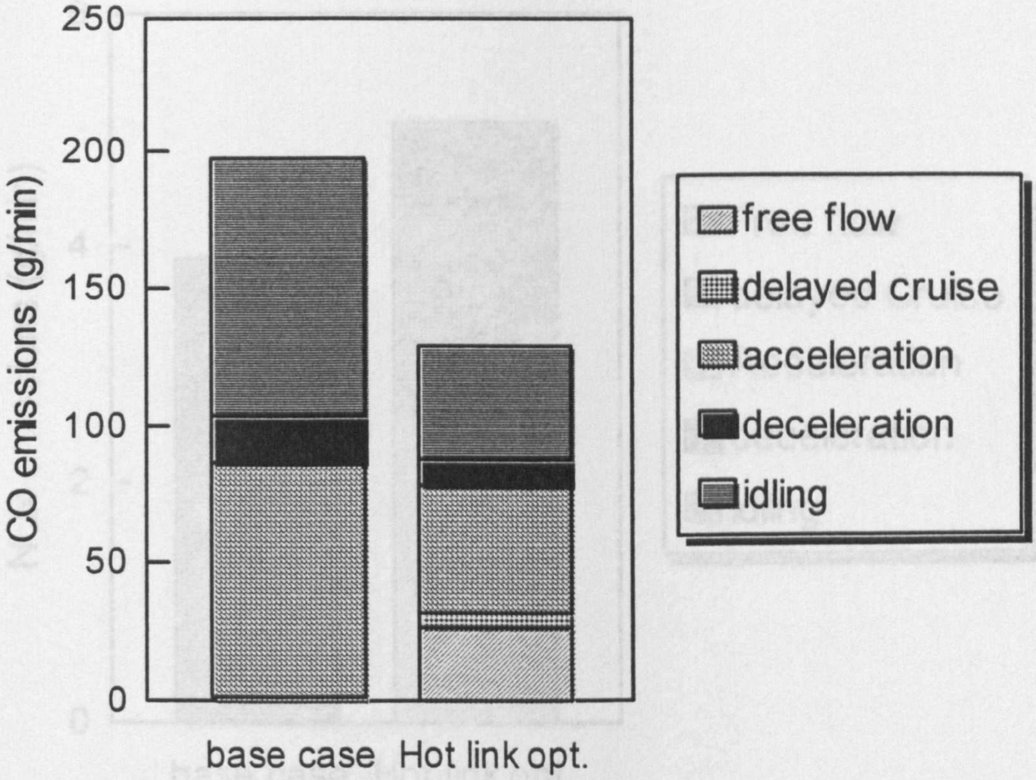

Figure 9.22 Hot link (195 196) emissions of CO by driving mode

Emissions from acceleration, deceleration and idling were reduced because the stops and delay had been reduced at the intersection. However, these reductions were outweighed by the increase in cruise emissions of NOx.

Likewise, opposite behaviour can be observed on links where emissions of CO and HC have increased, but NOx has decreased. The reason is the same as the above example, except that delay and queue length have increased instead of decreasing. An example of this behaviour was observed on link 259 216.

Analysis of similar behaviour for changes in CO and NOx

It has been shown above that emissions of CO and NOx can change in opposite directions on the same link for a given strategy. Although this occurred on many links, some links had emissions of CO and NOx change in the same direction. This section analyses this behaviour using link 213 218 as an example. This link was not a hot link and after hot link optimisation the delay on this link was increased.

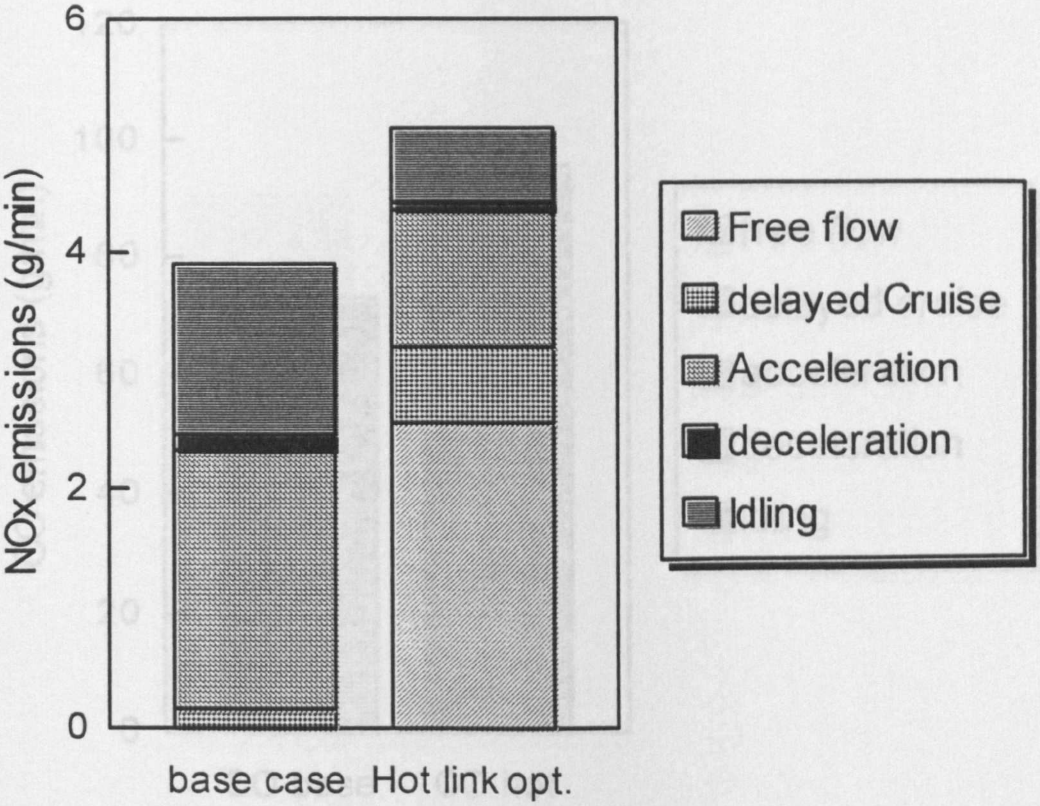

Figure 9.23 Hot link (195 196) emissions of NOx by driving mode

Emissions of CO, HC and NOx all increased after hot link optimisation by 30, 41 and 13 percent respectively.

Figure 9.24 illustrates the increase in emissions of CO by driving mode. Both before and after optimisation, there were no free flow cruise emissions. This was because all vehicles on this link were delayed. The change in emissions for delayed cruise, acceleration and deceleration were insignificant and the dominant factor was a significant increase in idling emissions.

Figure 9.25 illustrates the change in emissions of NOx by driving mode. The changes for each driving mode are similar to those for CO and the only significant change is the increase in NOx idling emissions. However, NOx idling emissions account for a much smaller proportion of total emissions from all modes compared to CO idling emissions. Consequently, the increase in total emissions of NOx is much smaller than that for CO.

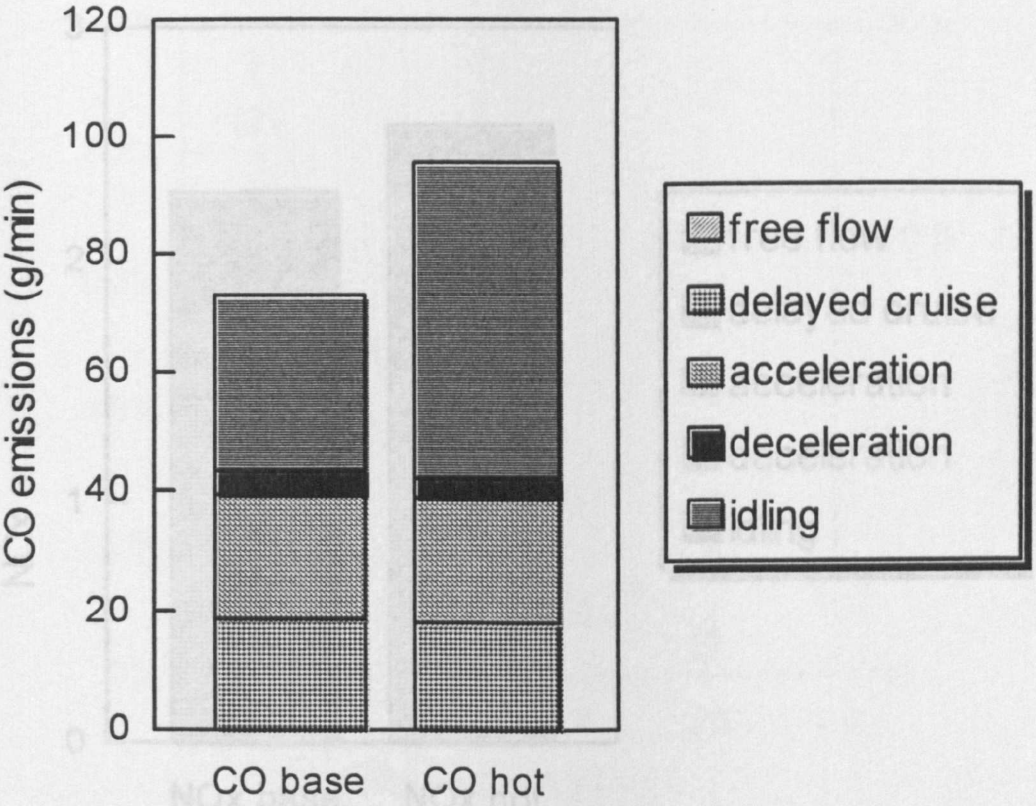

Figure 9.24 Hot link (213 218) emissions of CO by driving mode

Analysis of change in pollutants as a function of flow

It has been shown above that some links for this strategy have emissions of CO and NOx change in opposite directions to each other, while some links have CO and NOx change in the same direction. It is interesting to ask, does a particular link always have emissions of CO and NOx change in the same or opposite direction as a function of flow?

This section analyses the change in emissions, caused by the hot link optimisation strategy, as a function of flow. The analysis is based on link 213 218. For each flow tested, values were obtained for scenarios corresponding to before and after optimisation.

Figure 9.26 illustrates the impact of hot link optimisation on the link's degree of saturation and delay. For a flow scaling factor of 50 percent, the optimisation caused the saturation and delay on this link to rise considerably compared with their values

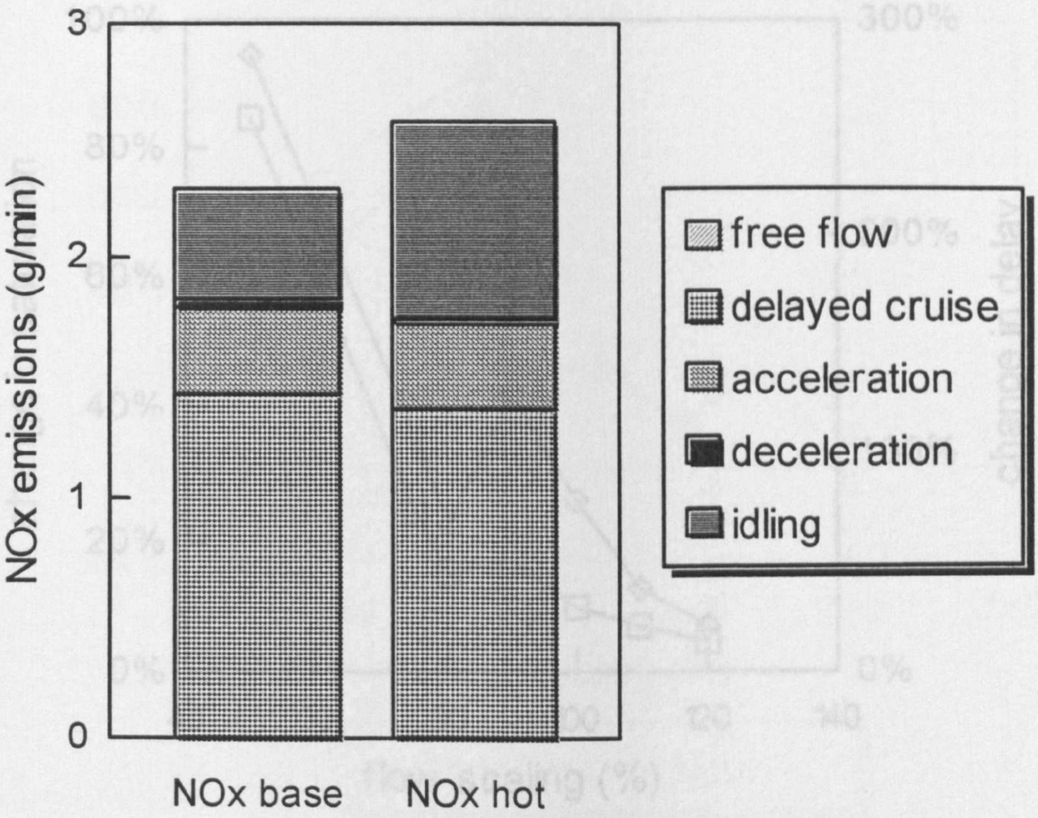

Figure 9.25 Hot link (213 218) emissions of NOx by driving mode

before optimisation. The degree of saturation was increased by over 80 percent and delay by almost 300 percent. The figure shows that the changes in delay were very sensitive to changes in the degree of saturation.

Figure 9.27 illustrates the impact the hot link strategy had on stops and queue length as a function of flow. The change in stops closely followed changes in queue. It is interesting to note that although the strategy used a constant weighting on the hot links, the changes to saturation, delay, stops and queue are relatively complex. Also, the change observed for delay did not follow the changes observed for stops and queue length.

The impact on emissions is illustrated in Figure 9.28. The change in emissions of CO and HC are similar to each other over the whole range of flows tested. These changes are clearly influenced by the changes in delay. For example, the peak in the change to delay also corresponds to the peak in the change of CO and HC.

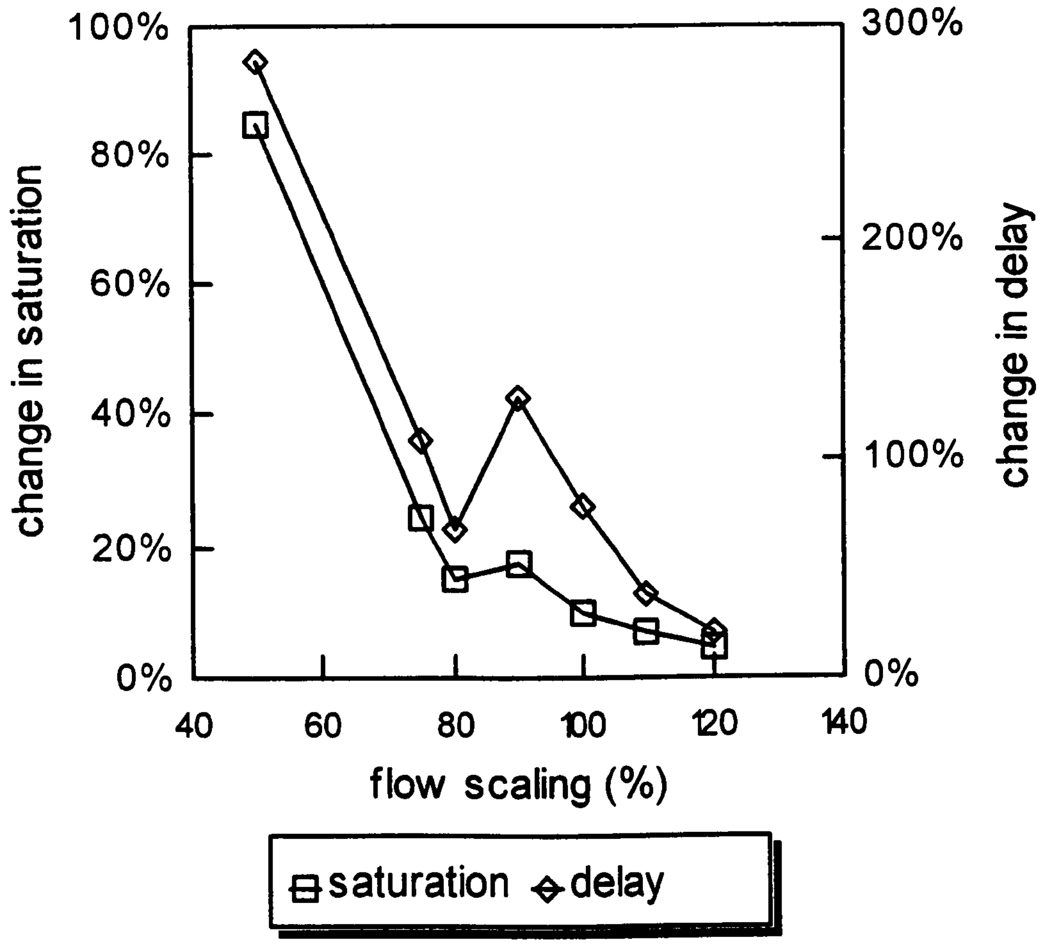

Figure 9.26 Impact of 500 percent delay weighting on link degree of saturation and delay as a function of flow

However, the changes in emissions of NOx reveal some interesting characteristics. Firstly, the changes in NOx do not correspond to the changes in CO and HC. Secondly, the changes in NOx are sometimes positive and sometimes negative. This, therefore, answers the above question: on a given link, changes in emissions of NOx caused by a particular strategy may or may not be in the same direction as changes in emissions of CO and HC.

The changes in NOx do not closely follow the change in delay. They do, however, indicate a relationship to stops, in that its trend is almost the inverse of the change in stops. The exception being at a flow scaling value of 90 percent where the change in NOx increases relative to the previous point. This is because, at this flow, the significant increase in idling emissions causes overall NOx emissions to increase.

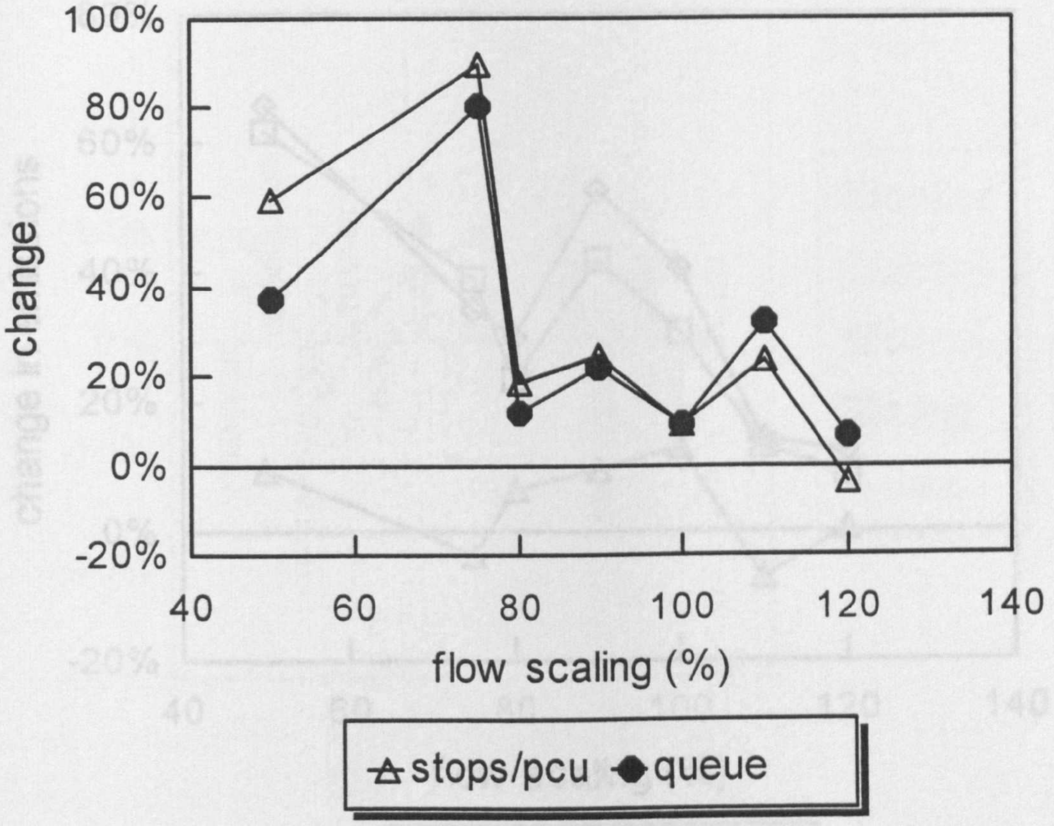

Figure 9.27 Impact of 500 percent delay weighting on link stops and queue length

The change in emissions from each driving mode were investigated to understand the behaviour of NOx emissions. Figure 9.29 illustrates the effect the strategy had on emissions from each driving mode as a function of flow. In this figure, the change in driving mode emissions represents the percentage change of total link emissions, as opposed to the percentage change in a particular driving mode's emissions. Hence, if changes from all driving mode emissions are totalled they give the change in total link emissions.

A number of important points may be derived from this figure. It can be seen that the changes in deceleration emissions were not significant (being barely detectable on the graph), whereas changes in acceleration emissions were significant. The changes in idling and cruise emissions were the dominant factors influencing the change in total NOx emissions. Changes in idling and cruise emissions were always in opposite directions and whichever had the greater magnitude of change usually determined the

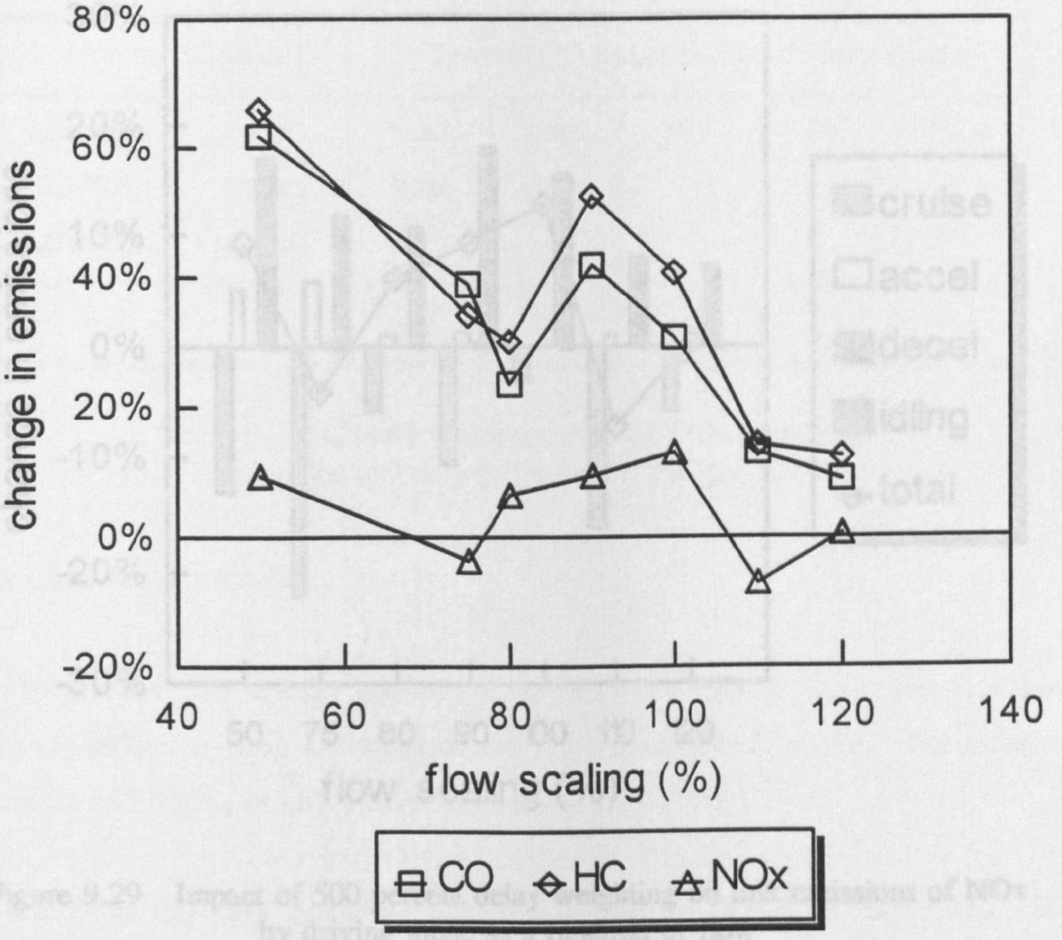

Figure 9.28 Impact of 500 percent delay weighting on link emissions as a function of flow

change in overall emissions.

At 50 percent flow the increase in idling emissions slightly outweighed the decrease in cruise emissions resulting in a net increase of NOx. In this particular case, the change in acceleration emissions also made a significant contribution to the net increase in NOx emissions.

At 100 percent flow, the strategy only caused a slight reduction in cruise emissions, but increased idling emissions substantially. Consequently, the net effect was a relatively large increase in total NOx emissions.

Comparing the change in cruise emissions with the change in stops, it can be seen that

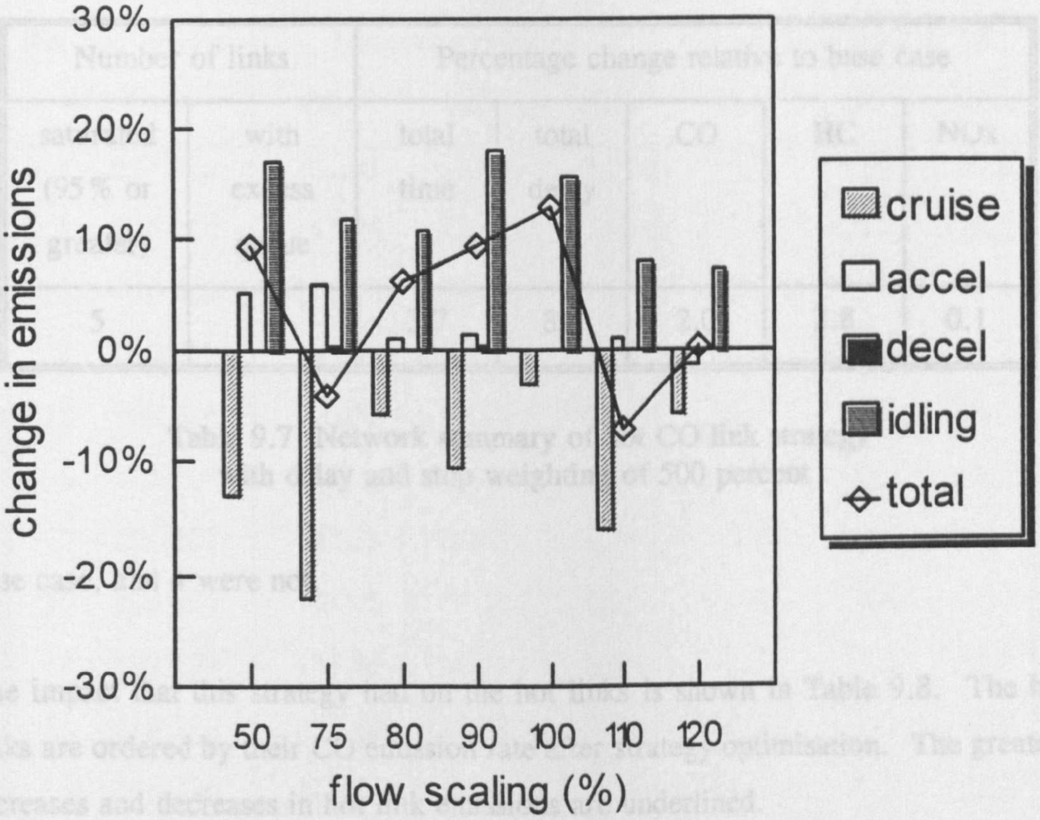

Figure 9.29 Impact of 500 percent delay weighting on link emissions of NOx by driving mode as a function of flow

they reflected the inverse behaviour of stops. The change in acceleration followed the change in stops, and the change in idling followed the change in delay.

Delay and stop weighting factor of 500 percent

This section describes the results obtained from a TRANSYT run which had both delay and stop weighting factors of 500 percent assigned to hot CO links. This resulted in 21 links having their flow reduced. The impact this strategy had on the network is summarised in Table 9.7. The number of saturated links had increased by one and the number of links with excessive queue lengths had increased by four.

In the base case 20 hot links had emissions of CO greater than, or equal to, 118 g/min. After the application of this strategy, only 17 links on the network had emissions greater than or equal to this value. Of these 13 links were hot links in the

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
5	11	3.7	8.4	2.0	2.8	0.1

Table 9.7 Network summary of hot CO link strategy with delay and stop weighting of 500 percent

base case, and 4 were not.

The impact that this strategy had on the hot links is shown in Table 9.8. The hot links are ordered by their CO emission rate after strategy optimisation. The greatest increases and decreases in hot link emissions are underlined.

Of the 20 hot CO links, emissions were reduced on 15, 15 and 7 links for CO, HC and NOx respectively. However, emissions increased on 5, 4 and 13 links for CO, HC and NOx respectively. Note that most hot CO links experienced reductions in emissions of CO and HC, but experienced increases in emissions of NOx.

Fourteen hot links experienced changes of CO in the opposite direction to changes in NOx. On a link by link basis, the changes in CO and HC were very similar to each other, with the change in CO usually (14 of the 20 hot links) being greater that the change in HC. The hot link changes in CO, and HC, reflected the changes in link delays and stops.

Hot NOx Links

This section describes the results of strategies which aimed to reduce emissions of NOx on those links which had the highest emissions of NOx. These links were referred to as hot NOx links.

Hot link number and nodes		Network emissions			Change in emissions (%)		
		CO	HC	NOx	CO	HC	NOx
2	227 226	382.25	51.80	8.37	56.7	73.4	15.6
1	225 226	247.96	32.46	5.15	-33.0	-36.9	-26.8
3	491 226	212.87	24.08	9.37	-2.9	-2.9	0.4
5	216 217	191.19	18.79	11.36	3.3	1.1	-1.2
15	259 216	170.58	19.58	4.90	39.4	34.4	-18.7
6	226 207	153.25	19.43	14.28	-8.3	-3.2	0.3
7	228 227	148.38	16.68	8.24	-3.3	-2.5	1.7
10	206 227	143.75	17.61	6.25	3.2	4.6	1.3
9	198 199	135.43	14.64	6.85	-5.3	-3.2	2.5
11	218 219	133.50	17.48	7.02	-2.6	-1.1	2.0
4	195 196	129.86	14.16	5.39	-34.5	-31.9	38.2
8	213 214	129.31	12.58	6.07	-11.0	-9.9	-1.5
18	219 220	120.89	16.57	9.94	0.5	0.0	-0.1
13	207 208	113.33	11.99	10.06	-12.3	-10.2	-0.8
16	196 197	113.19	11.81	8.12	-6.9	-6.0	0.1
17	262 261	112.25	13.81	3.10	-7.2	-7.3	4.0
20	199 212	108.26	12.40	5.68	-8.6	-10.5	-1.7
14	217 218	104.32	11.72	6.66	-17.6	-15.6	4.4
12	331 216	103.92	13.16	3.94	-20.8	-19.4	8.2
19	212 213	63.27	7.16	4.94	-46.8	-35.6	6.2

Table 9.8 Impact of 500 percent delay and stop weighting on hot CO links

The earlier sections of this chapter have shown that a significant proportion of NOx emissions arise from acceleration. Therefore, the first of the strategies described below aimed to reduce NOx emissions by reducing the number of stops on hot NOx links and hence the emissions contribution from acceleration. A number of runs were carried out using increased TRANSYT stop weighting factors on the hot NOx links, leaving other links with the delay and stop weights used in the base case scenario.

It has also been shown above that the major contribution to NOx emissions comes from cruise emissions. Therefore, strategies which aimed to increase the number of stops on hot NOx links were also tested by lowering the stop weighting factor on these links below their base case values.

Stop weighting factor of 9999 percent

The maximum stop weighting factor was applied to the hot NOx links, giving these links a stop weighting 99.99 times their base case value. Table 9.9 summarises the impact this strategy had on the network.

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
7	11	16.6	37.2	9.5	12.6	1.5

Table 9.9 Network summary of hot NOx link strategy with stop weighting of 9999 percent

The worst increases in emissions on the hot NOx links were 55, 71 and 16 percent for CO, HC and NOx respectively. The best decreases on the hot NOx links were 38, 40 and 28 percent for CO, HC and NOx respectively. Once again, this illustrates that the change in network emissions of CO and HC are larger than the change in emissions of NOx.

This strategy caused significant disruption to the network, with significant increases in total network emissions and would have also resulted in traffic rerouting. Therefore, these unrealistic results did not represent a viable solution.

Stop weighting factor of 500 percent

A stop weighting factor of 500 percent was tried on the hot NOx links, but this was also unsuccessful. The impact this strategy had on the network is summarised in Table 9.10.

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
4	9	0.5	1.1	0.0	0.3	0.3

Table 9.10 Network summary of hot NOx link strategy with stop weighting of 500 percent

The largest hot link increases were 10, 9 and 7 percent for CO, HC and NOx respectively. The best decreases in hot link emissions were 29 and 25 percent for CO and HC, but only 1 percent for NOx. Of the 20 hot NOx links, 9 had changes of CO in the opposite direction to changes in NOx, only 5 links had emissions of NOx reduced, 8 links had NOx increased and 7 had changes smaller than 0.1 percent.

Stop weighting factor of -500 percent

This strategy involved reducing the stop weighting factor on hot NOx links to encourage TRANSYT to increase the number of stops on these links, compared with the base case scenario. This resulted in significant disruption to the network, as illustrated in Table 9.11.

The largest percentage increase of the hot NOx links for CO and HC occurred on hot link 12, for which the increases were 472 and 495 percent respectively! The largest increase in NOx also occurred on the same link, and was an increase of 46 percent. The best reduction in emissions of CO and HC occurred on hot NOx link 17, for which the reductions were 17 and 19 percent respectively. Hot link 9 experienced the

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
10	9	19.5	43.1	21.5	17.1	3.9

Table 9.11 Network summary of hot NOx link strategy with stop weighting of -500 percent

best percentage reduction in NOx of 29 percent.

Of the 20 hot NOx links, 18 experienced changes in CO in the opposite direction to changes in NOx, and 17 links had emissions of NOx reduced.

Stop weighting factor of -200 percent

Although the above strategy reduced emissions of NOx by a significant amount, it caused significant delay to traffic on the network and increased emissions of CO and HC. Therefore, a compromise between emissions of CO and HC, and NOx was sought by applying a smaller stop weighting factor of -200 percent. The impact this strategy had on the network is summarised in Table 9.12.

Number of links		Percentage change relative to base case				
saturated (95% or greater)	with excess queue	total time	total delay	CO	HC	NOx
4	6	3.7	8.4	9.9	4.6	-3.9

Table 9.12 Network summary of hot NOx link strategy with stop weighting of -200 percent

This strategy resulted in the same number of saturated links as the base case scenario, reduced the number of links with excessive queue lengths by one, but had 7 links with reduced flows compared with 4 for the base case.

In the base case the emission rate of NOx for hot link number 20 was 6.68 grams per minute. After the application of this strategy only 14 links had emissions equal to, or greater than, this value.

The impact that this strategy had on the hot links is shown in Table 9.13. The hot links are ordered by their NOx emission rate after strategy optimisation. The greatest increases and decreases in hot link emissions are underlined.

Note that the increases in CO and HC were much less than the previous strategy, whilst changes in NOx were almost identical. The largest hot link percentage increase in emissions of CO occurred on the hottest NOx link and increased by 166 percent. The largest increase in HC was 77 percent on hot link 11. Hot NOx link 15 had the biggest increase in NOx emissions of 9 percent. The best hot link decrease in emissions of CO and HC occurred on hot link 17, for which the decreases were 17 and 19 percent respectively. Hot link 9 experienced the best percentage reduction in NOx of 25 percent.

Of the 20 hot NOx links, emissions increased on 17, 16 and 3 links and decreased on 3, 4, and 17 links for CO, HC and NOx respectively. Of the 20 hot links, 16 experienced changes of CO in the opposite direction to changes in NOx. The changes in emissions of NOx were also found to be in the opposite direction to changes in delays and stops.

Other strategies for hot NOx links

Other strategies were tried for reducing NOx emissions on hot links but they were unsuccessful or not practical. A stop weighting factor of -1000 was rejected on the basis of its impact on the traffic network and increases to network emissions of CO, HC and NOx of 53, 60 and 2 percent respectively. Setting the delay weighting factor on hot NOx links to a value of -500 was rejected based on its unacceptable impact

Hot link number and nodes	Network emissions			Change in emissions (%)		
	CO	HC	NOx	CO	HC	NOx
2 226 207	210.69	22.41	13.31	26.1	11.6	-6.5
1 210 211	308.46	24.61	13.09	166.3	75.7	-11.9
5 219 220	134.55	17.28	9.86	11.8	4.3	-0.9
3 216 217	227.58	22.13	9.42	23.0	19.0	-18.1
7 491 226	212.87	24.08	9.37	-2.9	-2.9	0.4
6 260 259	120.93	14.46	9.32	15.8	3.1	-4.3
4 207 208	245.94	21.02	8.53	90.2	57.5	-15.9
10 228 227	158.72	17.62	8.01	3.4	3.0	-1.1
12 205 206	170.97	14.76	7.99	115.1	74.9	4.2
15 227 226	292.33	38.44	7.89	19.8	28.7	9.0
13 226 227	107.91	11.27	7.58	45.7	35.9	-0.8
14 215 259	79.49	10.8	7.28	-0.2	-0.2	-0.1
8 214 215	160.04	14.18	6.86	80.4	45.1	-22.3
11 204 205	208.26	18.12	6.46	106.2	77.1	-18.9
18 218 219	140.9	17.44	6.42	2.8	-1.4	-6.7
20 198 199	160.61	16.3	6.27	12.3	7.8	-6.1
19 208 209	200.46	16.52	6.21	83.3	44.7	-9.5
17 225 226	307.55	41.72	6.07	-16.8	-18.8	-13.8
9 196 197	198.03	17.8	6.05	62.9	41.7	-25.4
16 209 210	191.6	16.78	5.71	92.9	59.7	-20.9

Table 9.13 Impact of -200 percent stop weighting on hot NOx links

on the traffic network. Similarly, a delay and stop weighting factor of -500 was also rejected.

Link Emissions by Driving Mode

As shown earlier, the reason as to why some links behave differently to others can be illustrated if individual link emissions are analyzed by driving mode. This section presents link emissions by driving mode and highlights reasons for particular link emission characteristics.

The impact that stops and delay have on link emissions is represented by the emissions resulting from acceleration, deceleration and idling. Therefore, significant changes in stops and delay will have significant changes on these emissions. If these emissions represent a significant proportion of overall link emissions, then the changes in stops and delay can have a significant impact on overall link emissions.

Analysis of the hot CO and hot NOx links by combined emissions from acceleration, deceleration and idling revealed the following. Of the 20 hot CO links, 14 links were in the top 20 links when sorted by combined CO emissions from these three driving modes. This illustrates the strong correlation between emissions from these driving modes and overall hot link emissions.

Whereas, of the 20 hot NOx links, only 8 links were in the top 20 links sorted by combined NOx emissions from these driving modes. This illustrates that hot NOx emissions are much less dependent on emissions from acceleration, deceleration and idling. Generally, for hot NOx links, cruise emissions were the dominant factor.

Figure 9.30 illustrates individual link emissions of CO by driving mode, for the hot CO links of the base case scenario. The x-axis represents individual links sorted by their CO emission rate. Many of the links with high emissions of CO have a substantial contribution from idling and significant contributions from acceleration and cruising. Some of the links with high CO emissions have major contributions from cruising. This is because one of the dominant factors in overall link emissions is, of course, the link flow. Therefore, a relatively unsaturated link, with most of its emissions arising from cruise emissions, can have high emissions simply because it has a high flow.

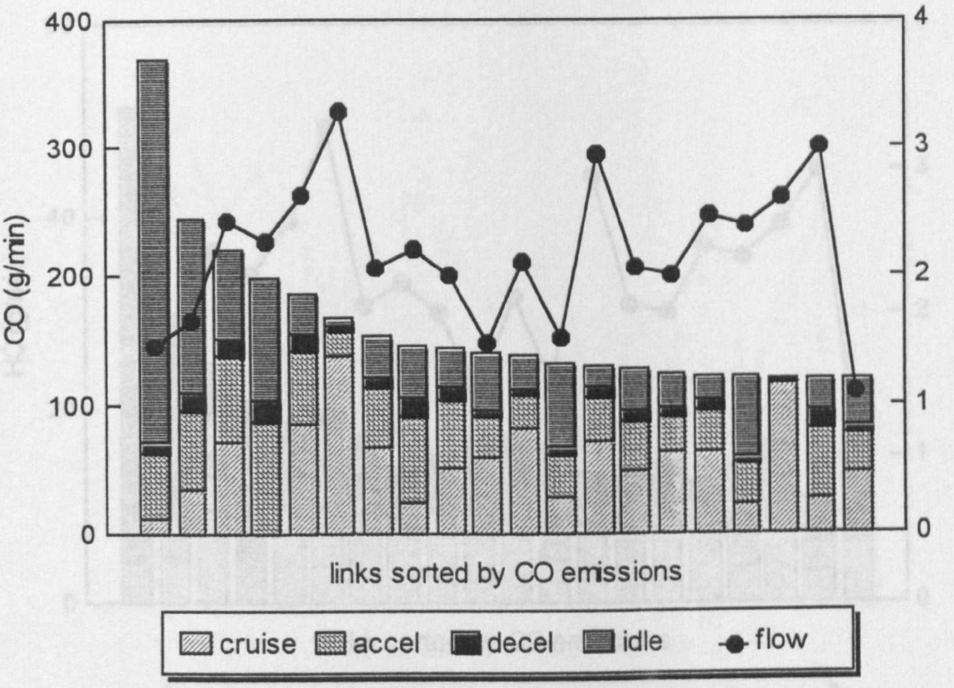

Figure 9.30 Link emissions of CO by driving mode for hot CO links

This figure also includes the link flow on each link. This illustrates that whilst link flow is a factor in link emissions, link emissions do not correlate well with flow alone, especially for the congested links.

Figure 9.31 illustrates individual link emissions of HC by driving mode, again with links sorted by their CO emission rate. Comparison with Figure 9.30 highlights the similarity between emissions of CO and HC, both in terms of overall link emissions and the relative contributions from each driving mode. Consequently, emissions of CO and HC generally behave in a similar manner to each other, for a given traffic control strategy. Although as shown earlier, there are occasions when their behaviour is different to some extent.

Link emissions of NOx by driving mode are illustrated in Figure 9.32. The x-axis represents hot NOx links sorted by their emission rate of NOx. This clearly illustrates the marked contrast between emissions of NOx and those of CO and HC. In particular, it can be seen that for most links, cruise emissions are the dominant factor for overall emissions of NOx. It is this factor that often explains the frequently observed opposite behaviour between changes in emissions of NOx and changes in CO

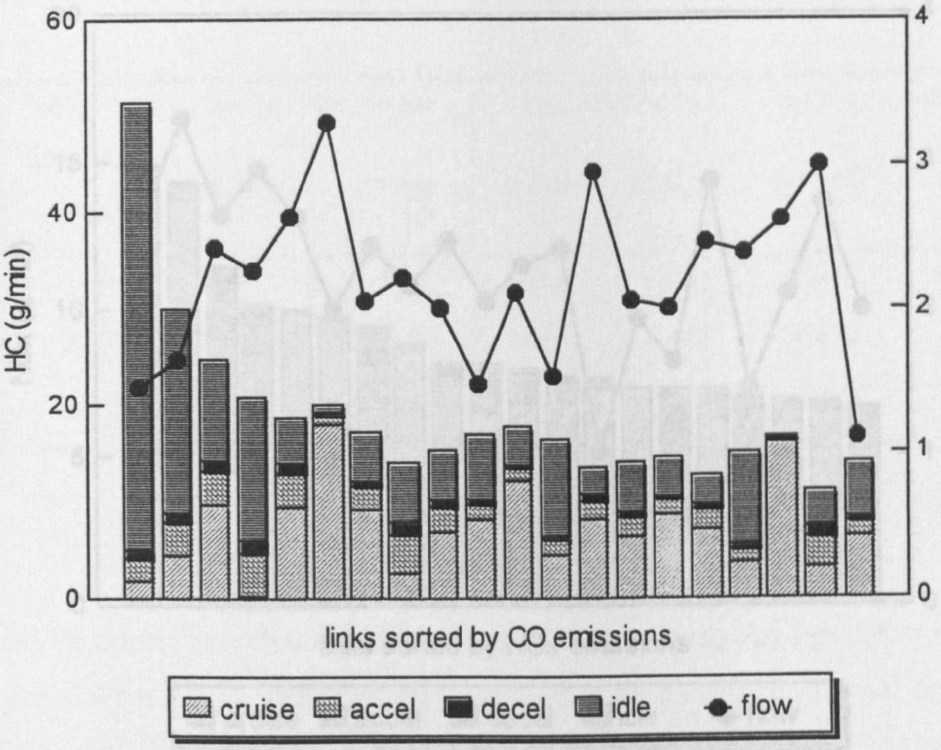

Figure 9.31 Link emissions of HC by driving mode for hot CO links

and HC. Note also that emissions from deceleration are negligible.

A few heavily saturated links have significant, and in one case major, contributions from idling and acceleration. Such links may have their overall emissions of NOx respond in the same manner as overall emissions of CO and HC for a given strategy.

If the major component of NOx emissions arise from acceleration and idling then a significant reduction in the link's degree of saturation may result in a significant reduction of overall NOx emissions. However, if emissions from acceleration and idling are comparable with cruise emissions, a reduction in the degree of saturation may result in a reduction of emissions from acceleration and idling, but these could be offset by a similar or slightly larger increase in cruise emissions. For links which have a high proportion of cruise emissions, it is likely that a reduction in the degree of saturation will increase overall NOx emissions.

Therefore, looking at Figure 9.32, most hot NOx links would be expected to increase their emissions of NOx, if the degree of saturation was reduced. Indeed, this was

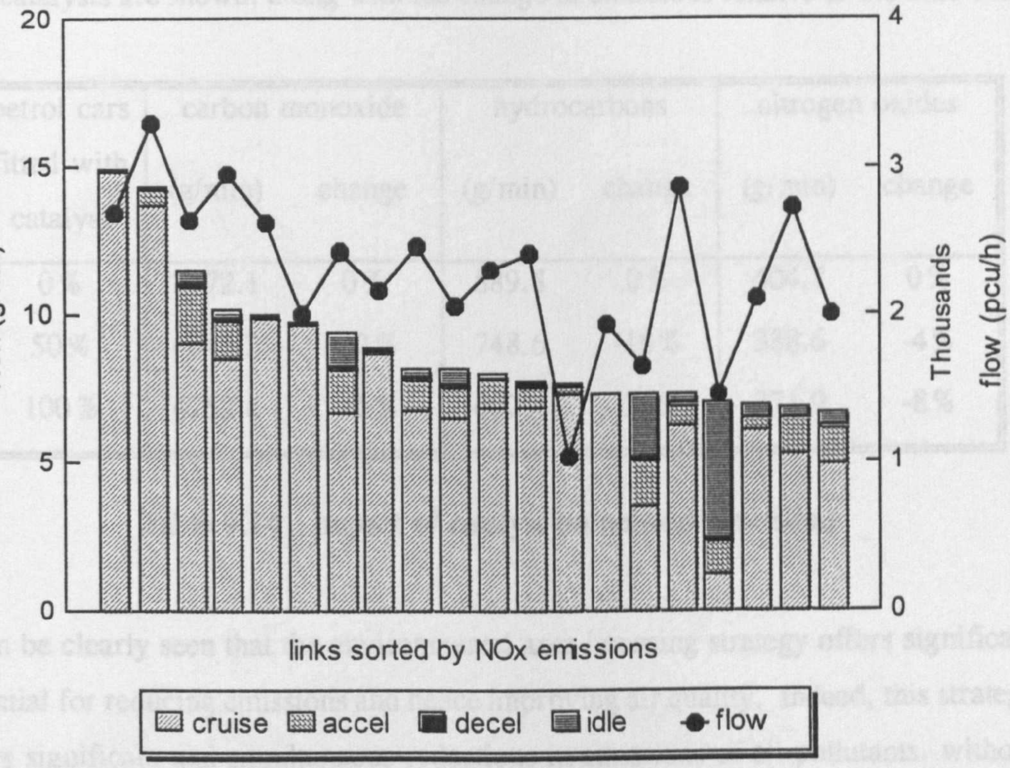

Figure 9.32 Link emissions of NOx by driving mode for hot NOx links

observed in the above strategies. Hence, to reduce NOx emissions on most of these links the degree of saturation needs to be increased by setting non-optimal, in terms of traffic performance, signal timings for these links. This was shown to be the case for the hot NOx link optimisation strategy. Emissions of NOx were decreased by reducing the cost of stops and, hence, allowing more traffic to be stopped on links which initially had high emissions of NOx.

9.9 ENVIRONMENTAL AREA LICENSING

This section describes the impact that the introduction of petrol powered cars equipped with catalytic converters would have on network emissions. The findings of this are directly applicable to the environmental area licensing strategy.

The impact of this strategy is illustrated in Table 9.14. Total network emissions for the base case, and scenarios with 50 and 100 percent of petrol powered cars fitted with catalysts are shown, along with the change in emissions relative to the base case.

petrol cars fitted with catalyst	carbon monoxide		hydrocarbons		nitrogen oxides	
	(g/min)	change	(g/min)	change	(g/min)	change
0%	7772.1	0%	889.8	0%	404.7	0%
50%	6043.2	-22%	748.6	-16%	388.6	-4%
100%	4252.6	-45%	602.4	-32%	371.9	-8%

Table 9.14 Impact of catalyst on network emissions

It can be clearly seen that the environmental area licensing strategy offers significant potential for reducing emissions and hence improving air quality. Indeed, this strategy offers significant and simultaneous reductions in emissions of all pollutants, without compromising the efficiency of the traffic network.

Analysis of the reductions in link emissions, as a result of environmental area licensing, revealed that the best reductions in individual link emissions were 53, 43 and 49 percent for CO, HC and NOx respectively. Note that all pollutants were reduced and the reduction in NOx was comparable to those for CO and HC.

Figure 9.33 illustrates the impact that the environmental area licensing strategy had on emissions by driving mode. It can be seen that significant changes were made to the proportions of emissions from each driving mode. In particular, the proportion from cruise emissions increased for all pollutants. While the proportion from all other driving modes decreased.

9.10 DISCUSSION

The results from each of the sensitivity tests and control strategies are discussed below. The control strategies either had a primary objective to minimise total network emissions, or particular hot link emissions. All of these strategies did of course have

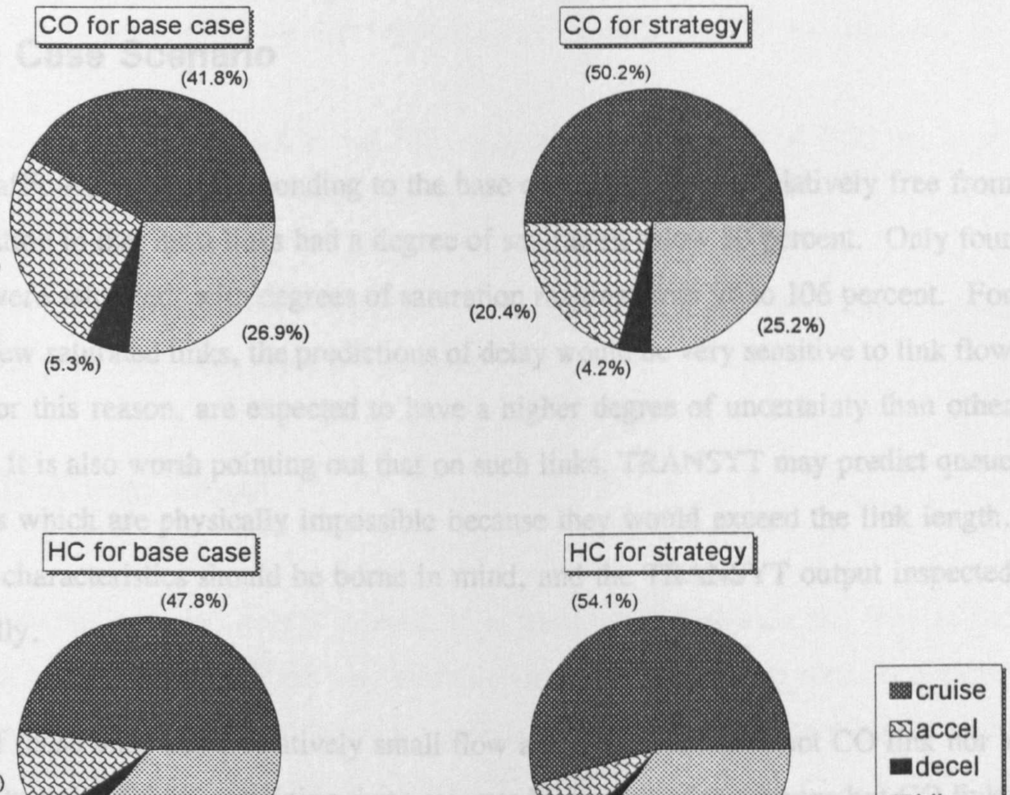

Figure 9.33 Breakdown of emissions by driving mode for the environmental area licensing strategy

an impact on both total network emissions and individual link emissions.

Base Case Scenario

The traffic network corresponding to the base case scenario was relatively free from congestion in that most links had a degree of saturation below 80 percent. Only four links were saturated, with degrees of saturation ranging from 98 to 106 percent. For these few saturated links, the predictions of delay would be very sensitive to link flow and, for this reason, are expected to have a higher degree of uncertainty than other links. It is also worth pointing out that on such links, TRANSYT may predict queue lengths which are physically impossible because they would exceed the link length. These characteristics should be borne in mind, and the TRANSYT output inspected carefully.

One of these links had a relatively small flow and it was neither a hot CO link nor a hot NOx link. Of the remaining three saturated links, all of them were hot CO links (hot CO link numbers 1, 2 and 4), but only two were hot NOx links (hot NOx link numbers 15 and 17). Therefore, these saturated links did make significant contributions to CO emissions, but made a much lower contribution to NOx emissions.

In terms of optimising link travel times, and emissions of CO and HC, a traffic engineer may target these links for improvements. However, the top three links with the highest emissions of CO compete for green time at the same intersection. Consequently, the traffic engineer may wish to make junction improvements. For example, in this particular case, significant benefits would be likely if an under- or over-pass was constructed at this intersection.

No Optimisation Scenario

Although this scenario did not reflect reality, because of unrealistically large delay, it does illustrate a number of important points, namely:

- poor signal timings can cause long delays;
- poor signal timings result in large emissions of CO and HC; and
- compared to CO and HC, total network emissions of NOx are much less sensitive to the change in signal timings.

These conclusions have been confirmed in the sensitivity tests and signal timing strategies presented throughout this chapter.

Sensitivity to Flow

Total network and link delays increase in a non-linear manner as the flow in the network is increased, and links near saturation are very sensitive to changes in flow. Therefore, any pollutant which has a significant contribution to its emissions from idling will respond in a non-linear manner. This was the case with CO and HC and their emissions increased non-linearly with flow. In the case of NOx, idling emissions did not represent a significant contribution to overall emissions. Consequently, overall NOx emissions had an almost linear relationship with flow.

The higher flow levels tested resulted in a few links being unrealistically over saturated and in reality some vehicles may have rerouted around these congested links. Therefore, for a more accurate representation of the overall process, an assignment model should be used. Nevertheless, the general relationships observed in this sensitivity test are still valid.

The analysis of emissions by driving mode was split into two parts: the top 20 hot links; and the remaining 76 links. This revealed that, for CO and HC, the total of the hot link emissions from idling almost matched the total idling emissions from all the other links. Whereas, hot link cruise emissions were considerably lower than total cruise emissions from the other links. Also it indicates that idling emissions are a major contributor to overall emissions of CO and HC. Indeed, at the higher flows they were the dominant source of these emissions. Emissions from acceleration remained a relatively constant proportion of overall emissions, over the range of flows tested. The proportion of overall emissions from deceleration also remained relatively constant, but these emissions only made a small contribution to overall emissions.

Emissions of NOx behaved differently to those of CO and HC. Cruise emissions remained the dominant source of emissions for all links over the range of flows tested. The proportion of emissions from acceleration were greater than those from idling at low flows, but the situation was reversed at high flows. Emissions from deceleration were negligible for all flows.

This sensitivity test showed that, for all pollutants, the proportion that each driving mode contributed to overall emissions varied with flow. It also indicated that, even for a given flow, these proportions varied significantly from link to link, particularly between hot links and other links.

The relationship between different pollutants as a function of flow revealed that the ratio of CO to HC remained relatively constant. However, the ratios of CO to NOx and HC to NOx did not remain constant, and the relationship was a non-linear one. At the higher flows, the emissions of CO and HC increased much quicker than that of NOx because idling emissions of CO and HC were the dominant factor and followed the non-linear response of total delay.

It was observed that the link emissions of CO and HC correlated well with each other. Whereas, link emissions of CO and HC did not correlate well with emissions of NOx.

Sensitivity to Cruise Speed

The sensitivity test of emissions with respect to cruise speed revealed an interesting aspect. Unlike most of the other tests and strategies described in this chapter, the behaviour of CO and NOx, in terms of changes relative to the base case, were very similar but HC behaved differently. For example, at the lowest speeds emissions of HC reached their highest. While emissions of CO and NOx were at their highest at the highest speeds tested.

This behaviour was relatively complex and can only be predicted by an emissions model which represents emissions from each driving mode, or one which models emissions as a function of instantaneous speed and acceleration.

For example, the reason that emissions of HC increased quicker than CO and NOx at low cruise speeds was as follows. Idling emissions were relatively insensitive to the cruise speed and deceleration emissions were relatively insignificant. Therefore, idling and deceleration did not play a significant role in the behaviour of overall emissions. At the lower speeds, acceleration emissions were relatively insensitive to changes in cruise speed. Therefore, the behaviour of overall emissions was mainly due to cruise emissions.

Cruise emissions of NOx increased relatively slowly, hence the relatively small increase in NOx emissions compared to HC. However, cruise emissions of CO increased in a similar way to those for HC, so why did overall CO emissions not increase as much as overall HC emissions? The reason was that the proportion of total emissions from cruising were higher for HC than they were for CO. In addition, cruise emissions of HC increased slightly faster than CO with reductions in cruise speed. Hence, overall HC emissions increased more than overall CO emissions.

Perhaps surprisingly, the analysis of the relationship between different pollutants revealed that the ratio between CO and HC is not constant as a function of speed.

Therefore, this sensitivity test illustrated two important points:

- each pollutant has its own unique characteristics and may respond in a different way to other pollutants; and

- it is important that such behaviour is recognised, and this can only be achieved by representing emissions from each driving mode.

Delay to Stops Weighting Ratio

The degree of success that this strategy had, in terms of reducing total network emissions, was small. Emissions of CO were not reduced below the base case emissions level. A delay weighting 100 times the stop weighting managed to achieve the best reductions for HC and NOx. However, these reductions were small at 0.4 and 0.9 percent for HC and NOx respectively. A stop weighting 100 times that of delay caused TRANSYT to predict unrealistically large delays on a few links.

On a positive note, the base case delay and stop weightings represented a good optimisation for network emissions of all pollutants. Therefore, using a fairly typical delay to stop weighting ratio of 55:50 not only gives a good optimisation in terms of stops and delay, it also appears to give a good optimisation in terms of the emissions of CO, HC and NOx.

Cycle Times

In general, changes to the cycle time reduced network emissions of CO and NOx. Whereas, for HC some cycle times increased emissions and others reduced emissions. A cycle time of 140 seconds gave relatively good reductions in all pollutants, particularly CO which had its emissions reduced to a minimum. The best reduction of HC emissions occurred at a cycle time of 100 seconds. While the best reduction in emissions of NOx occurred at a cycle time of 200 seconds, but this slightly increased emissions of CO and significantly increased emissions of HC.

The 'blip' for a cycle time of 180 seconds was because the automatic cycle time option of TRANSYT had been selected. This caused TRANSYT to automatically determine which nodes should be double cycled, resulting in a further reduction of pollutant emissions.

The results from this strategy showed that each pollutant behaved differently. Some cycles times represented a good compromise in terms of reducing all pollutant emissions, but other cycle times gave good reductions in one or two pollutants at the expense of others. This illustrates the need for the objectives of a pollution reduction strategy to be clearly defined, particularly in terms of which pollutants are to be reduced and which have priority.

Optimisation of Hot Links

The 'decision maker' should recognise that a traffic control strategy may have to address pollutant emissions on particular links, rather that total network emissions. For example, the EC directive for NOx defines limit and guideline pollutant concentrations which correspond to values measured at point locations. So for example, if a few streets were exceeding the limit value for NOx the traffic control strategy may have to address this. Lowering the NOx emissions on these streets may be at the expense of increased emissions on other streets, or even other pollutants on the same streets. This was the purpose of the strategies presented in this section: to address emissions on a street by street basis.

Hot links

The 20 links that had the highest emissions of CO, and typically the highest of HC, were labelled hot CO links. This strategy aimed to reduced the emissions of CO on the hot CO links.

It was shown that emissions of CO and HC could be significantly reduced on links that had high emissions of these pollutants, by increasing their cost of delay relative to other links. However, care had to be taken to ensure that unrealistic sacrifices were not made on other links sharing the same downstream intersection.

The reductions made in emissions of CO and HC frequently resulted in increased emissions of NOx on the same links. Closer inspection revealed that when link emissions of CO and HC were reduced, NOx emissions either increased, decreased or did not significantly change. The reasons for this could only be explained by analysing emissions from each driving mode.

For a given link, the response of NOx was dependent upon its initial emissions from cruise, acceleration and idling. For example, a heavily congested link may have most of its NOx emissions caused by idling and acceleration. When such a link is optimised to reduce emissions of CO and HC, the NOx idling and acceleration emissions may fall substantially. However, a significant increase in the amount of free flowing traffic can cause a much larger increase in cruise emissions. Hence, the net effect is an increase in overall emissions of NOx.

On some links the balance between emissions from idling and acceleration emissions, and those from cruising are such that the decrease in one is almost counteracted by an increase in the other resulting in no significant change to overall emissions of NOx.

In some cases, optimisation reduces emissions of CO and HC by only removing some delay on a link. This causes NOx idling emissions to fall, but it may not increase emissions from cruising. Hence, overall emissions of NOx fall, along with those of CO and HC.

In practice, identification of such links can only be performed with the use of a model, such as that used by the author in this research. Although the cause of this behaviour can be identified and explained, there are too many parameters involved to make generalisations. For example, some of the parameters which typically determine how a link's emissions of NOx will respond are: flow, degree of saturation, cruise speed, link length, delay, stops and queue length. This represents a multi-dimensional problem which is best solved through the aid of a computer model.

It should be stressed that no simple generalisation can be made about emissions of NOx, and each link must be treated as a unique case.

Although an exhaustive number of combinations were not tested, a good reduction in emissions of CO and HC was obtained by increasing delay and stop costs by 500 percent on hot CO links. This caused a slight increase in total network emissions by 2.0, 2.8 and 0.1 percent for CO, HC and NOx respectively.

Note that the change in idling and cruise emissions on a given link can be relatively large, but in opposite directions to each other. Also, these emissions are likely to be spatially separated. For example, idling emissions often occur near the downstream intersection, whereas cruise emissions are distributed along (part of) the link. Therefore, pollutant concentrations may change significantly at points along a link.

Bearing in mind the magnitude of these changes, it could be envisaged, for example, where a strategy makes no, or little, change in terms of total NOx emissions on a link, but increases idling and decreases cruise emissions by a significant amount. Such a scenario may result in lower pollutant concentrations along that part of the link corresponding to cruise emissions and increased concentrations nearer the downstream intersection.

As described above, the mechanisms responsible for the emissions of NOx are relatively complex and their behaviour is frequently opposite to that of CO or HC. Of the strategies tested by the author, the best strategy for reducing emissions of NOx, on hot NOx links, involved increasing the number of stops on hot NOx links.

Clearly, such a strategy has a negative impact on traffic performance and emissions of CO and HC. Initially, a scaling factor of -500 percent was applied to the cost of stops for hot NOx links. This gave good reductions in emissions of NOx, at the expense of severe increases in emissions of CO and HC. However, it was found that when the scaling factor was changed to -200 percent, the impact on emissions of NOx was the same but the increases in CO, HC and delay were much less severe.

Link emissions by driving mode

An analysis of hot link emissions by driving mode illustrated why individual link emissions behave in a particular manner. It was shown that the hot CO link emissions of CO and HC were dominated by emissions from idling, and to a lesser extent acceleration. Whereas, hot NOx link emissions of NOx, indeed most link emissions NOx, were dominated by cruise emissions.

Environmental Area Licensing

This strategy gave substantial reductions in individual link and total network emissions for all pollutants. From an environmental point of view, this strategy is superior to the above strategies based on the adjustment of traffic signal timings.

The reductions in emissions for the Athens study network could probably be improved further if the approach was applied to all vehicle categories. In the scenario tested catalytic converters were only fitted to petrol powered cars, which accounted for 57 percent of the Athens traffic fleet. Hence, some of the remaining emissions, after the application of this strategy, were due to diesel powered cars and buses.

The reduction in emissions of NOx were smaller than the reduction in emissions of CO and HC. There are two reasons for this. Firstly, the NOx cruise emissions of the Athens petrol car fleet were relatively low. The PREDICT consortium members recognised that the Athens fleet consisted of a high proportion of old vehicles. As was shown in earlier chapters of this thesis, old poorly maintained vehicles often have higher emissions of CO and HC but lower emissions of NOx. Secondly, it is also known that diesel cars have relatively high emissions of NOx compared with petrol cars equipped with a catalytic converter; and large diesel engines, such as those in buses, emit large quantities of NOx. As a large proportion of the Athens' fleet consisted of these diesel vehicles, they made a significant contribution to total network emissions of NOx.

Perhaps these factors could be investigated in a follow-up study, and the results of this work validated using emissions data suitable to other urban areas throughout Europe. As part of the QUARTET project, the author is currently assessing the implications of these strategies to other urban areas throughout Europe, and the corresponding modelling work will attempt to address these factors.

Chapter 10
SUMMARY

This chapter summarises the work carried out by the author and documented in this thesis. It covers the author's research from 1989 to 1994 into road traffic emissions and environmentally sensitive traffic control strategies.

Chapter 2 introduced the concepts, mechanisms and effects of air pollution. Emissions of carbon monoxide and hydrocarbons are formed as a result of incomplete combustion in a vehicle's engine. While emissions of nitrogen oxide are formed from the reaction between atmospheric nitrogen and oxygen as a result of the high temperatures in the combustion chamber. The mechanisms for pollutant generation tend to suggest that strategies which aim to regulate emissions based on traffic speed control or enhanced engine technology, may reduce emissions of some pollutants but increase others.

In general, emissions will be dispersed effectively when the source is exposed to relatively high wind speeds and unstable atmospheric conditions. However, sources sheltered in 'canyons', formed by tall buildings both sides of a road, may experience poor dispersion of pollutants, resulting in higher pollutant concentrations. Urban areas sheltered by the local geographic topology and stable atmospheric conditions, may also experience high pollutant concentrations. Under these conditions, and in bright sunlight, the primary pollutants react to form a photochemical smog. Examples of this phenomena are found in Los Angeles and Athens.

The effects of air pollution are wide ranging, affecting the environment, vegetation and health. The effects of air pollution form the basis for air pollution guidelines and standards. Ultimately, these represent the goals that environmentally sensitive traffic control strategies aim to achieve.

The regulatory framework for air quality has been briefly described in Chapter 3. Air quality standards serve to ensure that safe levels are maintained and these are supposed to be enforced by local or national organisations.

Chapter 3 has also described studies which aimed to improve our knowledge of emissions, collect data for emission inventories, and investigate pollution reduction strategies. Many of these studies involved measuring emissions over a standard driving cycle, usually that defined by ECE Regulation 15. Analysis of emissions as a function of speed, driving mode, vehicle age, ambient and engine temperature, engine capacity, vehicle maintenance, engine and emission reduction technology have been performed within these studies. Overall, the literature shows that a large number of studies have investigated vehicle emissions, but fewer studies investigated strategies for reducing urban traffic pollution. However, some studies have explored several aspects of the air pollution problem in an attempt to improve air quality. These studies provided a foundation on which the author was able to build, and identify new and important areas of research.

Some of the most extensive and innovative pan-European work was that carried out as part of the DRIVE research programme, which had objectives to improve traffic efficiency, safety and environmental quality. The author participated in two major environmental projects: PREDICT in DRIVE I, and QUARTET in the follow-up programme, DRIVE II.

One of the main objectives of Chapter 4 was to illustrate that there are many potential options available to the decision maker, and that no one option alone is likely to offer a completely satisfactory solution to the air pollution problem. In addition, the options available, and the demands of society, are evolving and as such should be anticipated. This was recognised by the author at an early stage in his research and consequently an approach was adopted that would provide a high degree of flexibility, allowing the incorporation of several technologies and strategic options. This aimed to ensure that the author's work would establish a foundation, upon which suitable strategies could be built. These strategies were based on state-of-the-art techniques and technologies. Indeed, not only does this approach allow optimum use of today's state-of-the-art technology, it also aims to provide a framework able to evolve with the vehicle technology and environmental demands of the future.

Although monitoring technology is capable of providing an accurate picture of traffic performance and air quality levels, its cost, the large number of sensors required for network-wide coverage, and problems associated with real-life experiments often make monitoring an impractical choice for air pollution studies. The alternative is a computer based model. Chapter 5 described the techniques and models available for representing the impact of transport policy and traffic control strategies on air quality. The technique can be broken into two key areas: traffic and air pollution. The traffic models are used to produce predictions of traffic flows, speeds and delays. These are used by a model to predict pollutant emission rates which are used by a dispersion model to predict pollutant concentrations.

A model predicts pollutant emission rates over an area or link by link. Emission modelling generally requires, as a minimum, the speed of the vehicle and emission rate as a function of speed. However, for detailed studies investigating urban emissions as a function of various control strategies, a more detailed modelling approach is required that specifically represents all driving modes, not just (cruise) speed. Emission modelling also needs to represent various types of vehicle and their corresponding emission characteristics. Emission factors can be influenced by many aspects, including vehicle type, vehicle condition and ambient factors.

Given pollutant emission rates, a dispersion model can predict pollutant concentrations for a given network (or link) topology and meteorological conditions. Dispersion modelling can be a complex process and often a model will be developed to work in a particular context, e.g. highways/rural roads or roads in a 'canyon'. However, dispersion modelling did not form part of this research.

In the early stages of the PREDICT project, it became apparent that to meet the objectives of the project a new emissions model had to be developed. The requirements specified that it would need to be user friendly, very flexible, and able to model emissions from all driving modes and several vehicle categories. By developing the model 'in-house' the exact requirements of the research team could be met, and if the objectives were changed at a later stage the model could readily be enhanced. Chapter 6 has highlighted the objectives of the model suite used in the author's research, and in the projects PREDICT and QUARTET. The PREDICT model suite's structure and functionality have been described and assessed.

The PREDICT model suite offered an effective combination of conventional and advanced modelling techniques. Most of the traffic modelling was based on conventional techniques and algorithms; whilst the PREMIT emissions model was based on state-of-the-art techniques and applied to a unique area of research. The model suite satisfied all its objectives and worked well in its operational context.

Chapter 7 documents four innovative strategies, designed to improve urban air quality whilst maintaining a high degree of mobility. These strategies were evaluated using central Athens as a case study area. With the exception of Strategy 2, modelling work was conducted by the author. These strategies were based on varying degrees of technological innovation in vehicle engine design, emission reduction systems, and the urban traffic control and monitoring infrastructure.

Strategy 1 aimed to improve air quality levels by optimising signalised traffic networks on the basis of emission rates. This offers a relatively low cost solution for two reasons: in many cases the traffic signal network will already exist; and the strategy does not require vehicle modifications. Traffic signal plans were developed with the aim of maintaining similar levels of traffic performance and reducing pollutant emissions.

Reductions to traffic levels can give a significant reduction in pollutant emissions and this formed the basis of Strategy 2: pollution sensitive traffic rerouting. When an air pollution episode is predicted to occur through traffic would be rerouted around an environmentally sensitive area in advance of the predicted episode to ensure that the air pollution episode is avoided or its severity reduced. The activation of the strategy would be indicated primarily by variable message signs which tell drivers to reroute. Rerouting information would also be broadcast to in-vehicle route guidance systems, allowing alternate routes to be automatically selected.

Significant reductions are expected if vehicle emissions are reduced at source, by developments in vehicle engine and emissions technology, such as lean burn engines and catalytic converters. Two strategies were developed based around this idea: the introduction of clean vehicles (Strategy 3a); and environmental area licensing (Strategy 3b). Strategy 3a reflects national or pan-European legislation and assumes a gradual introduction of low emission vehicles to the traffic fleet.

Strategy 3b, environmental area licensing only allows low emission vehicles to enter an environmentally sensitive area. In the short to medium term, this may mean restricting access to vehicles which have a catalytic converter and/or lean burn engine. However, as vehicle technology and emissions/air quality legislation evolve, the strategy may be readily revised to restrict access to very low and zero emission vehicles.

The strategy is implemented using variable message signs (indicating restricted access) and enforced by AVI systems. Permitted low emission vehicles are fitted with AVI transponders that indicate the vehicle has low emissions. These vehicles are allowed into the restricted area. Other vehicles attempting to enter the area will be photographed by the AVI enforcement system.

The work in PREDICT led to the demonstration of strategies 2 and 3b in a real-world environment as part of the QUARTET field trials. The two strategies shared a common system architecture with the exception of the AVI sub-system which was specific to Strategy 3b. This system had monitoring, information and control sub-systems networked to a central processing unit which predicted air quality levels, and selected and activated a suitable control strategy. Such a system should be able to anticipate and respond to the threat of poor air quality levels and may offer 'city managers' an effective method of controlling air quality levels and adhering to air quality standards, such as those introduced by the European Commission.

The modelling and analysis methodology have been described in Chapter 8 and the results presented in Chapter 9.

Network values summarised traffic statistics and emissions were derived for the base case scenario, against which sensitivity tests and strategies could be compared. A plot of emissions per pcu as a function of average link speed illustrated a trend of high emissions of CO and HC at low average speeds and lower emissions at higher speeds.

There was no obvious trend in emissions of NOx as a function of average link speed.

The sensitivity of emissions to changes in flow were investigated. Emissions of CO and HC increased non-linearly with flow, because of the increase in delay. On links with relatively high degrees of saturation, the delay and hence idling emissions were very sensitive to increases in flow. Indeed, total idling emissions from the 20 hot CO links were comparable to those from the other 76 links. However, idling emissions of NOx represented a relatively small proportion of total NOx emissions. Being relatively independent of delay, total NOx emissions had an approximately linear relationship with flow.

Emissions were sensitive to changes cruise speed, but in a more complex manner than their sensitivity to flow. Emissions of CO and NOx were at their highest when the cruise speed was doubled. While HC was at it's highest when the cruise speed was halved. Emissions of CO and HC were both reduced when the cruise speed was increased by 33 percent, but NOx increased.

The relatively complex behaviour was because of opposite trends in emissions from cruise, and acceleration and deceleration. Cruise emissions decreased with increasing speed. For CO and HC, this was partly due to the change in vehicle emission rates with speed. Although, for all pollutants, the significant factor was the reduction in the proportion of a link's length available for cruising. At higher speeds a large proportion of a link's length was occupied by acceleration and deceleration. Consequently, emissions from acceleration and deceleration also increased with increasing speed. This clearly illustrates the importance of modelling emissions by driving mode as opposed to average speed. It also indicates that each pollutant may respond differently to a given change in scenario, or traffic control strategy.

Two traffic control strategies that aimed to reduce total network emissions by adjusting traffic signal timings were investigated. The first of these strategies adjusted the ratio of the cost of delay to the cost of stops and evaluated the impact of the corresponding signal timings. However, this strategy was not particularly effective in reducing emissions.

The second of these strategies made adjustments to the cycle time of the signal timings. In general, changes to the cycle time reduced network emissions of CO and NOx. Whereas, for HC, some cycle times increased emissions and others reduced emissions. This strategy clearly illustrated that each pollutant responds differently.

An investigation of the strategies designed to reduce emissions on hot links (those with the highest emission rates), gave some interesting insights into the behaviour of pollutant emissions on a link. Different signal timing strategies were tested for reducing emissions on hot CO and hot NOx links respectively.

Link emissions of CO could be significantly reduced by increasing a link's cost of delay. However, care had to be taken to ensure that unrealistic sacrifices were not made on other links, in terms of delay and emissions. On the hot CO links, a reduction in emissions of CO often produced an increase in NOx. Not surprisingly then, a different approach was needed to reduce link emissions of NOx on hot NOx links. To reduce link emissions of NOx, hot links were given a lower cost for stops to encourage more stops on those links. This gave reductions in emissions of NOx on hot links and even reduced total network emissions of NOx. However, this unconventional strategy significantly increased total network emissions of CO and HC, and increased total network delay. Although the delay value was only slightly higher than that corresponding to the best CO hot link strategy.

The results of the hot link strategies showed an apparently random behaviour in the changes of link emissions of NOx. Sometimes they changed in the direction as CO, sometimes in the opposite directions, and at other times they didn't significantly change. A detailed analysis of link emissions by driving mode showed that the relative proportions and changes in emissions of NOx from idling, acceleration and cruise generally determined how total link emissions of NOx would respond.

In general, all of the above strategies were not able to produce significant and simultaneous reductions in total network emissions of all pollutants. Similarly, for a given link, it was difficult to significantly reduce emissions of all pollutants. However, there was potential for significantly reducing a link's emissions of either CO and HC, or NOx. This often meant increasing emissions of the other pollutant and increasing delay and emissions throughout the rest of the network.

The last strategy tested, environmental area licensing, was superior to the above strategies for three reasons: the magnitude of the reduction in a pollutant's emission rate was, in general, much larger; all pollutants were simultaneously reduced; and there were no detrimental impacts to the efficiency of the traffic network.

The final chapter of this thesis contains the author's conclusions drawn from the work described in this thesis. Recommendations are also made for further research, demonstration and evaluation.

Chapter 11
CONCLUSIONS

This chapter contains the author's conclusions, which have been based on the topics discussed in this thesis and findings arising from the results chapter. The final section of this chapter contains a set of recommendations for further areas of research, demonstration and evaluation.

The author has been actively involved in the design and evaluation of environmentally sensitive traffic control strategies for five years, and has made a significant contribution towards understanding traffic pollution in urban areas. His work has covered many key areas of research, development and evaluation:

1) the design of innovative environmentally sensitive traffic control strategies;
2) development of a state-of-the-art emissions model;
3) identification of environmentally sensitive modelling approaches;
4) a detailed understanding of road traffic emissions;
5) evaluation of the control strategies (based on modelling); and
6) demonstration of the control strategies in a real-world environment.

11.1 Environmentally sensitive traffic control strategies

Increasing concern over the impact of air pollution on health and the environment may result in a demand for action which aims to reduce urban traffic pollution. This action is likely to appear, at least partly, in the form of environmentally sensitive traffic control strategies. These aim to reduce emissions from road traffic and protect air quality levels network-wide and/or on particular streets.

The objectives of an environmentally sensitive strategy should be clearly defined. It is not adequate to simply state that pollution levels are to be reduced; objectives need more clarification. A whole range of potential objectives exist and a 'decision maker' must determine which objective, or combination of objectives, are to be achieved.

It is important to recognise that a particular strategy may be unable to simultaneously satisfy multiple objectives, because of conflicting requirements. Hence, the decision maker may have to relax some of the requirements or prioritise objectives. Objectives also need to be specified for each pollutant to be regulated. In some cases, it may not be feasible to achieve all objectives without significantly changing existing traffic patterns.

For example, consider the case where a local authority wishes to reduce the emission rate of CO and NOx on a particular link whilst maintaining the traffic flow. It may be possible to reduce emissions of CO by adjusting the signal timings at the downstream intersection so that link delay is reduced. However, as the author's research has shown, this may result in an increase of NOx emissions. Therefore, adjusting the signal timings in this way may reduce the emissions of CO below a specified limit value, but it may force emissions of NOx to rise above its corresponding limit value. Hence, in this case a contradictory set of objectives were specified. It may then be decided to relax the traffic flow objective so that the link's traffic flow can be reduced to allow emissions of CO and NOx to fall.

Hence, not only should strategy objectives be clearly defined, they should also be prioritised against each other in cases where they may be mutually exclusive. Ideally, a cost function would be associated with each objective. However, in practice this may be difficult to do.

In reality, the environmental objectives must be balanced against the objective to sustain a given degree of mobility. Therefore, environmentally sensitive traffic control strategies should be able to address both these aspects. Finally, having defined environmental and mobility objectives an environmental strategy may be designed to achieve those objectives.

11.2 Models

The author's work has involved reviewing current modelling techniques and developing a state-of-the-art emissions model. These activities contributed to the following conclusions.

A considerable number of studies and a substantial amount of emissions data are based around the concept of driving cycles. These driving cycles are usually fixed in that they effectively define the proportions of time a vehicle spends in each driving mode and the cruise speeds to be maintained. The fixed driving cycle aims to represent typical urban driving conditions. This approach provides a good method for comparing emissions from different vehicles and technologies, and is also used to set emission standards.

However, it must be emphasised that fixed driving cycles have serious limitations in terms of accurately predicting urban emissions on a link by link basis and are not suited to the evaluation of particular traffic control strategies. This is due to the fact that the driving cycle is meant to represent the average urban driving pattern not that of a specific link, which may vary significantly between links. Also, some strategies directly change the urban driving pattern, especially on particular links. In order to predict emissions and concentrations on a link by link basis the model must be able to specifically represent the driving modes on each link.

Modelling techniques are unavoidable when quantifying the effects of proposed strategies that do not exist and therefore cannot be monitored. However, it is recognised by the author, and others, that modelling techniques have inherent uncertainties as a result of their approximations and the limited availability of comprehensive data sets. For example, some of the state-of-the-art emissions models in the US are known to give predictions out by a factor of two or more. Therefore, the author recommends caution when using model results. The actual values predicted should not be interpreted literally (as absolute values), unless the model has been validated and it is known to give accurate results for the particular type of scenario being modelled. However, the relative changes predicted between strategies may be useful for comparative purposes.

As has been illustrated by the author's results, an accurate modelling approach for this type of research must represent emissions from each driving mode (cruising, acceleration, deceleration and idling) on a link by link basis. Vehicle emissions can also be studied and understood in much greater detail if an emissions model is able to report link emissions by driving mode.

Models may also be used in an on-line environment whereby all, or part, of the input data is supplied from actual measurements. This has two key advantages: the input data source is an accurate reflection of the study area; and the information is available in real-time. The operation of an on-line real-time model suite was being demonstrated in Athens, though the findings are not yet available. However, the benefits are expected to include a calibration mechanism for the model suite and improved accuracy in model predictions. This can also be used to form part of an air pollution early warning system, allowing a pro-active response to be taken against the threat of an air pollution episode.

11.3 Modelling control strategies

In order to determine the modelling approach to be used for the evaluation a particular strategy, the following questions need to be answered:

- what are the objectives of the strategy?;
- what is the design of the strategy?; and
- what modelling approaches will be suitable?

The answer to the first question should indicate which parameters need to be compared in the base case and control strategy scenarios. This means that the modelling approach will, at least, have to predict values for these parameters. The objectives will also provide input to the strategy design process. The strategy's design will indicate what parameters the modelling approach needs to represent, particularly with regard to data input requirements and model algorithms.

It should be recognised that all modelling approaches have limitations in terms of their accuracy because of approximations in algorithms and the unavailability of a complete set of input data specific to the study area. The study team should determine whether the level of accuracy provided by the model is adequate for their purpose and consider if there are any feasible alternatives that are likely to be more accurate.

11.4 Sensitivity of road traffic emissions

This section draws conclusions from the sensitivity tests of emissions as a function of traffic flow and speed, and the analysis of these emissions by driving mode.

In the study areas, large delays were responsible for a major proportion of CO and HC emissions, whereas emissions of NOx were relatively insensitive to delay.

A sensitivity test of emissions as a function of flow revealed that emissions of CO and HC behaved non-linearly as a function of flow, whereas NOx behaved linearly. Therefore, a slight reduction in traffic flow on a heavily loaded network can provide a significant reduction in the emissions of CO and HC, and a smaller reduction in NOx.

Analysis of the flow sensitivity test by network emissions from each driving mode provided a useful insight. Idling emissions responded non-linearly to flow and at the higher flows became the dominant source of emissions for CO and HC, and a much lower, though significant, source of NOx emissions. This relationship was caused by the non-linear relationship between total delay and flow. Links near saturation were very sensitive to increases in flow, resulting in delay increasing rapidly along with idling emissions, particularly for CO and HC.

The relationship between pollutants was also investigated as a function of flow. This showed an increasing non-linear ratio between CO and NOx, and between HC and NOx. The ratio between CO and HC was relatively constant.

A good correlation was found between link emissions of CO and HC for the base case, but the correlation between CO and NOx was poor. In general, this was observed for all scenarios. Also, the percentage change in emissions of CO were similar to the change in HC.

A sensitivity test of emissions as a function of cruise speed revealed some interesting characteristics. The scenarios corresponding to the lowest and highest cruise speeds tested both had higher pollutant emissions than the base case, with the exception of HC which had lower emissions at the highest speed. The surprising finding was that total emissions of CO and NOx behaved similar to each other as a function of speed, whereas HC did not. Emissions changed in a relatively complex manner as a function of speed. This was because cruise emissions decreased with increasing speed, but emissions from acceleration and deceleration increased. This was primarily due to an increasing proportion of a link's length being taken up by acceleration and deceleration.

The ratios of CO to NOx and HC to NOx increased slightly as speed was reduced. While the ratio of CO to HC fell significantly with decreasing speed. These changes, along with the change in the proportion of emissions from each driving mode, suggest that the impact of a traffic control strategy could be sensitive to cruise speed.

11.5 Evaluation of control strategies

The impacts of the environmentally sensitive traffic control strategies have been described in the results chapter; this section draws conclusions from those results.

Environmental optimisation of traffic signal timings

The adjustment of traffic signal timings provides a relatively inexpensive way of implementing an environmentally sensitive traffic control strategy because, typically, the infrastructure is already in place. A particular strategy is activated by downloading the appropriate signal timings to the traffic signal controllers at each intersection.

Delay to stop weight ratios

Values of the delay to stop weight ratio were tested over a range from 0.01 to 100. It was found that emissions could not be significantly reduced below their base case values. Emissions of CO were increased for all ratios tested. Hence, assuming that there are no significant dips between the ratios tested, this approach is not suitable for reducing total network emissions.

Cycle time

The base case scenario had a 90 second cycle time. For longer cycle times the change in emissions, compared to the base case, was relatively complex. The change in pollutants as a function of longer cycle times did not follow a simple trend and all pollutants responded differently.

All cycle times tested, up to 200 seconds, reduced network emissions for CO and NOx, except at 200 seconds CO increased. A cycle time of 200 seconds produced the largest increase in emissions of HC. For half the cycle times tested emissions of HC were reduced, and for the other half they were increased. The cycle times giving the best reductions in emissions were 140, 100 and 200 seconds for CO, HC and NOx respectively; the corresponding reductions were 3.3, 1.2 and 1.9 percent.

It was shown that a longer cycle time could reduce emissions of any pollutant, though some of these cycle times simultaneously increased emissions of other pollutants.

Surprisingly, over the range tested, the change in emissions of CO were significantly different to the change in emissions of HC. For example, three cycle times reduced emissions of CO but increased emissions of HC.

The complex behaviour observed for the change in pollutant emissions, and the different behaviour between pollutants, could only be explained by the analysis of emissions from each driving mode.

It was shown that the change in emissions of HC closely followed the change in delay. Whereas, the change in CO followed the change in delay to a lesser extent. This was because the change in emissions of CO were dominated by the change in emissions from acceleration; the change in idling emissions was a secondary factor. The reason for this behaviour is that, in the base case, CO emissions had almost equal contributions from idling and acceleration; whereas for HC, the contribution from idling was over three times that from acceleration, and so HC was more sensitive to delay.

Hot links

The hot link strategies demonstrated that emissions could be reduced on links that had high emissions. However, the strategies to reduce emissions of CO and HC appear to be mutually exclusive to those that reduce emissions of NOx. Nevertheless, links with high emissions could have their emissions reduced by adjusting the delay and/or stop weights for those links.

On congested links, emissions of CO and HC were very sensitive to delay and reductions to link delay significantly reduced these emissions. One of the most effective hot CO link strategies involved scaling hot link delay and stop weights up by 500 percent. Of the 20 hot links, 15 links had emissions of CO and HC reduced, and 7 links had emissions of NOx reduced. The percentage changes in CO and HC were similar, but the percentage change in CO was usually greater than that for HC.

However, care needs to be taken when using this approach as it may have a negative impact on emissions of NOx on those links, and increase emissions on other links.

For example, of the 20 hot CO links, 14 links showed changes of CO and NOx emissions in opposite directions to each other.

Hot NOx links, and NOx emissions in particular, are more difficult to predict and reduce. Many options were investigated and the best solution found involved reducing the proportion of time spent cruising, i.e. increase link congestion by reducing the cost of stops! One of the most effective strategies involved scaling the cost of stops, on hot NOx links, by -200 percent. Of the 20 hot links, 17 links had emissions of NOx reduced, 3 had CO reduced and 4 had HC reduced. Of the 20 hot NOx links, 16 showed changes of NOx and CO emissions in the opposite direction to each other. Hence, reducing stop weights on hot NOx links can significantly reduce emissions of NOx. However, the impact this has on traffic in terms of increased link and network congestion may not be acceptable.

This strategy was particularly effective on links with a significant level of cruise emissions. The philosophy is that the major contributor to overall NOx emissions are cruise emissions. Consequently, to reduce emissions of NOx the proportion of time spent cruising, on a given link, needs to be reduced. Reducing the green time at a downstream intersection will cause a longer queue to develop and reduce the average distance over which vehicles cruise for a given link.

However, it should be noted that the degree of impact that this approach has on emissions of NOx depends on the initial contributions from each driving mode on a given link. In some cases this approach will not reduce emissions and may even increase them. For example, a link with no, or very little, cruise emissions may not benefit from this strategy as the increase in emissions from acceleration would outweigh the decrease in cruise emissions.

It can be concluded that, in general, signal timing strategies which aim to reduce a particular link's emissions of CO and HC may increase emissions of NOx, and vice-a-versa. However, for a given strategy, changes in CO and HC generally tend to be larger than changes in NOx. Therefore, it may be reasonable to reduce link emissions of CO and HC, by increasing the delay and stop weights of hot links, as it also reduces link delay. The benefits of lower link emissions of CO and HC must be offset against a potential increase in emissions of NOx. However, for links that exceed, or are near to, the NO_2 air quality limit value this option may not be acceptable.

It is also important to note that, in general, a reduction in hot link emissions will be at the expense of an increase in total network emissions.

Environmental area licensing

The environmental area licensing strategy offered considerable benefits in terms of improved air quality for all three pollutants. Emissions of CO, HC and NOx were reduced by 45, 32 and 8 percent respectively. This strategy also has no impact on the efficiency of the traffic network.

The concept of this strategy can be extrapolated towards shorter and longer term solutions. For example, the strategy as described in this thesis was based on clean vehicles being fitted with catalytic converters, whereas a shorter term strategy could be based on clean vehicles corresponding to the ECE 15-04 emissions standard, or later. A longer term strategy could be based on very low emission vehicles (emissions lower than conventional vehicles fitted with catalysts), or ultimately zero emission vehicles (e.g. electric vehicles).

Chapter Four illustrated that there are several technologies and alternative fuels that have the potential to reduce vehicle emissions. The author has considered this aspect when designing the system architecture for the environmental area licensing strategy. The system's flexible design allows the implementation of a strategy that will be effective irrespective of the emission reduction technology available today and in the first few decades of the next century. This is because any vehicle type can be readily declared as the 'clean' vehicle type, and a hierarchy of clean vehicles, with different emission rates, could even be supported.

Implications for other strategies

Analysis of emissions by driving mode shows that on congested links the major proportion of CO and HC emissions are produced by idling. Therefore any strategy which reduces the delay on congested links is likely to reduce emissions of CO and HC. Further, the relationship between flow and delay on links at or near saturation is non-linear and extremely sensitive to changes in flow. Therefore, a slight reduction of flow on a link at or near saturation produces a significant reduction in emissions of CO and HC. Conversely, a slight increase on such links would produce a significant increase in those emissions. Therefore, a strategy which aims to distribute traffic more equally throughout a road network could, potentially, achieve significant reductions in emissions of CO and HC. Whereas, a network that focuses high volumes of traffic onto a few congested links may suffer very high emissions on those links, giving rise to high total network emissions.

11.6 Demonstration and evaluation

In Chapter Seven the author described each strategy and the demonstration of environmentally sensitive traffic rerouting and environmental area licensing. These two strategies were demonstrated in the QUARTET Athens field trial. Unfortunately, the final conclusions based on the evaluation of these control strategies were not available at the time this thesis was finalised.

However, a number of initial conclusions have been drawn. Before these strategies are implemented on a full-scale basis, it is recommended that they should be evaluated in a large scale demonstration. These strategies should be evaluated in a real-world environment which aims to test technical aspects of the system, operational procedures, traffic and environmental impact, socio-economic impact, and organisational and institutional issues.

It has also been recognised that the current Athens demonstration, though unique and significant, is too small to adequately evaluate all the above aspects. Therefore, to provide a comprehensive evaluation, a large scale demonstration is required such that it has a direct and measurable impact on traffic and traffic emissions. The effects of the demonstration need to be directly measured, understood and extrapolated, to determine the impact of a full-scale implementation.

11.7 Achievements

The outstanding achievements of the author's research are highlighted below. The author has extended the scope of academic knowledge and formulated effective environmentally sensitive traffic control strategies. This research has significant implications for emission modelling methodologies and environmentally sensitive traffic control strategies.

The author has demonstrated the importance of modelling traffic emissions by driving mode. He has also created a state-of-the-art emissions model and demonstrated the benefit of being able to analyse emissions by driving mode. A detailed analysis of traffic emissions by driving mode explained the relatively complex, and surprising, behaviour observed in pollutant emissions. Many of the characteristics of network and link emissions would not have been identified without the ability to model emissions by driving mode.

Emissions of NOx have been shown to be more complex than those of CO and HC. The change in emissions of NOx may be similar, or totally opposite, to the change in emissions of CO and HC, for a given strategy on a given street. Therefore, the belief that a traffic network optimised to reduce stops and delay will also reduce pollutant emissions, may not be true for NOx. It was also observed that the magnitude of the change in emissions of NOx, as the result of a particular strategy, were usually much less than the corresponding change in CO and HC. Surprisingly, the results presented in this thesis also show that in some cases even emissions of CO and HC behave differently to each other.

It was shown that traffic control strategies based only on the adjustment of signal timings were not very effective in reducing total network emissions, if the network was already optimised for traffic delay and stops. Whereas, high emissions of pollutants on particular streets could be reduced by adjusting signal timings. However, for many streets, mutually exclusive strategies exist for reducing emissions of CO and HC, and emissions of NOx. Hence, the decision maker may have to determine which pollutants should be reduced, perhaps, at the expense of an increase in other pollutants.

The author has designed innovative traffic control strategies and modelled their impact on emissions. He has also been involved in the development of the advanced transport telematics infrastructure required to implement these strategies. These were demonstrated in a real-world environment as part of the QUARTET field trials. The evaluation of the field trial aims to assess the overall effectiveness and socio-political acceptance of these strategies.

11.8 Recommendations

The author's research has produced several interesting findings and opened up a number of areas of innovative environmental research. Based on these findings many recommendations can be made for further research, data collection, modelling, strategy design, and strategy implementation. This section outlines these recommendations:-

1. Organisations responsible for maintaining urban air quality need to recognise existing air quality standards and formulate clear objectives that address air quality and the demand for mobility.

2. Existing air quality levels need to be determined either by monitoring alone, or a combination of monitoring and modelling. This should be used on an on-going basis to monitor air quality levels and ensure that air quality standards are not violated.

3. Based on the findings of recommendations 1 and 2, it may be necessary to implement an environmentally sensitive traffic control strategy. This should

bear in mind:

- air quality and mobility objectives;
- the degree to which air quality is violated, both in terms of magnitude, frequency and geographical scope;
- forecast trends in traffic growth and corresponding emissions, over the lifetime of the strategy;
- technical feasibility;
- overall strategy impact;
- socio-economic aspects and political acceptance.

4. It is strongly recommended that modelling methodologies represent emissions by driving mode, in order to accurately represent the impact of environmentally sensitive traffic control strategies on emissions.

5. Studies should be set up with the specific aim of collecting a comprehensive set of emissions data by driving mode for all major vehicle categories, under all typical operational conditions. This should be a coordinated pan-European effort. Ideally, the resulting emissions inventory should be publicly available, providing the necessary input to emission models that represent emissions by driving mode. It is the author's view that this would make a substantial contribution towards improving the accuracy of predictions in road traffic emissions. Also, it is felt that, the important findings of the author's work cannot be fully validated until these data are made available.

6. The findings of the author's modelling should be further validated. This should consider alternative sources of emissions input data, different network topologies, and ideally should be validated in a real-world demonstration using actual measurements for traffic, meteorological and air pollution parameters.

7. Though a valuable research tool, the concept of the PREDICT model suite should, ideally, be enhanced further to provide a higher degree of automation for analysis and strategy selection. As the author's research has shown, emissions sometimes behave in a complex manner, requiring unique solutions for particular pollutants and streets. Hence, an automated approach is expected to greatly assist in finding optimum solutions to a given air pollution problem.

8. The limitations and accuracy of current state-of-the-art models should be recognised and their predictions used with caution. Wherever feasible, it is recommended that model results are supplemented with direct measurements of traffic and environmental parameters. These measurements also allow a model to be calibrated and validated.

9. Studies should be set up to analyse the relationship between traffic and emissions, by directly measuring these parameters in an urban environment. They should aim to establish correlations between traffic parameters and emissions; and if correlations are not observed identify why. The variability in emissions between, and within, vehicle categories should be measured in the urban environment. Reasons for variability should be identified and understood (e.g. engine type, cold start, poor maintenance, driver behaviour). The results of such studies would be extremely useful for calibrating and validating emission models, and determining the overall suitability of a modelling approach.

   These studies should directly monitor exhaust emissions of individual vehicles, for all vehicles within the traffic flow of selected streets. This will allow the compilation of vehicle emission profiles by category and within categories. The implementation of these studies will, therefore, involve the use of roadside devices for monitoring exhaust emissions of individual vehicles. Though such devices exist, they may need further development to improve their operational accuracy and the range of pollutants that they are able to monitor.

10. Studies have shown that a small proportion of poorly maintained vehicles are

responsible for a large proportion of total fleet emissions. Therefore, strategies aimed at regulating these vehicles have the potential to give substantial improvements in urban air quality, whilst maintaining levels of traffic efficiency.

11. Strategies which aim to reduce delay may reduce emissions of CO and HC. However, the impact this has on emissions of NOx should be considered. Indeed, given the European Union's air quality directive for nitrogen dioxide, and the frequency with which it may be violated, it may be more important to reduce emissions of NOx, perhaps at the expense of an increase in emissions CO and HC.

12. Studies should investigate the potential benefits of vehicle modifications, such as reduced fuel consumption and lower emissions. The reduction of a vehicle's mass could potentially reduce fuel consumption and emissions caused by acceleration/deceleration cycles. At higher speeds, cruise emissions may be reduced by improved vehicle aerodynamics.

    If emissions from idling and acceleration could be substantially reduced, or eliminated, network emissions of CO and HC would fall substantially. The elimination of emissions from acceleration may also result in a significant reduction to emissions of NOx.

    This is may be feasible. Idling and acceleration emissions could be eliminated, or at least significantly reduced, by employing a regenerative braking system. As the vehicle brakes its kinetic energy is converted to potential energy within the regenerative braking system. When the vehicle stops the engine could automatically turn off, eliminating idling emissions. The potential energy stored in the regenerative braking system would then be used to accelerate the vehicle, perhaps, with some assistance from the vehicle's engine.

13. Further research is required into the design, development and implementation aspects of environmentally sensitive traffic control strategies. Whilst the technical feasibility is currently being evaluated, the overall impact and

acceptability needs further investigation. Large scale demonstrations are required to identify and evaluate all the aspects of environmentally sensitive traffic control strategies.

14. Strategies based on other philosophies and technologies should also be investigated. In particular, specific strategies should be developed for short-, medium- and long-term time frames.

Currently, the author is disseminating the findings of his research to a wider audience and actively pursuing several of the above recommendations. He acknowledges that to achieve satisfactory air quality levels whilst maintaining mobility is extremely difficult, though he also recognises that this research has taken a significant stride towards that goal.

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Appendix A
NETWORK MAPS

The Athens study area, as used in the PREDICT project, is show in Figure A.1. It was divided into three TRANSYT networks called Centre, North and South. For the purpose of the rerouting strategy another TRANSYT network called Ring was also used. The ring network corresponded to a ring road around the central area.

The central area, called Centre, corresponds to the grid network on the western side of the Athens study area.

In the author's research described in this thesis, all the work focused on the TRANSYT network called Centre. This study area is shown in Figure A.2. The map for the central area includes the node numbers corresponding to those listed in the PREMIT emission model's output.

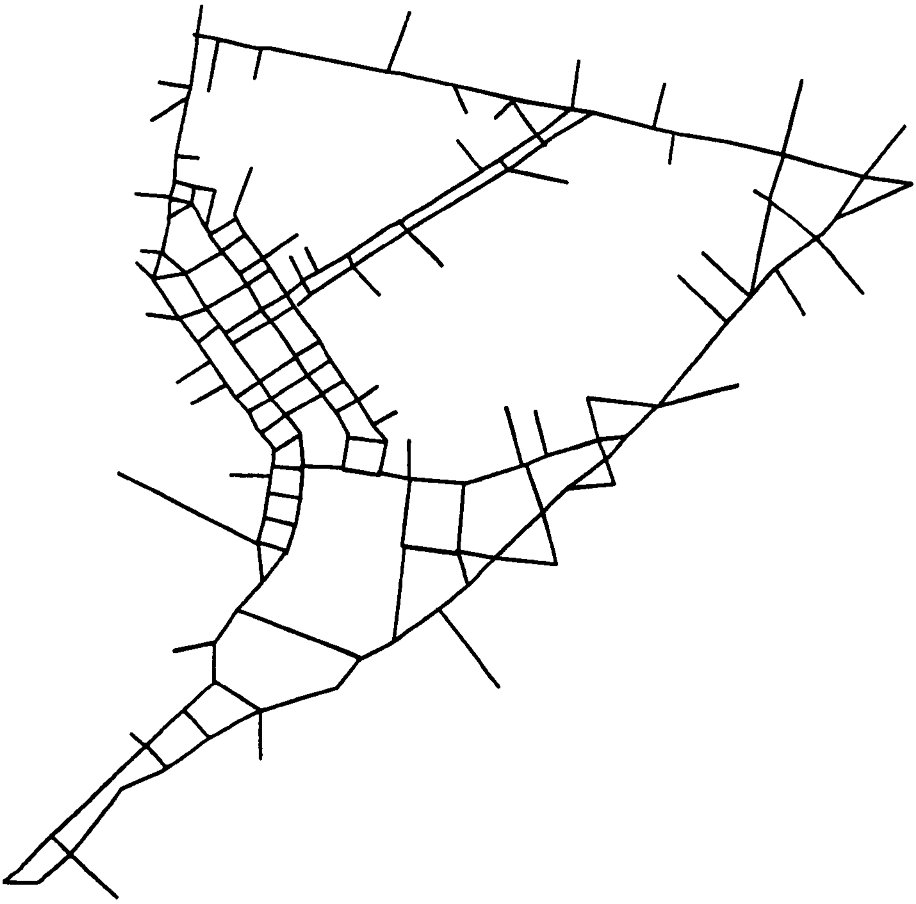

Figure A.1 The Athens study network used in PREDICT

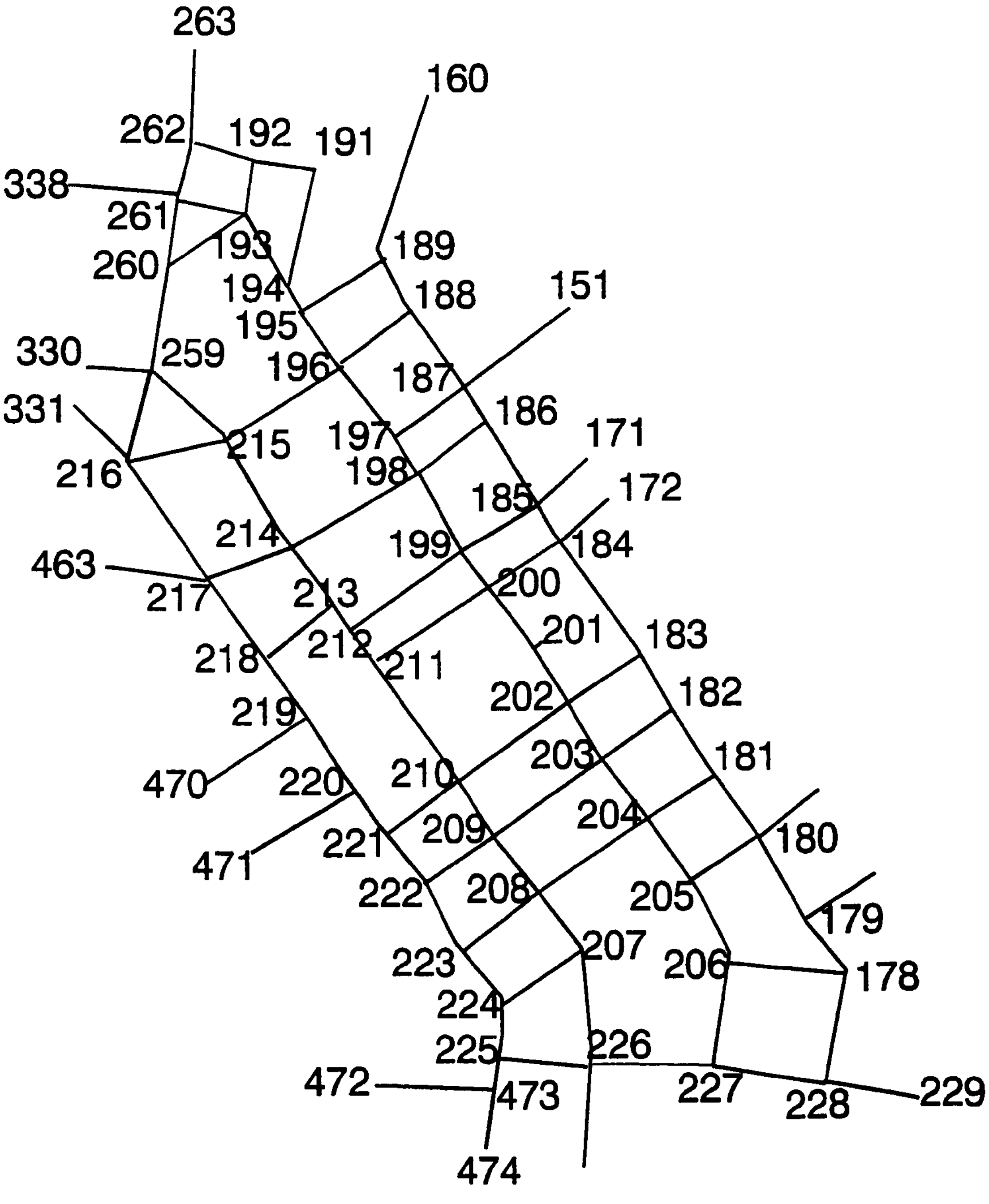

Figure A.2 The Athens central area used in this research

Appendix B

TRANSYT DATA

This appendix includes the TRANSYT output data. The listings included in this appendix are edited versions of the actual TRANSYT output files, because the complete listings are very large. The listings in this appendix only include the initial input and final output parts of the TRANSYT listings.

The TRANSYT output files have been included for the base case and some of the more interesting strategies described in the Results Chapter. The TRANSYT output files included in this appendix are summarised in Table B.1.

Scenario/strategy	Initial input data included?
1. Base case scenario.	Yes.
2. Delay:stop weighting ratio of 0.01.	No - same input as base case.
3. Delay:stop weighting ratio of 100.	No - same input as base case.
4. Cycle time of 140 seconds.	No - same input as base case.
5. Hot CO links with delay weighting of 500 percent.	Yes.
6. Hot CO links with delay and stop weighting of 500 percent.	No - similar to input for hot CO links with delay weighting of 500 percent.
7. Hot NOx links with stop weighting of -200 percent.	Yes.

Table B.1 Summary of output listings included in Appendix A

In cases where a TRANSYT run used the same link input data as an earlier TRANSYT file in this appendix, the input data has been left out. The only difference in the input data for such scenarios is on card type one. So card type one has always been included.

The link input data for the two hot CO link strategies are similar to each other. The only difference being that the strategy with a link weighting for delay and stops has an additional value in the stop weighting column. This value is equal to the value in the delay weighting column, for a given link.

Base Case Scenario

```
0CARD   CARD
  NO.   TYPE
 (  1)= TITLE:- ATHENS * CENTRAL ARTERIES * Optimisation ON
0CARD   CARD   CYCLE  NO. OF    TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW   CRUISE-SPEEDS   OPTIMISE EXTRA    HILL-    DELAY    STOP
  NO.   TYPE   TIME    STEPS  PERIOD DISPLACEMENTS  SETTINGS  INFO.    SCALE    SCALE  CARD32  0=NONE  COPIES    CLIMB    VALUE    VALUE
                        PER    1-1200   START    END    0=NO  2=CYCLE  10-200   50-200 0=TIMES  1=O/SET  FINAL  OUTPUT    P PER    P PER
               (SEC)   CYCLE   MINS.   (SEC)   (SEC)   1=YES  CHOICE     %        %   1=SPEEDS 2=FULL  OUTPUT  1=FULL    PCU-H     100
   2)=   1      90      45      120       2       3       1       0        0        0       0       2       0       0       55       50
0CARD   CARD                                             LIST  OF  NODES  TO  BE  OPTIMISED
  NO.   TYPE
   3)=   2     261     260     178     179     180     181     182     183     184     185     186     187     188     189     193
   4)=   2     194     195     196     197     198     199     200     201     202     203     204     205     206     227     226
   5)=   2     207     208     209     210     211     212     213     214     215     259     216     217     218     219     220
   6)=   2     221     222     223     224     225       0       0       0       0       0       0       0       0       0       0
0                                  NODE  CARDS:   STAGE  CHANGE  TIMES  AND  MINIMUM  STAGE  TIMES
 CARD   CARD   NODE          STAGE 1         STAGE 2          STAGE 3          STAGE 4          STAGE 5          STAGE 6          STAGE 7
  NO.   TYPE    NO.     CHANGE    MIN   CHANGE    MIN   CHANGE    MIN   CHANGE    MIN   CHANGE    MIN   CHANGE    MIN   CHANGE    MIN
   7)=  13     261        35      10      64      10      90      10       0       0       0       0       0       0       0       0
   8)=  14     260        44      10      55      10      66      10      33      10       0       0       0       0       0       0
   9)=  22     178         7      10      26      10       0       0       0       0       0       0       0       0       0       0
  10)=  22     179        14      10      33      10       0       0       0       0       0       0       0       0       0       0
  11)=  22     180        39      10      13      10       0       0       0       0       0       0       0       0       0       0
  12)=  22     181        16      10      34      10       0       0       0       0       0       0       0       0       0       0
  13)=  22     182        28      10      39      10       0       0       0       0       0       0       0       0       0       0
  14)=  22     183         9      10      38      10       0       0       0       0       0       0       0       0       0       0
  15)=  22     184        17      10      43      10       0       0       0       0       0       0       0       0       0       0
  16)=  22     185         3      10      21      10       0       0       0       0       0       0       0       0       0       0
  17)=  22     186        19      10      40      10       0       0       0       0       0       0       0       0       0       0
  18)=  22     187        31      10       4      10       0       0       0       0       0       0       0       0       0       0
  19)=  22     188        12      10      32      10       0       0       0       0       0       0       0       0       0       0
  20)=  22     189        35      10      20      10       0       0       0       0       0       0       0       0       0       0
  21)=  12     193        30      10      89      10       0       0       0       0       0       0       0       0       0       0
  22)=  12     194        30      10       9      10       0       0       0       0       0       0       0       0       0       0
  23)=  22     195         0      10      31      10       0       0       0       0       0       0       0       0       0       0
  24)=  22     196        10      10      36      10       0       0       0       0       0       0       0       0       0       0
  25)=  22     197        16      10       1      10       0       0       0       0       0       0       0       0       0       0
  26)=  22     198        13      10      40      10       0       0       0       0       0       0       0       0       0       0
  27)=  22     199        31      10      11      10       0       0       0       0       0       0       0       0       0       0
  28)=  22     200        31      10      16      10       0       0       0       0       0       0       0       0       0       0
  29)=  22     201         2      10      37      10       0       0       0       0       0       0       0       0       0       0
  30)=  22     202        40      10      19      10       0       0       0       0       0       0       0       0       0       0
  31)=  22     203        10      10      37      10       0       0       0       0       0       0       0       0       0       0
  32)=  22     204        16      10      43      10       0       0       0       0       0       0       0       0       0       0
  33)=  22     205        22      10       9      10       0       0       0       0       0       0       0       0       0       0
  34)=  12     206        28      10      17      10       0       0       0       0       0       0       0       0       0       0
  35)=  12     227        75      10      41      10       0       0       0       0       0       0       0       0       0       0
  36)=  13     226        49      10      80      10      25      10       0       0       0       0       0       0       0       0
  37)=  12     207        65      10      76      10       0       0       0       0       0       0       0       0       0       0
  38)=  12     208        80      10      57      10       0       0       0       0       0       0       0       0       0       0
  39)=  12     209        83      10      55      10       0       0       0       0       0       0       0       0       0       0
  40)=  12     210        85      10      60      10       0       0       0       0       0       0       0       0       0       0
  41)=  12     211        11      10       1      10       0       0       0       0       0       0       0       0       0       0
  42)=  12     212        33      10      88      10       0       0       0       0       0       0       0       0       0       0
  43)=  12     213        15      10      85      10       0       0       0       0       0       0       0       0       0       0
  44)=  12     214        26      10      82      10       0       0       0       0       0       0       0       0       0       0
  45)=  12     215        46      10      26      10       0       0       0       0       0       0       0       0       0       0
  46)=  12     259        85      10      45      10       0       0       0       0       0       0       0       0       0       0
  47)=  12     216        86      10      41      10       0       0       0       0       0       0       0       0       0       0
  48)=  12     217         7      10      76      10       0       0       0       0       0       0       0       0       0       0
  49)=  12     218        12      10      72      10       0       0       0       0       0       0       0       0       0       0
  50)=  12     219        43      10      21      10       0       0       0       0       0       0       0       0       0       0
  51)=  12     220        23      10      12      10       0       0       0       0       0       0       0       0       0       0
  52)=  12     221        35      10      18      10       0       0       0       0       0       0       0       0       0       0
  53)=  12     222        35      10       4      10       0       0       0       0       0       0       0       0       0       0
  54)=  12     223        29      10      11      10       0       0       0       0       0       0       0       0       0       0
  55)=  12     224        59      10      33      10       0       0       0       0       0       0       0       0       0       0
  56)=  13     225        40      10      59      10      74      10       0       0       0       0       0       0       0       0
1PROGRAM TRANSYT8     ATHENS * CENTRAL ARTERIES * Optimisation ON                                           PAGE    3   RUN ON 24/ 6/1993

0                                                  LINK  CARDS:   FIXED  DATA
                                       FIRST  GREEN                           SECOND  GREEN
 CARD   CARD   LINK      EXIT       START             END              START             END          LINK    STOP     SAT   DELAY   DISPSN
  NO.   TYPE    NO.      NODE    STAGE     LAG    STAGE     LAG    STAGE     LAG    STAGE     LAG   LENGTH WT.X100   FLOW WT.X100   X100
  57)=  31    2846      261       2       5       1       0       0       0       0       0      54       0    3500       0       0
  58)=  31    2845      261       3       6       1       3       0       0       0       0      54       0    1600       0       0
  59)=  31    2820      261       2       5       3       0       0       0       0       0     120       0    1800       0       0
  60)=  31    3850      261       1       7       2       0       0       0       0       0     120       0    5000       0       0
  61)=  31    2825      260       3       0       1       0       0       0       0       0      68       0    5000       0       0
  62)=  31    2800      260       2       4       4       0       0       0       0       0     156       0    1800       0       0
  63)=  31    1620      260       1       4       2       0       0       0       0       0      64       0    1800       0       0
  64)=  31    1820      178       2       4       1       0       0       0       0       0     130       0    2000       0       0
  65)=  31    2230      178       1       3       2       0       0       0       0       0     118       0    3200       0       0
  66)=  31    1330      179       1       4       2       0       0       0       0       0      75       0    3200       0       0
  67)=  31    1300      179       2       4       1       0       0       0       0       0     100       0    1500       0       0
  68)=  31    1340      180       2       3       1       0       0       0       0       0     124       0    3200       0       0
  69)=  31    1280      180       1       3       2       0       0       0       0       0      98       0    1500       0       0
  70)=  31    1350      181       2       3       1       0       0       0       0       0     114       0    3200       0       0
  71)=  31    1790      181       1       3       2       0       0       0       0       0     116       0    1500       0       0
  72)=  31    1380      182       2       4       1       0       0       0       0       0      81       0    3200       0       0
  73)=  31    1390      183       1       3       2       0       0       0       0       0      96       0    3200       0       0
  74)=  31    1750      183       2       3       1       0       0       0       0       0     128       0    1500       0       0
  75)=  31    1420      184       1       3       2       0       0       0       0       0     172       0    3200       0       0
  76)=  31    1720      184       2       3       1       0       0       0       0       0     140       0    1500       0       0
  77)=  31    1440      185       2       4       1       0       0       0       0       0      52       0    3200       0       0
  78)=  31    1210      185       1       4       2       0       0       0       0       0      92       0    4000       0       0
  79)=  31    1450      186       2       3       1       0       0       0       0       0     124       0    3200       0       0
  80)=  31    1680      186       1       3       2       0       0       0       0       0     122       0    3200       0       0
  81)=  31    1480      187       2       3       1       0       0       0       0       0      55       0    3200       0       0
  82)=  31     900      187       1       3       2       0       0       0       0       0     100       0    1500       0       0
  83)=  31    1490      188       2       3       1       0       0       0       0       0     110       0    3200       0       0
```

Base Case Scenario

```
  84)=  31    1650    188    1     3    2    0    0    0    0    0   122    0   1500    0    0
  85)=  31    1520    189    1     4    2    0    0    0    0    0    82    0   3200    0    0
  86)=  31    1060    189    2     4    1    0    0    0    0    0   100    0   1500    0    0
  87)=  31    2830    193    1     5    2    0    0    0    0    0    88    0   5500    0    0
  88)=  31    1590    193    2     3    1    0    0    0    0    0    50    0   1500    0    0
  89)=  31    1610    194    1    10    2    0    0    0    0    0    96    0   4300    0    0
  90)=  31    1580    194    2    10    1    0    0    0    0    0   100    0   1500    0    0
  91)=  31    1630    195    1     4    2    0    0    0    0    0    52    0   4300    0    0
  92)=  31    1540    195    2     3    1    0    0    0    0    0   108    0   1000    0    0
  93)=  31    1640    196    1     4    2    0    0    0    0    0    80    0   4300    0    0
  94)=  31    1990    196    2     3    1    0    0    0    0    0   188    0   1500    0    0
  95)=  31    1660    197    1     5    2    0    0    0    0    0   112    0   4300    0    0
  96)=  31    1500    197    2     4    1    0    0    0    0    0   108    0   1500    0    0
  97)=  31    1670    198    1     4    2    0    0    0    0    0    50    0   4300    0    0
  98)=  31    1970    198    2     3    1    0    0    0    0    0   208    0   3000    0    0
  99)=  31    1690    199    1     5    2    0    0    0    0    0   118    0   4300    0    0
 100)=  31    1460    199    2     4    1    0    0    0    0    0   110    0   4000    0    0
 101)=  31    1700    200    1     7    2    0    0    0    0    0    62    0   5500    0    0
1PROGRAM TRANSYT8     ATHENS * CENTRAL ARTERIES * Optimisation ON                  PAGE   4   RUN ON 24/ 6/1993

 102)=  31    1920    200    2     4    1    0    0    0    0    0   160    0   3000    0    0
 103)=  31    1730    201    1     0    2    0    0    0    0    0   108    0   5500    0    0
 104)=  31    1740    202    1     6    2    0    0    0    0    0    64    0   5500    0    0
 105)=  31    1900    202    2    12    1    0    0    0    0    0   180    0   2400    0    0
 106)=  31    1760    203    1     4    2    0    0    0    0    0    90    0   5500    0    0
 107)=  31    1400    203    2     3    1    0    0    0    0    0   106    0   1800    0    0
 108)=  31    1770    204    1     4    2    0    0    0    0    0    82    0   5500    0    0
 109)=  31    1860    204    2     3    1    0    0    0    0    0   178    0   1800    0    0
 110)=  31    1800    205    1     4    2    0    0    0    0    0   116    0   5500    0    0
 111)=  31    1360    205    2     3    1    0    0    0    0    0   106    0   1500    0    0
 112)=  31    1810    206    1     7    2    0    0    0    0    0   104    0   5500    0    0
 113)=  31    1830    227    1     3    2    3    0    0    0    0   130    0   3000    0    0
 114)=  31    1831    227    1     3    2    0    0    0    0    0   130    0   3000    0    0
 115)=  31    2200    227    2     6    1    0    0    0    0    0   240    0   4000    0    0
 116)=  31    2225    227    2     0    1    1    0    0    0    0   140    0   4500    0    0
 117)=  31    2215    226    1     4    2    0    0    0    0    0   132    0   8000    0    0
 118)=  31    2205    226    2     4    3    0    0    0    0    0   138    0   2500    0    0
 119)=  31    2206    226    2     4    3    0    0    0    0    0   138    0   4000    0    0
 120)=  31    2170    226    3     4    2    0    0    0    0    0   120    0   1500    0    0
 121)=  31    2171    226    3     4    1    0    0    0    0    0   120    0   4500    0    0
 122)=  31    2190    207    2     0    1    0    0    0    0    0   142    0   9000    0    0
 123)=  31    1840    208    1     5    2    0    0    0    0    0   114    0   9000    0    0
 124)=  31    2140    208    2     4    1    0    0    0    0    0   114    0   2800    0    0
 125)=  31    1870    209    1     5    2    0    0    0    0    0    82    0   9000    0    0
 126)=  31    1780    209    2     4    1    0    0    0    0    0   166    0   2000    0    0
 127)=  31    1880    210    1     5    2    0    0    0    0    0    84    0   9000    0    0
 128)=  31    2110    210    2     4    1    0    0    0    0    0   114    0   2800    0    0
 129)=  31    1910    211    1     4    2    0    0    0    0    0   182    0   9000    0    0
 130)=  31    1930    212    1     5    2    0    0    0    0    0    66    0   7500    0    0
 131)=  31    1710    212    2     4    1    0    0    0    0    0   172    0   3800    0    0
 132)=  31    1940    213    1    10    2    0    0    0    0    0    54    0   7500    0    0
 133)=  31    1950    214    1     7    2    0    0    0    0    0    86    0   7500    0    0
 134)=  31    2040    214    2     7    1    0    0    0    0    0   114    0   1800    0    0
 135)=  31    1980    215    1     5    2    0    0    0    0    0   134    0   7500    0    0
 136)=  31    2010    215    2     3    1    0    0    0    0    0   100    0   1500    0    0
 137)=  31    2000    259    2     7    2    0    0    0    0    0   120    0   7500    0    0
 138)=  31    2805    259    1     4    1    0    0    0    0    0   156    0   4000    0    0
 139)=  31    2790    216    2     4    1    0    0    0    0    0   100    0   5000    0    0
 140)=  31    3730    216    1     6    2    0    0    0    0    0    82    0   5000    0    0
 141)=  31    2020    217    1     8    2    0    0    0    0    0   164    0   5000    0    0
 142)=  31    5800    217    2     4    1    0    0    0    0    0   100    0   1800    0    0
 143)=  31    2050    218    1     8    2    0    0    0    0    0   110    0   5000    0    0
 144)=  31    1960    218    2     4    1    0    0    0    0    0    92    0   2800    0    0
 145)=  31    2060    219    1     7    2    0    0    0    0    0   106    0   5000    0    0
 146)=  31    5930    219    2    10    1    0    0    0    0    0   100    0   1800    0    0
 147)=  31    2080    220    1     0    2    0    0    0    0    0   118    0   7000    0    0
 148)=  31    2090    221    1     0    2    0    0    0    0    0    70    0   5000    0    0
 149)=  31    5940    221    2     6    1    0    0    0    0    0   100    0   1800    0    0
 150)=  31    2120    222    1     4    2    0    0    0    0    0    82    0   5000    0    0
 151)=  31    1890    222    2     4    1    0    0    0    0    0   128    0   1600    0    0
1PROGRAM TRANSYT8     ATHENS * CENTRAL ARTERIES * Optimisation ON                  PAGE   5   RUN ON 24/ 6/1993

 152)=  31    2130    223    1    10    2    0    0    0    0    0    72    0   5000    0    0
 153)=  31    2150    224    1     4    2    0    0    0    0    0   116    0   5000    0    0
 154)=  31    1850    224    2     6    1    0    0    0    0    0    98    0   1600    0    0
 155)=  31    2161    225    3     1    2    0    0    0    0    0    48    0   4500    0    0
 156)=  31    2160    225    3    10    1    0    0    0    0    0    48    0   1500    0    0
 157)=  31    2185    225    2     4    3   10    0    0    0    0   100    0   3000    0    0
0                                          LINK CARDS:   FLOW DATA
                                   ENTRY 1 ..........  ENTRY 2 ..........  ENTRY 3 ..........  ENTRY 4 ..........
 CARD  CARD  LINK  TOTAL  UNIFORM  LINK         CRUISE  LINK        CRUISE  LINK        CRUISE  LINK        CRUISE
  NO.  TYPE   NO.   FLOW     FLOW   NO.   FLOW   TIME    NO.  FLOW   TIME    NO.  FLOW   TIME    NO.  FLOW   TIME
 158)=  32   2846   1755      0        0     0     20      0     0     0      0     0     0      0     0     0
 159)=  32   2845    617      0        0     0     20      0     0     0      0     0     0      0     0     0
 160)=  32   2820    300      0     2800   300     15   1620    30    15      0     0     0      0     0     0
 161)=  32   3850   1000      0        0     0     20      0     0     0      0     0     0      0     0     0
 162)=  32   2825   1700      0     2846  1700     15      0     0     0      0     0     0      0     0     0
 163)=  32   2800    300      0     2000   300     25      0     0     0      0     0     0      0     0     0
 164)=  32   1620    156      0     1590   156     25      0     0     0      0     0     0      0     0     0
 165)=  32   2230    945      0        0     0     22      0     0     0      0     0     0      0     0     0
 166)=  32   1820    550      0     1810   550     26      0     0     0      0     0     0      0     0     0
 167)=  32   1330    995      0     2230   945     11   1820    50    11      0     0     0      0     0     0
 168)=  32   1300    307      0        0     0     18      0     0     0      0     0     0      0     0     0
 169)=  32   1340   1302      0     1330   995     18   1300   307    18      0     0     0      0     0     0
 170)=  32   1280    361      0        0     0     18      0     0     0      0     0     0      0     0     0
 171)=  32   1350   1393      0     1340  1157     25   1280   236    25      0     0     0      0     0     0
 172)=  32   1790    302      0     1860   205     18   1770    97    18      0     0     0      0     0     0
 173)=  32   1380   1147      0     1350  1030     13   1790   117    13      0     0     0      0     0     0
 174)=  32   1390    930      0     1380   900     16      0     0     0      0     0     0      0     0     0
 175)=  32   1750    242      0     1900   182     20   1740    60    20      0     0     0      0     0     0
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Base Case Scenario

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 176)= 32 1420   1010   0   1390    860  24   1750    150   24      0      0      0      0      0      0
 177)= 32 1720    259   0   1920    159  30   1700    100   30      0      0      0      0      0      0
 178)= 32 1440   1088   0   1420    832   6   1720    256    6      0      0      0      0      0      0
 179)= 32 1210   1094   0      0      0  17      0      0    0      0      0      0      0      0      0
 180)= 32 1450   1059   0   1440    937  19   1210    122   19      0      0      0      0      0      0
 181)= 32 1680   1228   0   1970    545  30   1670    683   30      0      0      0      0      0      0
 182)= 32 1480    820   0   1450    780  10   1680     40   10      0      0      0      0      0      0
 183)= 32  900    222   0      0      0  18      0      0    0      0      0      0      0      0      0
 184)= 32 1490    849   0   1480    754  24    900     95   24      0      0      0      0      0      0
 185)= 32 1650    605   0   1990    445  26   1640    160   26      0      0      0      0      0      0
 186)= 32 1520   1020   0   1490    805  13   1650    214   13      0      0      0      0      0      0
 187)= 32 1060    142   0      0      0  18      0      0    0      0      0      0      0      0      0
 188)= 32 2830   1847   0      0      0  15      0      0    0      0      0      0      0      0      0
 189)= 32 1590    190   0      0      0   9      0      0    0      0      0      0      0      0      0
 190)= 32 1610   1948   0   2830   1847  12   1590    101   12      0      0      0      0      0      0
 191)= 32 1580     22   0      0      0  18      0      0    0      0      0      0      0      0      0
 192)= 32 1630   1970   0   1610   1948   9   1580     22    9      0      0      0      0      0      0
 193)= 32 1540    230   0   1060     95  22   1520    135   22      0      0      0      0      0      0
 194)= 32 1640   2255   0   1630   2025  13   1540    230   13      0      0      0      0      0      0
 195)= 32 1990    530   0   2010    259  30   1980    271   30      0      0      0      0      0      0
 196)= 32 1660   2452   0   1640   2095  14   1990    357   14      0      0      0      0      0      0
1PROGRAM TRANSYT8    ATHENS * CENTRAL ARTERIES * Optimisation ON                     PAGE   6   RUN ON 24/ 6/1993

 197)= 32 1500    192   0    900    127  22   1480     65   22      0      0      0      0      0      0
 198)= 32 1670   2284   0   1660   2091  11   1500    193   11      0      0      0      0      0      0
 199)= 32 1970    597   0   2040    597  32      0      0    0      0      0      0      0      0      0
 200)= 32 1690   1995   0   1670   1601  21   1970    394   21      0      0      0      0      0      0
 201)= 32 1460   1123   0   1210    972  20   1440    151   20      0      0      0      0      0      0
 202)= 32 1700   2015   0   1690   1467   7   1460    548    7      0      0      0      0      0      0
 203)= 32 1920    740   0   1910    740  30      0      0    0      0      0      0      0      0      0
 204)= 32 1730   1960   0   1700   1789  12   1920    171   12      0      0      0      0      0      0
 205)= 32 1740   1823   0   1730   1823  20      0      0    0      0      0      0      0      0      0
 206)= 32 1900    582   0   2110    373  30   1880    209   30      0      0      0      0      0      0
 207)= 32 1760   2003   0   1740   1848  14   1900    155   14      0      0      0      0      0      0
 208)= 32 1400    370   0   1380    250  20      0      0    0      0      0      0      0      0      0
 209)= 32 1770   2100   0   1760   2000   8   1400     67    8      0      0      0      0      0      0
 210)= 32 1860    511   0   2140    231  28   1840    280   28      0      0      0      0      0      0
 211)= 32 1800   2300   0   1770   1903  13   1860    314   13      0      0      0      0      0      0
 212)= 32 1360    260   0   1280    125  22   1340    135   22      0      0      0      0      0      0
 213)= 32 1810   2400   0   1800   2055  10   1360    260   10      0      0      0      0      0      0
 214)= 32 1831    729   0   1810    729  30      0      0    0      0      0      0      0      0      0
 215)= 32 1830    738   0   1810    738  30      0      0    0      0      0      0      0      0      0
 216)= 32 2200   1043   0   2171    560  25   2215    483   25      0      0      0      0      0      0
 217)= 32 2225   2050   0      0      0  25      0      0    0      0      0      0      0      0      0
 218)= 32 2215   2417   0      0      0  24      0      0    0      0      0      0      0      0      0
 219)= 32 2205    824   0   2225    568  22   1831    256   22      0      0      0      0      0      0
 220)= 32 2206    827   0   2225    357  22   1831    470   22      0      0      0      0      0      0
 221)= 32 2170    955   0   2185    567  22   2160    388   22      0      0      0      0      0      0
 222)= 32 2171    500   0   2185    150  22   2160    350   22      0      0      0      0      0      0
 223)= 32 2190   3300   0   2215   1933  23   2205    833   23   2170    370     23      0      0      0
 224)= 32 1840   2955   0   2190   2955  12      0      0    0      0      0      0      0      0      0
 225)= 32 2140    523   0   2130    373  22      0      0    0      0      0      0      0      0      0
 226)= 32 1870   2725   0   1840   2666   9   2140     59    9      0      0      0      0      0      0
 227)= 32 1780    528   0   1400    182  24   1760    346   24      0      0      0      0      0      0
 228)= 32 1880   2861   0   1870   2500  10   1780    361   10      0      0      0      0      0      0
 229)= 32 2110    590   0   5940     10  20   2090    580   20      0      0      0      0      0      0
 230)= 32 1910   2681   0   1880   2475  17   2110    206   17      0      0      0      0      0      0
 231)= 32 1930   1895   0   1910   1895   7      0      0    0      0      0      0      0      0      0
 232)= 32 1710   1099   0   1460    638  30   1690    214   30      0      0      0      0      0      0
 233)= 32 1940   3000   0   1930   1100   8   1710   1895    8      0      0      0      0      0      0
 234)= 32 1950   2200   0   1940   2200   9      0      0    0      0      0      0      0      0      0
 235)= 32 2040    721   0   5800    307  20   2020    414   20      0      0      0      0      0      0
 236)= 32 1980   2165   0   1950   2095  16   2040     70   16      0      0      0      0      0      0
 237)= 32 2010    268   0   3730    258  18   2790     10   18      0      0      0      0      0      0
 238)= 32 2000   1933   0   1980   1883  22   2010     50   22      0      0      0      0      0      0
 239)= 32 2805   2000   0   2825   1733  28   1620    256   28      0      0      0      0      0      0
 240)= 32 2790   2000   0   2805   1624  25   2000    370   25      0      0      0      0      0      0
 241)= 32 3730   1520   0      0      0  25      0      0    0      0      0      0      0      0      0
 242)= 32 2020   2620   0   2790   1360  20   3730   1260   20      0      0      0      0      0      0
 243)= 32 5800    330   0      0      0  25      0      0    0      0      0      0      0      0      0
 244)= 32 2050   2050   0   2020   2021  18   5800     23   18      0      0      0      0      0      0
 245)= 32 1960    850   0   1940    850  25      0      0    0      0      0      0      0      0      0
 246)= 32 2060   2100   0   2050   1725  30   1960    375   30      0      0      0      0      0      0
1PROGRAM TRANSYT8    ATHENS * CENTRAL ARTERIES * Optimisation ON                     PAGE   7   RUN ON 24/ 6/1993

 247)= 32 5930    420   0      0      0  25      0      0    0      0      0      0      0      0      0
 248)= 32 2080   2600   0   2060   2100  25   5930    500   25      0      0      0      0      0      0
 249)= 32 2090   2038   0   2080   2038  20      0      0    0      0      0      0      0      0      0
 250)= 32 5940     50   0      0      0  25      0      0    0      0      0      0      0      0      0
 251)= 32 2120   1500   0   2090   1424  15   5940     50   15      0      0      0      0      0      0
 252)= 32 1890    570   0   1780    352  25   1870    218   25      0      0      0      0      0      0
 253)= 32 2130   2036   0   2120   1474  12   1890    562   12      0      0      0      0      0      0
 254)= 32 2150   1675   0   2130   1625  25      0      0    0      0      0      0      0      0      0
 255)= 32 1850    200   0   2190    180  25      0      0    0      0      0      0      0      0      0
 256)= 32 2161   2000   0   2150   1900  20   1850    200   20      0      0      0      0      0      0
 257)= 32 2160    600   0   2150    600  20   1850     20   20      0      0      0      0      0      0
 258)= 32 2185    667   0      0      0  15      0      0    0      0      0      0      0      0      0
0*****END OF SUBROUTINE TINPUT*****
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Base Case Scenario

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1PROGRAM TRANSYT8      ATHENS * CENTRAL ARTERIES * Optimisation ON                                                      PAGE  20   RUN ON 24/ 6/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK      FLOW     SAT   DEGREE  MEAN TIMES  -------DELAY--------   ----STOPS----   ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER     INTO     FLOW    OF      PER PCU   UNIFORM RANDOM+ COST    MEAN   COST   MEAN               INDEX.      NODE   START  START
            LINK            SAT   CRUISE                 OVERSAT  OF   STOPS    OF   MAX.  AVERAGE  WEIGHTED SUM             END      END
                                        DELAY  (U+R+O=MEAN Q) DELAY    /PCU  STOPS          EXCESS  OF ( ) VALUES           1ST     2ND
          (PCU/H)  (PCU/H)   (%)   (SEC) (SEC)    (PCU-H/H)    ($/H)    (%)   ($/H)   (PCU)  (PCU)     ($/H)                 (SECONDS)

     900      222     1500      37     18    14      .6 +    .3  (   .5)      72  (   .2)       2                  .7     187    37  54  82   9
    1060      142     1500      47     18    27      .6 +    .4  (   .6)     104  (   .2)       2                  .7     189    84   2  39  47
    1210     1094     4000      68     17    15     3.4 +   1.1  (  2.5)      80  (   .8)      12                 3.3     185    10  27  55  72
    1280      361     1500      72     18    26     1.3 +   1.3  (  1.4)     104  (   .4)       5                 1.8     180    55  69  10  24
    1300      307     1500      58     18    20     1.0 +    .7  (   .9)      89  (   .3)       4                 1.2     179    43  58  88  13
    1330      995     3200      61     11     4      .4 +    .8  (   .6)      18  (   .3)       4                  .9     179    17  39  62  84
    1340     1302     3200      70     18     7     1.4 +   1.2  (  1.4)      38  (   .8)       7                 2.2     180    72   7  27  52
    1350     1392     3200      70     25     8     1.8 +   1.2  (  1.6)      45  (   .4)       9                 2.1     181    40  67  85  22
    1360      260     1500      65     22    29     1.1 +    .9  (  1.1)     111  (   .2)       4                 1.4     205    59  70  14  25
    1380     1147     3200      50     13     3      .4 +    .5  (   .5)      16  (   .2)       3                  .7     182    49  80   4  35
    1390      929     3200      47     16     4      .6 +    .4  (   .6)      23  (   .3)       3                  .8     183    17  44  62  89
    1400      369     1800      58     20    16      .9 +    .7  (   .9)      84  (   .3)       4                 1.2     203    40  55  85  10
    1420     1007     3200      52     24     6     1.3 +    .6  (  1.0)      40  (   .7)       6                 1.7     184    33  59  78  14
    1440     1085     3200      73      6    12     2.4 +   1.3  (  2.0)      61  (  1.7)      10                 3.7     185    31  51  76   6
    1450     1058     3200      78     19    12     1.7 +   1.8  (  1.9)      58  (   .9)      11                 2.8     186    49  67   4  22
    1460     1121     4000      90     20    23     2.7 +   4.4  (  3.9)     101  (  1.1)      18                 5.0     199    32  45  77   0
    1480      818     3200      50     10     3      .3 +    .5  (   .4)      13  (   .1)       2                  .5     187    57  79  12  34
    1490      848     3200      70     24    12     1.7 +   1.2  (  1.6)      72  (   .4)       9                 2.0     188    41  57  86  12
    1500      192     1500      72     22    39      .8 +   1.3  (  1.1)     123  (   .2)       3                 1.3     197    58  65  13  20
    1520     1020     3200      48     13     3      .3 +    .5  (   .4)      15  (   .2)       3                  .6     189    51  80   6  35
    1540      230     1000      74     22    34      .8 +   1.4  (  1.2)     125  (   .2)       4                 1.4     195    33  46  78   1
    1580       22     1500      44     18   106      .3 +    .4  (   .4)     153  (   .0)       1                  .4     194    28  30
    1590      190     1500      60      9    46     1.7 +    .7  (  1.3)     101  (   .2)       5                 1.5     193     8  26
    1610     1948     4300      59     12     3      .7 +    .7  (   .8)      15  (   .6)      23                 1.4     194    40  18
    1620      156     1800      60     25    34      .7 +    .7  (   .8)     114  (   .0)       5                  .9     260    52  64
    1630     1970     4300      79      9     7     2.2 +   1.9  (  2.2)      43  (   .9)      19                 3.2     195     5  30  50  75
    1640     2255     4300      98     13    36     3.1 +  19.5  ( 12.4)     108  (  3.2)      47       +        15.6     196    14  37  59  82
    1650      606     1500      76     26    14      .8 +   1.5  (  1.3)      60  (   .2)       6                 1.5     188    15  38  60  83
    1660     2457     4300      86     14     6     1.3 +   3.0  (  2.4)      30  (  1.6)      14                 3.9     197    25  54  70   9
    1670     2287     4300      83     11     6     1.4 +   2.3  (  2.1)      39  (   .6)      18                 2.7     198    35  63  80  18
    1680     1230     3200      79     30    17     3.9 +   1.8  (  3.2)      93  (   .6)      17                 3.8     186    25  46  70   1
    1690     1994     4300      87     21    13     4.0 +   3.3  (  4.0)      73  (  1.6)      25                 5.6     199     5  28  50  73
    1700     2015     5500      79      7    10     4.0 +   1.8  (  3.2)      60  (  3.1)      19                 6.3     200    55  75  10  30
    1710     1096     3800      79     30    28     6.7 +   1.8  (  4.7)      79  (   .9)      24                 5.6     212     0  32
    1720      259     1500      55     30    19      .8 +    .6  (   .8)      83  (   .1)       3                  .9     184    62  75  17  30
    1730     1961     5500      45     12     1      .1 +    .4  (   .3)       4  (   .2)       2                  .5     201    20  55  65  10
    1740     1823     5500      88     20    15     4.0 +   3.5  (  4.2)      90  (   .5)      25                 4.7     202    46  62   1  17
    1750      240     1500      55     20    19      .7 +    .6  (   .7)      69  (   .2)       3                  .9     183    47  59   2  14
    1760     2004     5500      68     14     3      .9 +   1.1  (  1.1)      19  (   .5)       9                 1.6     203    14  37  59  82
    1770     2100     5500      72      8     3      .6 +   1.3  (  1.0)      12  (   .9)       5                 1.9     204    20  43  65  88
    1780      526     2000      61     24    27     3.2 +    .8  (  2.2)      81  (   .7)      11                 2.8     209    47  85
    1790      300     1500      69     18    25      .9 +   1.1  (  1.1)     105  (   .4)       5                 1.6     181    25  37  70  82
    1800     2297     5500      67     13     4     1.2 +   1.0  (  1.2)      21  (  1.3)       8                 2.6     205    29  56  74  11
    1810     2397     5500      53     10     2      .6 +    .6  (   .6)      10  (   .8)       8                 1.5     206    36  19
    1820      551     2000      65     26    16     1.4 +    .9  (  1.3)      90  (   .4)       7                 1.7     178    32  50  77   5
    1830      738     3000      62     30    24     4.2 +    .8  (  2.7)      77  (   .3)      15                 3.1     227    17  52
    1831      729     3000      66     30    26     4.3 +   1.0  (  2.9)      80  (   .4)      15                 3.3     227    17  49
    1840     2940<    9000      52     12     5     3.4 +    .5  (  2.1)      19  (  1.7)      17                 3.9     208    84  50
    1850      197     1600      55     25    35     1.3 +    .6  (  1.1)      93  (   .1)       5                 1.1     224    26  45
    1860      507     1800      79     28    26     1.8 +   1.9  (  2.0)     111  (   .7)       8                 2.8     204    46  61   1  16
    1870     2711<    9000      62      9     8     4.9 +    .8  (  3.2)      22  (  1.6)      21                 4.8     209     0  43
    1880     2848<    9000      57     10     5     3.1 +    .7  (  2.1)      16  (  1.1)      11                 3.1     210     2  51
    1890      567     1600      71     25    20     1.9 +   1.2  (  1.7)      59  (   .3)      10                 2.0     222    60  14
    1900      583     2400      91     30    52     3.8 +   4.7  (  4.7)     146  (  1.0)      14                 5.7     202    74  85  29  40
1PROGRAM TRANSYT8      ATHENS * CENTRAL ARTERIES * Optimisation ON                                                      PAGE  21   RUN ON 24/ 6/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK      FLOW     SAT   DEGREE  MEAN TIMES  -------DELAY--------   ----STOPS----   ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER     INTO     FLOW    OF      PER PCU   UNIFORM RANDOM+ COST    MEAN   COST   MEAN               INDEX.      NODE   START  START
            LINK            SAT   CRUISE                 OVERSAT  OF   STOPS    OF   MAX.  AVERAGE  WEIGHTED SUM             END      END
                                        DELAY  (U+R+O=MEAN Q) DELAY    /PCU  STOPS          EXCESS  OF ( ) VALUES           1ST     2ND
          (PCU/H)  (PCU/H)   (%)   (SEC) (SEC)    (PCU-H/H)    ($/H)    (%)   ($/H)   (PCU)  (PCU)     ($/H)                 (SECONDS)

    1910     2673     9000      35     17     0      .1 +    .3  (   .2)       1  (   .1)       1                  .3     211    15   1
    1920      738     3000      74     30    25     3.7 +   1.4  (  2.8)     105  (   .8)      15                 3.6     200    79   3  34  48
    1930     1887     7500      45      7     5     2.2 +    .4  (  1.4)      36  (  2.0)      21                 3.4     212    37  86
    1940     2992     7500      51      8     7     5.4 +    .5  (  3.3)      47  (  2.2)      40       +         5.4     213    39  19
    1950     2196     7500      75      9    15     7.9 +   1.5  (  5.2)      50  (  3.4)      30                 8.6     214    39  73
    1960      850     2800      83     25    30     4.7 +   2.4  (  3.9)     102  (   .4)      22                 4.3     218    69  11
    1970      597     3000      81     32    36     3.8 +   2.1  (  3.3)     108  (   .9)      13                 4.2     198    66  76  21  31
    1980     2161     7500      52     16     2      .5 +    .5  (   .6)       4  (   .2)       2                  .8     215    49   8
    1990      534     1500     100     30   124     2.0 +  16.4  ( 10.1)     227  (  1.6)      23                11.7     196    40  55  85  10
    2000     1931     7500      28     22     0      .0 +    .2  (   .1)       1  (   .0)       1                  .1     259    47  40
    2010      270     1500      48     18     9      .2 +    .5  (   .4)      22  (   .1)       2                  .4     215    11  44
    2020     2618     5000      79     20    10     5.2 +   1.8  (  3.8)      49  (  2.9)      44                 6.7     217     4  63
    2040      721     1800      84     20    31     3.8 +   2.5  (  3.5)      96  (   .7)      18                 4.2     214    80  32
    2050     2049     5000      78     18    13     5.6 +   1.8  (  4.1)      50  (  1.3)      34                 5.4     218    19  65
    2060     2101     5000      77     30    11     4.6 +   1.7  (  3.5)      52  (   .4)      34                 3.9     219    45   3
    2080     2601     7000      41     25     1      .1 +    .4  (   .3)       3  (   .1)       3                  .3     220    66  56
    2090     2039     5000      46     20     3     1.1 +    .4  (   .9)      35  (   .3)      23                 1.1     221    10  89
    2110      589     2800      57     20    25     3.4 +    .7  (  2.2)      89  (   .6)      14                 2.8     210    55  87
    2120     1503     5000      69     15    14     4.7 +   1.1  (  3.2)      47  (   .7)      21                 3.9     222    18  56
    2130     2035     5000      52     12     2      .5 +    .5  (   .6)       8  (   .2)       5                  .8     223    27   7
    2140      521     2800      64     22    27     2.9 +    .9  (  2.1)      71  (   .3)      11                 2.4     208    54  79
    2150     1673     5000      49     25     3     1.1 +    .5  (   .9)      15  (   .2)       8                 1.1     224    49  20
    2160      598     1500      73     20    15     1.1 +   1.4  (  1.4)      62  (   .1)      10       +         1.4     225    69  27
    2161     1994     4500      59     20     3      .9 +    .7  (   .9)      13  (   .0)       7                  .9     225    60  37
    2170      953     1500     106     22   249     5.0 +  60.9  ( 36.3)     228  (  2.1)      86       +        38.4     226    34  87
    2171      498     4500      71     22    40     4.3 +   1.2  (  3.0)     102  (   .5)      13                 3.5     226    34  47
    2185      667     3000      69     15    33     4.9 +   1.1  (  3.3)      89  (   .9)      16                 4.2     225    41  69
    2190     3282<    9000      43     23     1      .8 +    .4  (   .7)      16  (   .7)      26                 1.4     207    76  62
    2200     1042     4000      47     25     4      .7 +    .4  (   .6)      11  (   .3)       4                 1.0     227    55  14
    2205      826     2500      99     22   104     6.8 +  17.2  ( 13.2)     165  (  1.8)      38       +        14.9     226     1  30
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Base Case Scenario

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  2206    826   4000     62    22    36    7.6 +   .8  (  4.6)     95  (  1.0)       20                     5.6    226      1  30
  2215   2417   8000     73    24    24   15.0 +  1.4  (  9.0)     81  (  1.9)       51                    10.9    226     51  87
  2225   2050   4500     72    25    13    6.3 +  1.3  (  4.2)     63  (  1.4)       35                     5.6    227     49  15
  2230    945   3200     63    22    12    2.4 +   .9  (  1.8)     72  (   .7)       10                     2.4    178      8  28   53  73
  2790   1999   5000     71    25    11    5.0 +  1.2  (  3.4)     55  (   .6)       32                     4.0    216     26  76
  2800    301   1800     25    25     7     .4 +   .2  (   .3)     27  (   .1)        2                      .4    260     68  38
  2805   2001   4000     52    28     1     .0 +   .5  (   .3)      2  (   .0)        1                      .3    259     89  85
  2820    301   1800     84    15    63    2.8 +  2.5  (  2.9)    126  (   .8)       10                     3.7    261     54  71
  2825   1699   5000     47    15     2     .4 +   .4  (   .5)     16  (   .2)       12                      .7    260     74  48
  2830   1847   5500     46    15     6    2.7 +   .4  (  1.7)     37  (   .8)       19                     2.5    193     31   5
  2845    617   1600     89    20    46    4.0 +  3.8  (  4.3)    112  (   .1)       18        +            4.5    261     77  25
  2846   1755   3500     76    20    14    5.2 +  1.6  (  3.8)     68  (   .3)       31        +            4.0    261     54  22
  3730   1520   5000     88    25    37   11.7 +  3.7  (  8.5)    100  (   .5)       39                     9.0    216     82  22
  3850   1000   5000     86    20    44    9.2 +  2.9  (  6.7)    102  (  1.2)       27                     7.9    261     29  49
  5800    330   1800     83    25    58    3.1 +  2.3  (  2.9)    118  (   .2)       10                     3.1    217     67  86
  5930    420   1800     81    25    47    3.5 +  2.1  (  3.0)    108  (   .2)       12                     3.3    219     13  38
  5940     50   1800     42    25    66     .6 +   .4  (   .5)    119  (   .0)        2                      .5    221      5  10
1PROGRAM TRANSYT8    ATHENS * CENTRAL ARTERIES * Optimisation ON                                          PAGE  22   RUN ON 24/ 6/1993
0     90 SECOND CYCLE  45 STEPS
0  TOTAL            TOTAL       MEAN          TOTAL    TOTAL      TOTAL         TOTAL        PENALTY        TOTAL
  DISTANCE           TIME      JOURNEY       UNIFORM  RANDOM+      COST          COST          FOR       PERFORMANCE
 TRAVELLED          SPENT       SPEED         DELAY   OVERSAT       OF            OF          EXCESS        INDEX
                                                       DELAY      DELAY         STOPS         QUEUES
 (PCU-KM/H)      (PCU-H/H)     (KM/H)      (PCU-H/H) (PCU-H/H)    ($/H)         ($/H)         ($/H)         ($/H)
0 13281.2         1125.6       11.8          267.6     234.3     ( 276.1) + (    72.6)  + (      .0)   =     348.7      TOTALS
0*********************************************************************************************************************************
*
0                                     CRUISE             DELAY                STOPS               TOTALS
                                 LITRES PER HOUR    LITRES PER HOUR     LITRES PER HOUR     LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS       1243.4        +     702.7         +      208.6        =     2154.7
0
 NO. OF ENTRIES TO SUBPT:    142
 NO. OF LINKS RECALCULATED: 2668
 SYSTEM TIME:        21:22:10

 EXECUTION TIME:    559 SECONDS
 PROGRAM TRANSYT8 FINISHED
```

Delay:stop weighting ratio of 0.01

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0CARD   CARD
  NO.   TYPE
 (  1)= TITLE:- ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 0.01
0CARD   CARD  CYCLE  NO. OF    TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW   CRUISE-SPEEDS    OPTIMISE EXTRA    HILL-    DELAY    STOP
  NO.   TYPE  TIME    STEPS  PERIOD DISPLACEMENTS   SETTINGS  INFO.    SCALE   SCALE  CARD32  0=NONE  COPIES    CLIMB    VALUE    VALUE
                        PER  1-1200  START    END     0=NO  2=CYCLE  10-200  50-200 0=TIMES  1=O/SET  FINAL    OUTPUT   P PER    P PER
              (SEC)   CYCLE   MINS.  (SEC)   (SEC)    1=YES  CHOICE     %       %   1=SPEEDS 2=FULL  OUTPUT   1=FULL   PCU-H     100
   2)=    1    90      45     120      2       3       1       0        0       0      0        2       0        0        5      500
1PROGRAM TRANSYT8    ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 0.01                    PAGE  20   RUN ON 29/ 7/1993
0       90 SECOND CYCLE   45 STEPS
0 LINK     FLOW    SAT  DEGREE MEAN TIMES   -------DELAY--------    ----STOPS----   ----QUEUE----      PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO   FLOW     OF    PER PCU    UNIFORM RANDOM+  COST     MEAN   COST   MEAN               INDEX.      NODE   START START
           LINK           SAT  CRUISE                OVERSAT   OF    STOPS     OF   MAX.  AVERAGE   WEIGHTED SUM            END      END
                                     DELAY  (U+R+O=MEAN Q) DELAY     /PCU  STOPS         EXCESS   OF ( ) VALUES           1ST      2ND
         (PCU/H) (PCU/H)    (%)  (SEC) (SEC)    (PCU-H/H)    ($/H)     (%)   ($/H)   (PCU)  (PCU)      ($/H)              (SECONDS)

    900     222    1500     42    18    17      .7 +    .4  (   .1)     79  (  1.9)     2                 1.9    187   35 50  80   5
   1060     142    1500     53    18    31      .7 +    .6  (   .1)    112  (  1.7)     2                 1.8    189   34 41  79  86
   1210    1094    4000     68    17    15     3.4 +   1.1  (   .2)     80  (  8.4)    12                 8.7    185    7 24  52  69
   1280     361    1500     77    18    31     1.4 +   1.7  (   .2)    115  (  4.0)     6                 4.2    180   55 68  10  23
   1300     307    1500     66    18    25     1.1 +   1.0  (   .1)    100  (  3.3)     4                 3.4    179   45 58   0  13
   1330     993    3200     56    11     3      .2 +    .6  (   .0)     12  (  1.9)     3                 1.9    179   17 41  62  86
   1340    1300    3200     68    18     6     1.1 +   1.0  (   .1)     34  (  6.9)     7                 7.0    180   71  7  26  52
   1350    1391    3200     75    25    12     3.2 +   1.5  (   .2)     69  (  6.6)    13                 6.8    181   34 59  79  14
   1360     260    1500     87    22    61     1.4 +   3.0  (   .2)    166  (  3.3)     6                 3.6    205   63 71  18  26
   1380    1144    3200     50    13     2      .3 +    .5  (   .0)     13  (  1.9)     3                 1.9    182   45 76   0  31
   1390     927    3200     47    16     3      .4 +    .4  (   .0)     18  (  2.0)     3                 2.0    183   14 41  59  86
   1400     368    1800     51    20    15     1.1 +    .5  (   .1)     89  (  3.2)     5                 3.3    203   38 55  83  10
   1420    1004    3200     52    24     6     1.1 +    .5  (   .1)     37  (  6.2)     5                 6.3    184   31 57  76  12
   1440    1078    3200     72     6    13     2.5 +   1.3  (   .2)     62  ( 17.4)    10                17.6    185   28 48  73   3
   1450    1051    3200     70    19     9     1.3 +   1.2  (   .1)     41  (  6.2)     8                 6.3    186   45 65   0  20
   1460    1120    4000     84    20    22     4.3 +   2.6  (   .3)     78  (  8.5)    12                 8.9    199   63 77  18  32
   1480     812    3200     46    10     3      .2 +    .4  (   .0)     11  (   .8)     1                  .9    187   53 77   8  32
   1490     842    3200     59    24     9     1.3 +    .7  (   .1)     56  (  3.2)     7                 3.3    188   81 10  36  55
   1500     192    1500     82    22    57      .9 +   2.2  (   .2)    153  (  2.3)     4                 2.4    197   56 62  11  17
   1520     945<   3200     43    13     2      .2 +    .4  (   .0)     10  (  1.3)     1                 1.4    189    0 30  45  75
   1540     220    1000     71    22    33      .8 +   1.2  (   .1)    117  (  2.1)     4                 2.2    195   30 43  75  88
   1580      22    1500     66    18   191      .3 +    .9  (   .1)    207  (   .5)     1                  .5    194   28 29
   1590     190    1500     67     9    53     1.8 +   1.0  (   .1)    109  (  2.2)     5                 2.4    193   10 26
   1610    1948    4300     58    12     3      .7 +    .7  (   .1)     12  (  4.9)    10                 4.9    194   39 18
   1620     156    1800     87    25    83      .7 +   2.9  (   .2)    157  (   .5)     7                  .7    260   48 56
   1630    1970    4300     79     9     8     2.3 +   1.9  (   .2)     42  (  8.9)    19                 9.1    195    2 27  47  72
   1640    2245    4300     76    13     4      .7 +   1.6  (   .1)     18  (  5.3)     9                 5.5    196   12 42  57  87
   1650     409<   1500     58    26    14      .8 +    .7  (   .1)     41  (  1.7)     3                 1.8    188   58 78  13  33
   1660    2290<   4300     77    14     4     1.1 +   1.7  (   .1)     22  ( 11.4)    10                11.5    197   22 52  67   7
   1670    2144<   4300     80    11     7     2.2 +   2.0  (   .2)     42  (  6.5)    18                 6.7    198   29 56  74  11
   1680    1187<   3200     83    30    21     4.3 +   2.5  (   .3)     95  (  6.1)    19                 6.5    186   23 42  68  87
   1690    1894<   4300     86    21    15     5.0 +   3.1  (   .4)     74  ( 15.9)    24                16.3    199   37 59  82  14
   1700    1941<   5500     69     7     8     3.1 +   1.1  (   .2)     45  ( 23.2)    14                23.4    200   39 61  84  16
   1710    1081<   3800     88    30    43     9.2 +   3.7  (   .6)     97  ( 11.5)    27                12.1    212   67  5
   1720     254    1500     54    30    20      .8 +    .6  (   .1)     92  (  1.6)     3                 1.7    184   60 73  15  28
   1730    1893<   5500     43    12     1      .1 +    .4  (   .0)      4  (  2.3)     2                 2.3    201    4 39  49  84
   1740    1761<   5500     90    20    25     7.6 +   4.4  (   .6)    112  (  6.6)    27                 7.2    202   46 61   1  16
   1750     237    1500     55    20    20      .7 +    .6  (   .1)     69  (  2.4)     2                 2.4    183   44 56  89  11
   1760    1940<   5500     72    14     4     1.1 +   1.3  (   .1)     22  (  6.2)     9                 6.3    203   14 35  59  80
   1770    2035<   5500     69     8     3      .5 +   1.1  (   .1)     10  (  7.2)     3                 7.3    204   20 43  65  88
   1780     515<   2000     61    24    28     3.2 +    .8  (   .2)     82  (  6.7)    11                 6.9    209   46 83
   1790     296    1500     59    18    17      .7 +    .7  (   .1)     69  (  2.9)     3                 3.0    181   17 31  62  76
   1800    2234<   5500     59    13     2      .7 +    .7  (   .1)     15  (  9.3)     6                 9.4    205   30 60  75  15
   1810    2338<   5500     52    10     2      .6 +    .5  (   .1)     10  (  8.8)     7                 8.8    206   36 19
   1820     538<   2000     58    26    12     1.2 +    .7  (   .1)     76  (  3.6)     6                 3.7    178   30 50  75   5
   1830     720<   3000     80    30    38     5.5 +   2.0  (   .4)     98  (  4.4)    19                 4.7    227   25 51
   1831     711<   3000     89    30    48     5.7 +   3.8  (   .5)    109  (  4.8)    21                 5.3    227   25 48
   1840    2922<   9000     50    12     4     2.7 +    .5  (   .2)     15  ( 14.2)    12                14.3    208   84 51
   1850     196    1600     73    25    55     1.6 +   1.4  (   .1)    117  (  1.2)     6                 1.4    224   48 62
   1860     504    1800     79    28    25     1.7 +   1.8  (   .2)    108  (  7.2)     8                 7.4    204   46 61   1  16
   1870    2694<   9000     60     9     8     5.3 +    .7  (   .3)     21  ( 15.9)    16                16.2    209   88 42
   1880    2825<   9000     61    10     7     4.5 +    .8  (   .3)     19  ( 13.2)    14                13.4    210    2 47
   1890     558<   1600     68    25    21     2.3 +   1.1  (   .2)     84  (  4.1)    13                 4.3    222   73 28
   1900     581    2400     84    30    32     2.6 +   2.5  (   .3)    108  (  7.4)    10                 7.7    202   73 85  28  40
1PROGRAM TRANSYT8    ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 0.01                    PAGE  21   RUN ON 29/ 7/1993
0       90 SECOND CYCLE   45 STEPS
0 LINK     FLOW    SAT  DEGREE MEAN TIMES   -------DELAY--------    ----STOPS----   ----QUEUE----      PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO   FLOW     OF    PER PCU    UNIFORM RANDOM+  COST     MEAN   COST   MEAN               INDEX.      NODE   START START
           LINK           SAT  CRUISE                OVERSAT   OF    STOPS     OF   MAX.  AVERAGE   WEIGHTED SUM            END      END
                                     DELAY  (U+R+O=MEAN Q) DELAY     /PCU  STOPS         EXCESS   OF ( ) VALUES           1ST      2ND
         (PCU/H) (PCU/H)    (%)  (SEC) (SEC)    (PCU-H/H)    ($/H)     (%)   ($/H)   (PCU)  (PCU)      ($/H)              (SECONDS)

   1910    2652<   9000     34    17     0      .1 +    .3  (   .0)      1  (  1.3)     1                 1.3    211   17  3
   1920     732    3000     84    30    28     3.1 +   2.7  (   .3)    114  (  8.2)    14                 8.5    200   65 77  20  32
   1930    1872<   7500     42     7     7     3.1 +    .4  (   .2)     22  ( 12.3)    11                12.5    212   10 63
   1940    2958<   7500     51     8     3     1.8 +    .5  (   .1)     17  (  7.9)    14                 8.0    213   68 46
   1950    2172<   7500     67     9    11     5.7 +   1.0  (   .3)     28  ( 19.2)    18                19.5    214   72 20
   1960     840    2800     93    25    56     6.8 +   6.2  (   .6)    103  (  4.0)    24                 4.6    218   83 21
   1970     596    3000     75    32    27     3.0 +   1.5  (   .2)     94  (  7.9)    12                 8.1    198   59 70  14  25
   1980    2138<   7500     43    16     1      .3 +    .4  (   .0)      4  (  1.9)     2                 2.0    215   77 45
   1990     531    1500    177    30  1628     8.5 +231.7  ( 12.0)    257  ( 17.7)   245     +          29.7    196   45 53   0   8
   2000    1910<   7500     27    22     1      .1 +    .2  (   .0)      4  (   .7)     3                  .7    259   65 58
   2010     270    1500     65    18    27     1.1 +    .9  (   .1)    106  (  3.1)     7                 3.2    215   48 72
   2020    2615    5000     76    20     8     4.0 +   1.6  (   .3)     34  ( 20.2)    28                20.5    217   19 80
   2040     720    1800     92    20    49     4.3 +   5.5  (   .5)    117  (  9.1)    22     +           9.6    214   27 65
   2050    2047    5000     72    18    11     5.0 +   1.3  (   .3)     35  (  9.2)    20                 9.5    218   29 79
   2060    2095    5000     82    30    17     7.7 +   2.3  (   .5)     86  (  6.9)    48                 7.4    219   67 22
   2080    2595    7000     41    25     1      .1 +    .4  (   .0)      3  (   .5)     2                  .5    220   87 77
   2090    2034    5000     46    20     2      .6 +    .4  (   .1)     20  (  1.6)    16                 1.7    221   27 16
   2110     588    2800     51    20    15     1.9 +    .5  (   .1)     55  (  3.5)     9                 3.6    210   51 87
   2120    1499    5000     71    15    17     5.8 +   1.2  (   .4)     47  (  6.8)    19                 7.2    222   32 69
   2130    2023<   5000     51    12     2      .3 +    .5  (   .0)      6  (  1.4)     3                 1.4    223   41 21
   2140     518    2800     67    22    38     4.5 +   1.0  (   .3)     77  (  3.5)    10                 3.8    208   55 79
   2150    1663<   5000     45    25     2      .5 +    .4  (   .0)     10  (  1.2)     6                 1.2    224   66 42
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Delay:stop weighting ratio of 0.01

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 2160     594   1500      85     20     30    2.2 +  2.7  (   .2)    89  (   .9)     14      +            1.2   225    83  34
 2161    1982<  4500      65     20      6    2.3 +   .9  (   .2)    25  (   .9)     14                   1.0   225    74  44
 2170     951   1500     110     22    362    6.1 + 89.4  (  4.8)   254  ( 23.5)    115      +           28.3   226    34  85
 2171     496   4500      66     22     34    3.7 +  1.0  (   .2)    91  (  4.4)     12                   4.7   226    34  48
 2185     667   3000      56     15     24    3.9 +   .6  (   .2)    76  (  7.8)     13                   8.0   225    48  83
 2190    3261<  9000      42     23      1     .5 +   .4  (   .0)    11  (  4.7)     17                   4.8   207    76  63
 2200    1039   4000      40     25      2     .2 +   .3  (   .0)     4  (  1.2)      1                   1.2   227    54  22
 2205     820   2500      92     22     53    6.5 +  5.5  (   .6)   118  ( 12.7)     25                  13.3   226    89  30
 2206     814<  4000      57     22     32    6.6 +   .7  (   .4)    92  (  9.9)     19                  10.2   226    89  30
 2215    2417   8000      80     24     28   16.8 +  2.0  (   .9)    87  ( 20.3)     56                  21.2   226    52  85
 2225    2050   4500      62     25      7    3.3 +   .8  (   .2)    43  (  9.6)     25                   9.8   227    48  23
 2230     945   3200      70     22     15    2.8 +  1.2  (   .2)    81  (  7.4)     11                   7.6   178     8  26  53  71
 2790    1995   5000      68     25      9    4.0 +  1.1  (   .3)    41  (  4.4)     24                   4.6   216    42   4
 2800     298   1800      23     25      7     .4 +   .2  (   .0)    46  (  1.8)      4                   1.8   260    60  33
 2805    2001   4000      52     28      1     .0 +   .5  (   .0)     1  (   .3)      1                    .3   259    13   9
 2820     298   1800      75     15     41    1.9 +  1.4  (   .2)    66  (  4.2)      5                   4.3   261    67  86
 2825    1699   5000      45     15      2     .6 +   .4  (   .0)     8  (   .9)      3                   1.0   260    67  44
 2830    1847   5500      45     15      5    2.3 +   .4  (   .1)    34  (  7.4)     18                   7.5   193    31   7
 2845     617   1600      96     20     82    4.5 +  9.5  (   .7)   147  (  2.0)     24      +            2.7   261     2  37
 2846    1755   3500      78     20     15    5.6 +  1.7  (   .4)    70  (  2.7)     32      +            3.0   261    67  34
 3730    1520   5000      94     25     48   12.5 +  7.7  (  1.0)   113  (  5.6)     44      +            6.6   216    10  38
 3850    1000   5000      82     20     40    8.9 +  2.2  (   .6)    98  ( 11.6)     25                  12.1   261    41  62
 5800     330   1800      92     25     87    3.2 +  4.7  (   .4)   144  (  2.5)     13                   2.9   217    84  11
 5930     420   1800      72     25     38    3.1 +  1.3  (   .2)    97  (  2.1)     11                   2.4   219    32  60
 5940      50   1800      42     25     66     .6 +   .4  (   .0)   120  (   .3)      2                    .4   221    22  27
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 0.01                  PAGE  22   RUN ON 29/ 7/1993
0      90 SECOND CYCLE  45 STEPS
0  TOTAL            TOTAL       MEAN           TOTAL     TOTAL     TOTAL          TOTAL          PENALTY          TOTAL
  DISTANCE           TIME     JOURNEY         UNIFORM   RANDOM+     COST           COST            FOR          PERFORMANCE
 TRAVELLED          SPENT       SPEED           DELAY   OVERSAT      OF             OF            EXCESS           INDEX
                                                         DELAY     DELAY          STOPS           QUEUES
  (PCU-KM/H)       (PCU-H/H)    (KM/H)        (PCU-H/H) (PCU-H/H)   ($/H)          ($/H)           ($/H)           ($/H)
0 13281.2          1374.5        9.7           280.0     470.9     (  37.5) + (  618.5)  + (       .0)   =       656.0       TOTALS
0+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+
0                                           CRUISE               DELAY                 STOPS                 TOTALS
                                      LITRES PER HOUR     LITRES PER HOUR      LITRES PER HOUR       LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS              1243.4      +       1051.2        +        177.7         =       2472.3
0
 NO. OF ENTRIES TO SUBPT:     124
 NO. OF LINKS RECALCULATED: 2733
 SYSTEM TIME:          20:46: 6

 EXECUTION TIME:   488 SECONDS
 PROGRAM TRANSYT8 FINISHED
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Delay:stop weighting ratio of 100

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0CARD   CARD
  NO.   TYPE
 (   1)= TITLE:- ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 100
0CARD   CARD   CYCLE  NO. OF    TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE    FLOW   CRUISE-SPEEDS    OPTIMISE EXTRA    HILL-    DELAY    STOP
  NO.   TYPE   TIME    STEPS  PERIOD DISPLACEMENTS  SETTINGS  INFO.     SCALE   SCALE  CARD32  0=NONE  COPIES   CLIMB    VALUE    VALUE
                         PER  1-1200  START     END     0=NO  2=CYCLE  10-200  50-200 0=TIMES  1=O/SET  FINAL  OUTPUT    P PER    P PER
              (SEC)    CYCLE   MINS.  (SEC)   (SEC)    1=YES  CHOICE      %       %  1=SPEEDS 2=FULL  OUTPUT  1=FULL    PCU-H     100
   2)=   1     90       45     120      2       3        1       0        0       0      0        2      0        0      500        5
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 100                                   PAGE  20   RUN ON 30/ 7/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK     FLOW    SAT   DEGREE  MEAN TIMES   -------DELAY--------    ----STOPS----    ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF      PER PCU    UNIFORM RANDOM+ COST     MEAN    COST    MEAN              INDEX.      NODE   START  START
           LINK            SAT   CRUISE                OVERSAT  OF     STOPS    OF     MAX.  AVERAGE  WEIGHTED SUM              END      END
                                        DELAY  (U+R+O=MEAN Q) DELAY     /PCU   STOPS          EXCESS  OF ( ) VALUES            1ST      2ND
         (PCU/H) (PCU/H)   (%)   (SEC) (SEC)    (PCU-H/H)     ($/H)    (%)     ($/H)   (PCU)  (PCU)    ($/H)                   (SECONDS)

    900     222   1500     35     18    13      .5 +   .3   (  4.1)     69  (   .0)      2                   4.1    187    33 51 78  6
   1060     142   1500     43     18    24      .6 +   .4   (  4.8)     97  (   .0)      2                   4.8    189    84  3 39 48
   1210    1094   4000     68     17    15     3.4 +  1.1   ( 22.3)     80  (   .1)     12                  22.4    185    50 67  5 22
   1280     361   1500     68     18    23     1.2 +  1.0   ( 11.4)     97  (   .0)      5                  11.4    180    55 70 10 25
   1300     307   1500     58     18    20     1.0 +   .7   (  8.4)     89  (   .0)      4                   8.4    179    42 57 87 12
   1330     995   3200     61     11     4      .5 +   .8   (  6.2)     27  (   .0)      9                   6.2    179    16 38 61 83
   1340    1302   3200     73     18     8     1.5 +  1.4   ( 14.2)     43  (   .1)     10                  14.3    180    73  7 28 52
   1350    1392   3200     73     25     7     1.4 +  1.3   ( 13.7)     47  (   .0)     11                  13.7    181    50 76  5 31
   1360     260   1500     65     22    29     1.2 +   .9   ( 10.6)    113  (   .0)      4                  10.7    205    17 28 62 73
   1380    1147   3200     50     13     3      .3 +   .5   (  4.0)     15  (   .0)      3                   4.0    182    17 48 62  3
   1390     929   3200     52     16     5      .6 +   .5   (  5.9)     35  (   .0)      6                   6.0    183    35 59 80 14
   1400     369   1800     62     20    17      .9 +   .8   (  8.5)     74  (   .0)      4                   8.5    203    41 55 86 10
   1420    1007   3200     54     24     8     1.8 +   .6   ( 11.8)     68  (   .1)     10                  11.9    184    24 49 69  4
   1440    1085   3200     73      6     9     1.5 +  1.3   ( 14.2)     53  (   .1)     13                  14.4    185    71  1 26 46
   1450    1058   3200     78     19    12     1.6 +  1.8   ( 17.1)     55  (   .1)     11                  17.1    186    44 62 89 17
   1460    1121   4000     90     20    24     3.1 +  4.4   ( 37.2)    111  (   .1)     18                  37.4    199    31 44 76 89
   1480     818   3200     52     10     4      .3 +   .5   (  4.2)     17  (   .0)      3                   4.2    187    54 75  9 30
   1490     848   3200     70     24    13     1.9 +  1.2   ( 15.3)     83  (   .0)     10                  15.3    188    41 57 86 12
   1500     192   1500     72     22    39      .8 +  1.3   ( 10.3)    127  (   .0)      4                  10.4    197    57 64 12 19
   1520    1020   3200     49     13     3      .4 +   .5   (  4.5)     20  (   .0)      4                   4.5    189    52 80  7 35
   1540     230   1000     74     22    34      .8 +  1.4   ( 10.9)    124  (   .0)      4                  10.9    195    33 46 78  1
   1580      22   1500     33     18    82      .3 +   .2   (  2.5)    134  (   .0)      1                   2.5    194    27 30
   1590     190   1500     63      9    49     1.7 +   .9   ( 13.0)    105  (   .0)      5                  13.0    193    10 27
   1610    1948   4300     60     12     3      .8 +   .7   (  7.8)     14  (   .1)     13                   7.9    194    40 17
   1620     156   1800     60     25    30      .5 +   .7   (  6.4)    109  (   .0)      4                   6.4    260    47 59
   1630    1970   4300     79      9     7     2.2 +  1.9   ( 20.4)     43  (   .1)     19                  20.5    195     5 30 50 75
   1640    2255   4300     98     13    36     3.2 + 19.5   (113.7)    106  (   .3)     49     +           114.0    196    13 36 58 81
   1650     606   1500     76     26    14      .8 +  1.5   ( 11.6)     62  (   .0)      6                  11.6    188    15 38 60 83
   1660    2457   4300     86     14     6     1.3 +  3.0   ( 21.6)     31  (   .2)     14                  21.7    197    24 53 69  8
   1670    2287   4300     83     11     6     1.6 +  2.3   ( 19.9)     45  (   .1)     20                  19.9    198    35 63 80 18
   1680    1230   3200     79     30    16     3.5 +  1.8   ( 26.5)     90  (   .1)     17                  26.5    186    20 41 65 86
   1690    1994   4300     87     21    13     4.0 +  3.3   ( 36.4)     71  (   .2)     23                  36.6    199     4 27 49 72
   1700    2015   5500     79      7    10     4.0 +  1.8   ( 29.2)     61  (   .3)     19                  29.5    200    54 74  9 29
   1710    1096   3800     74     30    26     6.5 +  1.4   ( 39.7)     83  (   .1)     25                  39.8    212     4 38
   1720     259   1500     52     30    20      .9 +   .5   (  7.2)     83  (   .0)      4                   7.2    184    52 66  7 21
   1730    1961   5500     45     12     1      .1 +   .4   (  2.5)      4  (   .0)      2                   2.5    201    19 54 64  9
   1740    1823   5500     88     20    15     4.1 +  3.5   ( 37.9)     91  (   .1)     25                  38.0    202    45 61  0 16
   1750     240   1500     45     20    16      .7 +   .4   (  5.3)     88  (   .0)      3                   5.3    183    62 77 17 32
   1760    2004   5500     66     14     3      .9 +  1.0   (  9.3)     24  (   .1)     15                   9.4    203    14 38 59 83
   1770    2100   5500     75      8     4      .7 +  1.5   ( 11.1)     19  (   .1)     20                  11.3    204    21 43 66 88
   1780     526   2000     66     24    27     3.1 +  1.0   ( 20.1)     80  (   .1)     11                  20.1    209    59  4
   1790     300   1500     64     18    23     1.1 +   .9   (  9.8)    103  (   .0)      4                   9.8    181    34 47 79  2
   1800    2297   5500     67     13     4     1.2 +  1.0   ( 11.2)     25  (   .2)     15                  11.3    205    77 14 32 59
   1810    2397   5500     53     10     2      .5 +   .6   (  5.4)      8  (   .1)      7                   5.5    206    84 67
   1820     551   2000     65     26    14     1.2 +   .9   ( 10.5)     82  (   .0)      7                  10.5    178    30 48 75  3
   1830     738   3000     65     30    26     4.3 +   .9   ( 26.4)     82  (   .0)     16                  26.4    227    25 58
   1831     729   3000     71     30    29     4.6 +  1.2   ( 29.0)     87  (   .0)     17                  29.1    227    25 55
   1840    2940<  9000     61     12    10     7.3 +   .8   ( 40.7)     55  (   .5)     50                  41.2    208    89 46
   1850     197   1600     50     25    32     1.2 +   .5   (  8.6)     87  (   .0)      5                   8.6    224    25 46
   1860     507   1800     75     28    22     1.7 +  1.4   ( 15.8)    103  (   .1)      8                  15.9    204    46 62  1 17
   1870    2711<  9000     58      9     2     1.1 +   .7   (  9.0)     10  (   .1)     14                   9.1    209     9 55
   1880    2848<  9000     57     10     5     2.9 +   .7   ( 18.0)     18  (   .1)     21                  18.1    210    16 65
   1890     567   1600     69     25    20     2.1 +  1.1   ( 16.0)     55  (   .0)      8                  16.0    222    65 20
   1900     583   2400     91     30    50     3.3 +  4.7   ( 40.2)    152  (   .1)     14                  40.3    202    73 84 28 39
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 100                                   PAGE  21   RUN ON 30/ 7/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK     FLOW    SAT   DEGREE  MEAN TIMES   -------DELAY--------    ----STOPS----    ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF      PER PCU    UNIFORM RANDOM+ COST     MEAN    COST    MEAN              INDEX.      NODE   START  START
           LINK            SAT   CRUISE                OVERSAT  OF     STOPS    OF     MAX.  AVERAGE  WEIGHTED SUM              END      END
                                        DELAY  (U+R+O=MEAN Q) DELAY     /PCU   STOPS          EXCESS  OF ( ) VALUES            1ST      2ND
         (PCU/H) (PCU/H)   (%)   (SEC) (SEC)    (PCU-H/H)     ($/H)    (%)     ($/H)   (PCU)  (PCU)    ($/H)                   (SECONDS)

   1910    2673   9000     35     17     0      .1 +   .3   (  1.8)      3  (   .0)      4                   1.9    211    33 19
   1920     738   3000     74     30    19     2.5 +  1.4   ( 19.7)     99  (   .1)     14                  19.7    200    78  2 33 47
   1930    1887   7500     47      7     4     1.9 +   .4   ( 11.8)     25  (   .1)     16                  11.9    212    43  0
   1940    2992   7500     51      8     4     2.5 +   .5   ( 15.3)     45  (   .2)     46     +            15.5    213    17 87
   1950    2196   7500     78      9    20    10.4 +  1.7   ( 60.7)     84  (   .6)     51                  61.3    214    33 66
   1960     850   2800     80     25    31     5.3 +  2.0   ( 36.8)    101  (   .0)     22                  36.9    218    73 16
   1970     597   3000     81     32    29     2.7 +  2.1   ( 24.2)    101  (   .1)     11                  24.3    198    66 76 21 31
   1980    2161   7500     52     16     2      .5 +   .5   (  5.0)      4  (   .0)      3                   5.0    215    46  5
   1990     533   1500    100     30   122     1.7 + 16.4   ( 90.6)    226  (   .2)     24                  90.7    196    39 54 84  9
   2000    1931   7500     28     22     0      .0 +   .2   (  1.0)      1  (   .0)      0                   1.0    259    49 42
   2010     270   1500     48     18    12      .4 +   .5   (  4.3)     60  (   .0)      5                   4.3    215     8 41
   2020    2618   5000     80     20    11     6.0 +  2.0   ( 40.1)     61  (   .4)     46                  40.4    217    89 57
   2040     721   1800     82     20    30     3.7 +  2.2   ( 29.6)     95  (   .1)     18                  29.7    214    73 26
   2050    2049   5000     80     18    12     4.8 +  2.0   ( 34.0)     67  (   .2)     41                  34.2    218    24 69
   2060    2101   5000     79     30    12     5.0 +  1.9   ( 34.0)     55  (   .0)     38                  34.1    219    50  7
   2080    2601   7000     41     25     1      .1 +   .4   (  2.4)      3  (   .0)      3                   2.4    220    72 62
   2090    2039   5000     46     20     2     1.0 +   .4   (  7.0)     31  (   .0)     22                   7.0    221    13  2
   2110     589   2800     57     20    29     4.1 +   .7   ( 23.7)     91  (   .1)     14                  23.8    210    69 11
   2120    1503   5000     71     15    15     5.0 +  1.2   ( 31.1)     57  (   .1)     27                  31.2    222    24 61
   2130    2035   5000     52     12     2      .7 +   .5   (  6.1)     11  (   .0)      6                   6.1    223    27  7
   2140     521   2800     48     22    17     2.1 +   .5   ( 12.6)     44  (   .0)      6                  12.6    208    50 84
   2150    1673   5000     50     25     4     1.2 +   .5   (  8.7)     16  (   .0)      7                   8.7    224    50 19
```

Delay:stop weighting ratio of 100

```
  2160    598   1500     72    20    13    .9 +  1.3  ( 11.0)    41  (   .0)      7            11.0   225    68  27
  2161   1994   4500     58    20     3    .8 +   .7  (  7.4)    13  (   .0)      6             7.5   225    59  37
  2170    953   1500    106    22   248   4.7 + 60.9  (328.2)   227  (   .2)     85    +      328.4   226    36  89
  2171    498   4500     71    22    41   4.4 +  1.2  ( 28.2)   102  (   .0)     13            28.3   226    36  49
  2185    667   3000     71    15    34   5.1 +  1.2  ( 31.7)    91  (   .1)     16            31.8   225    41  68
  2190   3282<  9000     41    23     1    .3 +   .3  (  3.1)     4  (   .0)      4             3.1   207    62  51
  2200   1042   4000     45    25     3    .6 +   .4  (  4.9)    26  (   .1)     11             5.0   227    61  22
  2205    826   2500     99    22   103   6.6 + 17.1  (118.6)   164  (   .2)     38    +      118.8   226     3  32
  2206    826   4000     62    22    34   7.0 +   .8  ( 38.9)    95  (   .1)     20            39.0   226     3  32
  2215   2417   8000     73    24    24  15.0 +  1.4  ( 81.9)    81  (   .2)     51            82.1   226    53  89
  2225   2050   4500     69    25    12   5.6 +  1.1  ( 33.6)    59  (   .1)     33            33.7   227    55  23
  2230    945   3200     63    22    12   2.4 +   .9  ( 16.2)    72  (   .1)     10            16.3   178     6  26  51  71
  2790   1999   5000     73    25    13   5.8 +  1.4  ( 36.0)    57  (   .1)     31            36.0   216    17  65
  2800    301   1800     25    25     6    .4 +   .2  (  2.7)    24  (   .0)      2             2.7   260    63  33
  2805   2001   4000     52    28     1    .0 +   .5  (  2.7)     1  (   .0)      1             2.7   259     1  87
  2820    301   1800     84    15    62   2.7 +  2.5  ( 26.0)   126  (   .1)     10            26.0   261    49  66
  2825   1699   5000     47    15     2    .4 +   .4  (  4.2)    16  (   .0)     11             4.2   260    69  43
  2830   1847   5500     46    15     6   2.5 +   .4  ( 14.5)    35  (   .1)     19            14.6   193    32   7
  2845    617   1600     89    20    46   4.0 +  3.8  ( 39.4)   112  (   .0)     18    +       39.4   261    72  20
  2846   1755   3500     76    20    14   5.2 +  1.6  ( 34.2)    68  (   .0)     32    +       34.2   261    49  17
  3730   1520   5000     83    25    32  10.9 +  2.4  ( 66.8)    93  (   .0)     36            66.8   216    71  13
  3850   1000   5000     86    20    44   9.2 +  2.9  ( 60.7)   103  (   .1)     27            60.8   261    24  44
  5800    330   1800     79    25    52   3.0 +  1.8  ( 23.8)   111  (   .0)      9            23.8   217    61  81
  5930    420   1800     78    25    44   3.4 +  1.7  ( 25.4)   103  (   .0)     11            25.4   219    17  43
  5940     50   1800     42    25    66    .6 +   .4  (  4.6)   120  (   .0)      2             4.6   221     8  13
1PROGRAM TRANSYT8    ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 100              PAGE  22   RUN ON 30/ 7/1993
0    90 SECOND CYCLE  45 STEPS
0  TOTAL          TOTAL       MEAN           TOTAL     TOTAL      TOTAL         TOTAL          PENALTY        TOTAL
  DISTANCE         TIME      JOURNEY        UNIFORM   RANDOM+     COST          COST             FOR       PERFORMANCE
 TRAVELLED        SPENT       SPEED          DELAY    OVERSAT      OF            OF            EXCESS         INDEX
                                                       DELAY     DELAY         STOPS           QUEUES
 (PCU-KM/H)    (PCU-H/H)    (KM/H)      (PCU-H/H) (PCU-H/H)     ($/H)         ($/H)            ($/H)        ($/H)
0 13281.2       1117.2      11.9          262.0     231.5      (2467.4) + (     8.0)  +  (       .0)    =     2475.4      TOTALS
0**************************************************************************************************************************************
*
0                             CRUISE               DELAY                  STOPS                  TOTALS
                          LITRES PER HOUR     LITRES PER HOUR       LITRES PER HOUR       LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS     1243.4        +       690.9        +       228.8        =       2163.1
0
 NO. OF ENTRIES TO SUBPT:    129
 NO. OF LINKS RECALCULATED: 2391
 SYSTEM TIME:        19: 2:55

 EXECUTION TIME:    419 SECONDS
 PROGRAM TRANSYT8 FINISHED
```

Cycle time of 140 seconds

```
0CARD   CARD
 NO.    TYPE
 (  1)= TITLE:- ATHENS * Central Arteries * Opt on; CYCLE TIME = 140 with 60 steps
0CARD   CARD   CYCLE  NO. OF   TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW  CRUISE-SPEEDS   OPTIMISE EXTRA    HILL-   DELAY   STOP
 NO.    TYPE   TIME   STEPS  PERIOD DISPLACEMENTS  SETTINGS  INFO.   SCALE   SCALE  CARD32  0=NONE  COPIES   CLIMB   VALUE  VALUE
                       PER   1-1200  START    END    0=NO  2=CYCLE 10-200  50-200 0=TIMES  1=O/SET  FINAL  OUTPUT   P PER  P PER
               (SEC)  CYCLE   MINS.  (SEC)   (SEC)   1=YES  CHOICE     %       %   1=SPEEDS 2=FULL  OUTPUT  1=FULL   PCU-H    100
   2)=   1     140     60     120      2       3       1       0       0       0       0       2       0       0      55     50
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; CYCLE TIME = 140 with 60 steps                  PAGE  20   RUN ON 31/ 7/1993
0     140 SECOND CYCLE   60 STEPS
0 LINK   FLOW    SAT DEGREE  MEAN TIMES  -------DELAY--------  ----STOPS-----  ----QUEUE----     PERFORMANCE   EXIT  GREEN TIMES
 NUMBER  INTO   FLOW     OF     PER PCU  UNIFORM RANDOM+ COST    MEAN   COST    MEAN                  INDEX.    NODE  START   START
         LINK           SAT  CRUISE              OVERSAT  OF    STOPS    OF     MAX.  AVERAGE   WEIGHTED SUM             END     END
                                   DELAY (U+R+O=MEAN Q) DELAY    /PCU  STOPS          EXCESS  OF ( ) VALUES           1ST     2ND
       (PCU/H) (PCU/H)  (%)  (SEC) (SEC)    (PCU-H/H)   ($/H)    (%)   ($/H)   (PCU)  (PCU)       ($/H)               (SECONDS)

   900    222   1500     32    18    16     .7 +   .2  (   .5)     63  (   .2)      3                  .7    187     35  66 105 136
  1060    142   1500     41    18    32     .9 +   .4  (   .7)     92  (   .1)      3                  .8    189     92 107  22  37
  1210   1094   4000     64    17    19    4.8 +   .9  (  3.1)     76  (   .8)     17                 3.9    185      8  37  78 107
  1280    361   1500     67    18    29    1.9 +  1.0  (  1.6)     92  (   .3)      7                 1.9    180     91 115  21  45
  1300    307   1500     53    18    23    1.4 +   .6  (  1.1)     80  (   .3)      5                 1.3    179     78 104   8  34
  1330    995   3200     59    11     4     .4 +   .7  (   .6)     12  (   .2)      3                  .8    179     38  74 108   4
  1340   1302   3200     69    18     8    1.9 +  1.1  (  1.7)     35  (   .7)     11                 2.4    180    118  18  48  88
  1350   1392   3200     69    25     7    1.6 +  1.1  (  1.5)     30  (   .3)     10                 1.8    181     66 109 136  39
  1360    260   1500     71    22    40    1.7 +  1.2  (  1.6)    109  (   .2)      6                 1.8    205     79  95   9  25
  1380   1147   3200     44    13     2     .1 +   .4  (   .3)      6  (   .1)      2                  .4    182      7  63  77 133
  1390    929   3200     52    16     7    1.2 +   .5  (   .9)     34  (   .4)      7                 1.3    183     94 132  24  62
  1400    369   1800     48    20    16    1.2 +   .5  (   .9)     77  (   .3)      6                 1.2    203     51  80 121  10
  1420   1007   3200     52    24     6    1.1 +   .6  (   .9)     36  (   .6)     10                 1.5    184     47  88 117  18
  1440   1086   3200     70     6    14    3.0 +  1.2  (  2.3)     50  (  1.4)     12                 3.7    185     41  74 111   4
  1450   1059   3200     77    19    14    2.3 +  1.7  (  2.2)     62  (   .9)     19                 3.1    186     63  92 133  22
  1460   1121   4000     85    20    23    4.2 +  2.9  (  3.9)     63  (   .7)     19                 4.6    199     93 115  23  45
  1480    819   3200     53    10     4     .3 +   .6  (   .5)     10  (   .1)      2                  .6    187     69 102 139  32
  1490    848   3200     66    24    13    2.0 +  1.0  (  1.7)     73  (   .4)     14                 2.1    188     33  60 103 130
  1500    192   1500     69    22    45    1.3 +  1.1  (  1.3)    119  (   .2)      5                 1.5    197     75  87   5  17
  1520   1020   3200     47    13     3     .4 +   .4  (   .4)     12  (   .2)      3                  .6    189     41  88 111  18
  1540    230   1000     67    22    33    1.1 +  1.0  (  1.2)     94  (   .2)      4                 1.3    195     52  75 122   5
  1580     22   1500     23    18    86     .4 +   .1  (   .3)    109  (   .0)      1                  .3    194     53  61
  1590    190   1500     63     9    68    2.7 +   .9  (  2.0)    100  (   .2)      8     +           2.2    193     32  59
  1610   1948   4300     56    12     3     .8 +   .6  (   .8)     14  (   .6)     21                 1.3    194     71  43
  1620    156   1800     40    25    13     .2 +   .3  (   .3)     45  (   .0)      4                  .3    260     62  91
  1630   1970   4300     78     9     9    3.1 +  1.8  (  2.7)     41  (   .9)     31     +           3.6    195      9  49  79 119
  1640   2255   4300     94    13    18    4.0 +  7.6  (  6.4)     52  (  1.5)     45     +           7.9    196     12  50  82 120
  1650    606   1500     74    26    16    1.3 +  1.4  (  1.5)     49  (   .2)      6                 1.7    188    133  30  63 100
  1660   2457   4300     80    14     5    1.1 +  2.0  (  1.7)     19  (  1.0)     13                 2.7    197     22  71  92   1
  1670   2287   4300     81    11     6    2.0 +  2.1  (  2.3)     35  (   .6)     25     +           2.8    198    103   8  33  78
  1680   1230   3200     75    30    16    4.0 +  1.5  (  3.0)     67  (   .4)     19                 3.5    186     25  60  95 130
  1690   1995   4300     81    21    12    4.8 +  2.1  (  3.8)     62  (  1.3)     33                 5.1    199     50  89 120  19
  1700   2015   5500     67     7    10    4.7 +  1.0  (  3.2)     46  (  2.4)     19                 5.6    200     44  81 114  11
  1710   1096   3800     65    30    33    9.2 +   .9  (  5.6)     82  (  1.0)     37                 6.6    212     40 101
  1720    259   1500     50    30    31    1.7 +   .5  (  1.2)     90  (   .2)      5                 1.4    184     91 114  21  44
  1730   1961   5500     41    12     1     .1 +   .3  (   .2)      2  (   .1)      2                  .3    201     51 111 121  41
  1740   1824   5500     75    20    13    5.2 +  1.5  (  3.7)     58  (   .3)     25                 4.0    202     74 104   4  34
  1750    241   1500     42    20    14     .6 +   .4  (   .5)     43  (   .1)      2                  .7    183    135  21  65  91
  1760   2005   5500     73    14     5    1.6 +  1.3  (  1.6)     17  (   .5)      7                 2.1    203     14  48  84 118
  1770   2101   5500     70     8     3     .7 +  1.2  (  1.1)      8  (   .6)      5                 1.6    204     21  58  91 128
  1780    526   2000     67    24    38    4.5 +  1.0  (  3.0)     79  (   .6)     17                 3.7    209     30  84
  1790    301   1500     64    18    34    2.0 +   .9  (  1.6)    102  (   .4)      6                 2.0    181     42  63 112 133
  1800   2299   5500     61    13     3    1.1 +   .8  (  1.0)     14  (   .9)      8                 1.9    205     29  76  99   6
  1810   2398   5500     49    10     1     .4 +   .5  (   .5)      6  (   .5)      6                 1.0    206     99  82
  1820    552   2000     60    26    14    1.4 +   .8  (  1.2)     54  (   .3)      6                 1.5    178     64  95 134  25
  1830    739   3000     66    30    37    6.5 +  1.0  (  4.1)     76  (   .3)     23                 4.5    227    127  38
  1831    729   3000     69    30    39    6.8 +  1.1  (  4.4)     78  (   .3)     23                 4.7    227    127  35
  1840   2952   9000     54    12    10    8.0 +   .6  (  4.7)     29  (  2.7)     37                 7.4    208     82  26
  1850    198   1600     52    25    49    2.2 +   .5  (  1.5)     94  (   .1)      7                 1.6    224      9  41
  1860    508   1800     73    28    25    2.1 +  1.4  (  1.9)     86  (   .6)     10                 2.5    204     61  87 131  17
  1870   2721   9000     54     9     4    2.7 +   .6  (  1.8)     10  (   .8)     19                 2.6    209     89  26
  1880   2858   9000     61    10    10    7.3 +   .8  (  4.4)     21  (  1.4)     24                 5.9    210     88  20
  1890    568   1600     68    25    27    3.1 +  1.1  (  2.3)     81  (   .4)     18                 2.7    222     67 139
  1900    584   2400     74    30    28    3.1 +  1.4  (  2.5)     76  (   .5)     11                 3.0    202    116 138  46  68
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; CYCLE TIME = 140 with 60 steps                  PAGE  21   RUN ON 31/ 7/1993
0     140 SECOND CYCLE   60 STEPS
0 LINK   FLOW    SAT DEGREE  MEAN TIMES  -------DELAY--------  ----STOPS-----  ----QUEUE----     PERFORMANCE   EXIT  GREEN TIMES
 NUMBER  INTO   FLOW     OF     PER PCU  UNIFORM RANDOM+ COST    MEAN   COST    MEAN                  INDEX.    NODE  START   START
         LINK           SAT  CRUISE              OVERSAT  OF    STOPS    OF     MAX.  AVERAGE   WEIGHTED SUM             END     END
                                   DELAY (U+R+O=MEAN Q) DELAY    /PCU  STOPS          EXCESS  OF ( ) VALUES           1ST     2ND
       (PCU/H) (PCU/H)  (%)  (SEC) (SEC)    (PCU-H/H)   ($/H)    (%)   ($/H)   (PCU)  (PCU)       ($/H)               (SECONDS)

  1910   2681   9000     33    17     0     .0 +   .2  (   .1)      1  (   .1)      1                  .2    211     98  84
  1920    740   3000     75    30    27    4.0 +  1.5  (  3.0)     98  (   .7)     19                 3.7    200     85 107  15  37
  1930   1893   7500     50     7     8    3.8 +   .5  (  2.4)     16  (   .9)     12                 3.2    212    106  36
  1940   2996   7500     46     8     1     .5 +   .4  (   .5)      5  (   .2)      7                  .8    213    111  91
  1950   2199   7500     63     9    17    9.5 +   .9  (  5.7)     43  (  2.9)     37                 8.6    214     31  95
  1960    851   2800     80    25    47    9.2 +  2.0  (  6.2)     95  (   .4)     32     +           6.5    218    120  32
  1970    597   3000     73    32    30    3.6 +  1.4  (  2.7)     92  (   .8)     13                 3.5    198     11  29  81  99
  1980   2164   7500     54    16     3     .9 +   .6  (   .8)      5  (   .2)      4                 1.1    215     42 116
  1990    534   1500     96    30    77    3.0 +  8.4  (  6.3)    156  (  1.1)     19                 7.4    196     53  78 123   8
  2000   1933   7500     27    22     0     .0 +   .2  (   .1)      1  (   .0)      0                  .1    259     14   7
  2010    270   1500     43    18    19    1.0 +   .4  (   .8)     24  (   .1)      2                  .8    215    119  37
  2020   2618   5000     78    20    15    9.1 +  1.8  (  6.0)     63  (  3.7)     68                 9.7    217     19 112
  2040    721   1800     89    20    46    5.4 +  3.9  (  5.1)     77  (   .6)     22     +           5.7    214    102  24
  2050   2050   5000     75    18     9    3.6 +  1.5  (  2.8)     35  (   .9)     41                 3.7    218     40 116
  2060   2102   5000     72    30    13    6.5 +  1.3  (  4.3)     65  (   .5)     59     +           4.8    219     71  12
  2080   2602   7000     40    25     1     .1 +   .3  (   .2)      2  (   .0)      3                  .2    220     46  36
  2090   2040   5000     45    20     4    2.0 +   .4  (  1.3)     40  (   .3)     36     +           1.7    221      5 131
  2110    589   2800     49    20    22    3.0 +   .5  (  1.9)     61  (   .4)     16                 2.3    210     24  83
  2120   1503   5000     69    15    19    6.9 +  1.1  (  4.4)     49  (   .7)     31                 5.1    222      3  63
  2130   2037   5000     47    12     1     .2 +   .4  (   .4)      4  (   .1)      4                  .5    223     12 132
  2140    521   2800     54    22    31    3.8 +   .6  (  2.4)     51  (   .2)     11                 2.7    208     30  77
  2150   1674   5000     47    25     4    1.6 +   .4  (  1.1)     32  (   .4)     29                 1.5    224     45   3
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Cycle time of 140 seconds

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  2160   598   1500     66    20    14   1.4 +  1.0  (  1.3)    70  (   .1)     18      +            1.3   225    64   8
  2161  1996   4500     60    20     4   1.6 +   .7  (  1.3)    19  (   .1)     25      +            1.4   225    55  18
  2170   953   1500    102    22   149   4.4 + 34.9  ( 21.6)   167  (  1.5)     73      +           23.2   226    38 124
  2171   499   4500     82    22    84   9.5 +  2.2  (  6.4)   105  (   .5)     21                   6.9   226    38  56
  2185   667   3000     72    15    50   8.0 +  1.3  (  5.1)    91  (   .9)     24                   6.1   225    22  64
  2190  3295   9000     40    23     0    .1 +   .3  (   .2)     2  (   .1)      2                    .3   207    78  66
  2200  1042   4000     43    25     6   1.4 +   .4  (  1.0)    12  (   .4)      5                   1.3   227    41 124
  2205   827   2500     98    22   111  10.6 + 14.9  ( 14.0)   136  (  1.5)     47      +           15.5   226   128  34
  2206   826   4000     62    22    38   8.0 +   .8  (  4.8)    62  (   .7)     20                   5.5   226   128  34
  2215  2417   8000     65    24    30  19.3 +   .9  ( 11.1)    74  (  1.7)     72                  12.9   226    60 124
  2225  2050   4500     70    25    18   9.0 +  1.2  (  5.6)    61  (  1.3)     52                   6.9   227    35 125
  2230   945   3200     63    22    17   3.6 +   .8  (  2.5)    73  (   .7)     14                   3.1   178    28  60   98 130
  2790  2000   5000     70    25    21  10.2 +  1.2  (  6.3)    69  (   .7)     56      +            7.0   216    38 117
  2800   302   1800     25    25     3    .1 +   .2  (   .1)    10  (   .0)      1                    .2   260    95  48
  2805  2001   4000     51    28     1    .0 +   .5  (   .3)     2  (   .0)      3                    .3   259    81  77
  2820   302   1800     78    15    85   5.4 +  1.8  (  3.9)    96  (   .6)     11                   4.5   261    90 119
  2825  1699   5000     49    15     2    .3 +   .5  (   .4)     3  (   .0)      2                    .5   260   101  58
  2830  1847   5500     44    15     7   3.2 +   .4  (  2.0)    33  (   .7)     26                   2.7   193    64  29
  2845   617   1600     86    20    51   5.9 +  2.9  (  4.9)    99  (   .1)     24      +            5.0   261   125  47
  2846  1755   3500     74    20    17   7.1 +  1.4  (  4.7)    63  (   .2)     44      +            4.9   261    90  44
  3730  1520   5000     82    25    45  16.8 +  2.2  ( 10.5)    91  (   .4)     56      +           10.9   216   123  34
  3850  1000   5000     80    20    56  13.7 +  2.0  (  8.6)    95  (  1.1)     38                   9.7   261    51  85
  5800   330   1800     71    25    61   4.3 +  1.2  (  3.1)    97  (   .2)     13                   3.2   217   116  11
  5930   420   1800     76    25    57   5.1 +  1.6  (  3.7)    96  (   .2)     16                   3.9   219    22  64
  5940    50   1800     43    25    90    .9 +   .4  (   .7)   113  (   .0)      2                    .7   221   137   5
1PROGRAM TRANSYT8     ATHENS * Central Arteries * Opt on; CYCLE TIME = 140 with 60 steps                    PAGE  22   RUN ON 31/ 7/1993
0    140 SECOND CYCLE  60 STEPS
0  TOTAL           TOTAL      MEAN           TOTAL    TOTAL     TOTAL          TOTAL          PENALTY       TOTAL
  DISTANCE          TIME    JOURNEY         UNIFORM  RANDOM+    COST           COST             FOR       PERFORMANCE
  TRAVELLED        SPENT     SPEED            DELAY  OVERSAT     OF             OF            EXCESS        INDEX
                                                      DELAY    DELAY          STOPS           QUEUES
  (PCU-KM/H)      (PCU-H/H)    (KM/H)     (PCU-H/H) (PCU-H/H)   ($/H)          ($/H)           ($/H)         ($/H)
0 13281.2         1148.0      11.6         360.9    163.4     ( 288.4) + (    59.4)  +  (    .0)    =      347.8       TOTALS
0******************************************************************************************************************************************************************
*
0                                   CRUISE               DELAY               STOPS              TOTALS
                               LITRES PER HOUR     LITRES PER HOUR     LITRES PER HOUR     LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS     1243.4         +      734.0          +     170.7          =     2148.1
0
 NO. OF ENTRIES TO SUBPT:     125
 NO. OF LINKS RECALCULATED: 3288
 SYSTEM TIME:           17:55:27

 EXECUTION TIME:    713 SECONDS
 PROGRAM TRANSYT8 FINISHED
```

Hot CO links with delay weighting of 500 percent

```
0CARD   CARD
 NO.    TYPE
 (  1)= TITLE:- ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS
0CARD   CARD   CYCLE  NO. OF   TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW   CRUISE-SPEEDS    OPTIMISE EXTRA   HILL-   DELAY   STOP
 NO.    TYPE   TIME   STEPS   PERIOD DISPLACEMENTS  SETTINGS  INFO.   SCALE    SCALE  CARD32  0=NONE  COPIES   CLIMB   VALUE   VALUE
                       PER    1-1200  START   END     0=NO  2=CYCLE  10-200  50-200 0=TIMES  1=O/SET  FINAL  OUTPUT   P PER   P PER
               (SEC)  CYCLE   MINS.   (SEC)  (SEC)    1=YES  CHOICE    %       %   1=SPEEDS 2=FULL  OUTPUT  1=FULL   PCU-H    100
  2)=    1      90     45     120       2      3        1       0       0       0       0        2       0       0       55      50
0CARD   CARD                                         LIST  OF  NODES  TO  BE  OPTIMISED
 NO.    TYPE
  3)=    2     261    260    178     179     180     181     182     183     184     185     186     187     188     189     193
  4)=    2     194    195    196     197     198     199     200     201     202     203     204     205     206     227     226
  5)=    2     207    208    209     210     211     212     213     214     215     259     216     217     218     219     220
  6)=    2     221    222    223     224     225       0       0       0       0       0       0       0       0       0       0
0                                     NODE  CARDS:   STAGE  CHANGE  TIMES  AND  MINIMUM  STAGE  TIMES
 CARD   CARD   NODE       STAGE 1          STAGE 2          STAGE 3          STAGE 4          STAGE 5          STAGE 6          STAGE 7
  NO.   TYPE    NO.    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN
  7)=   13     261       35      10       64      10       90      10        0       0        0       0        0       0        0       0
  8)=   14     260       44      10       55      10       66      10       33      10        0       0        0       0        0       0
  9)=   22     178        7      10       26      10        0       0        0       0        0       0        0       0        0       0
 10)=   22     179       14      10       33      10        0       0        0       0        0       0        0       0        0       0
 11)=   22     180       39      10       13      10        0       0        0       0        0       0        0       0        0       0
 12)=   22     181       16      10       34      10        0       0        0       0        0       0        0       0        0       0
 13)=   22     182       28      10       39      10        0       0        0       0        0       0        0       0        0       0
 14)=   22     183        9      10       38      10        0       0        0       0        0       0        0       0        0       0
 15)=   22     184       17      10       43      10        0       0        0       0        0       0        0       0        0       0
 16)=   22     185        3      10       21      10        0       0        0       0        0       0        0       0        0       0
 17)=   22     186       19      10       40      10        0       0        0       0        0       0        0       0        0       0
 18)=   22     187       31      10        4      10        0       0        0       0        0       0        0       0        0       0
 19)=   22     188       12      10       32      10        0       0        0       0        0       0        0       0        0       0
 20)=   22     189       35      10       20      10        0       0        0       0        0       0        0       0        0       0
 21)=   12     193       30      10       89      10        0       0        0       0        0       0        0       0        0       0
 22)=   12     194       30      10        9      10        0       0        0       0        0       0        0       0        0       0
 23)=   22     195        0      10       31      10        0       0        0       0        0       0        0       0        0       0
 24)=   22     196       10      10       36      10        0       0        0       0        0       0        0       0        0       0
 25)=   22     197       16      10        1      10        0       0        0       0        0       0        0       0        0       0
 26)=   22     198       13      10       40      10        0       0        0       0        0       0        0       0        0       0
 27)=   22     199       31      10       11      10        0       0        0       0        0       0        0       0        0       0
 28)=   22     200       31      10       16      10        0       0        0       0        0       0        0       0        0       0
 29)=   22     201        2      10       37      10        0       0        0       0        0       0        0       0        0       0
 30)=   22     202       40      10       19      10        0       0        0       0        0       0        0       0        0       0
 31)=   22     203       10      10       37      10        0       0        0       0        0       0        0       0        0       0
 32)=   22     204       16      10       43      10        0       0        0       0        0       0        0       0        0       0
 33)=   22     205       22      10        9      10        0       0        0       0        0       0        0       0        0       0
 34)=   12     206       28      10       17      10        0       0        0       0        0       0        0       0        0       0
 35)=   12     227       75      10       41      10        0       0        0       0        0       0        0       0        0       0
 36)=   13     226       49      10       80      10       25      10        0       0        0       0        0       0        0       0
 37)=   12     207       65      10       76      10        0       0        0       0        0       0        0       0        0       0
 38)=   12     208       80      10       57      10        0       0        0       0        0       0        0       0        0       0
 39)=   12     209       83      10       55      10        0       0        0       0        0       0        0       0        0       0
 40)=   12     210       85      10       60      10        0       0        0       0        0       0        0       0        0       0
 41)=   12     211       11      10        1      10        0       0        0       0        0       0        0       0        0       0
 42)=   12     212       33      10       88      10        0       0        0       0        0       0        0       0        0       0
 43)=   12     213       15      10       85      10        0       0        0       0        0       0        0       0        0       0
 44)=   12     214       26      10       82      10        0       0        0       0        0       0        0       0        0       0
 45)=   12     215       46      10       26      10        0       0        0       0        0       0        0       0        0       0
 46)=   12     259       85      10       45      10        0       0        0       0        0       0        0       0        0       0
 47)=   12     216       86      10       41      10        0       0        0       0        0       0        0       0        0       0
 48)=   12     217        7      10       76      10        0       0        0       0        0       0        0       0        0       0
 49)=   12     218       12      10       72      10        0       0        0       0        0       0        0       0        0       0
 50)=   12     219       43      10       21      10        0       0        0       0        0       0        0       0        0       0
 51)=   12     220       23      10       12      10        0       0        0       0        0       0        0       0        0       0
 52)=   12     221       35      10       18      10        0       0        0       0        0       0        0       0        0       0
 53)=   12     222       35      10        4      10        0       0        0       0        0       0        0       0        0       0
 54)=   12     223       29      10       11      10        0       0        0       0        0       0        0       0        0       0
 55)=   12     224       59      10       33      10        0       0        0       0        0       0        0       0        0       0
 56)=   13     225       40      10       59      10       74      10        0       0        0       0        0       0        0       0
1PROGRAM TRANSYT8     ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS                         PAGE   3   RUN ON 10/ 8/1993

0                                             LINK  CARDS:   FIXED  DATA
                                    FIRST  GREEN                           SECOND  GREEN
 CARD   CARD   LINK     EXIT        START           END             START           END        LINK    STOP     SAT    DELAY  DISPSN
  NO.   TYPE    NO.     NODE     STAGE   LAG    STAGE   LAG     STAGE   LAG    STAGE   LAG   LENGTH  WT.X100   FLOW  WT.X100   X100
 57)=   31    2846      261        2      5       1      0        0      0       0      0      54       0     3500    500      0
 58)=   31    2845      261        3      6       1      3        0      0       0      0      54       0     1600    500      0
 59)=   31    2820      261        2      5       3      0        0      0       0      0     120       0     1800      0      0
 60)=   31    3850      261        1      7       2      0        0      0       0      0     120       0     5000      0      0
 61)=   31    2825      260        3      0       1      0        0      0       0      0      68       0     5000      0      0
 62)=   31    2800      260        2      4       4      0        0      0       0      0     156       0     1800      0      0
 63)=   31    1620      260        1      4       2      0        0      0       0      0      64       0     1800      0      0
 64)=   31    1820      178        2      4       1      0        0      0       0      0     130       0     2000      0      0
 65)=   31    2230      178        1      3       2      0        0      0       0      0     118       0     3200      0      0
 66)=   31    1330      179        1      4       2      0        0      0       0      0      75       0     3200      0      0
 67)=   31    1300      179        2      4       1      0        0      0       0      0     100       0     1500      0      0
 68)=   31    1340      180        2      3       1      0        0      0       0      0     124       0     3200      0      0
 69)=   31    1280      180        1      3       2      0        0      0       0      0      98       0     1500      0      0
 70)=   31    1350      181        2      3       1      0        0      0       0      0     114       0     3200      0      0
 71)=   31    1790      181        1      3       2      0        0      0       0      0     116       0     1500      0      0
 72)=   31    1380      182        2      4       1      0        0      0       0      0      81       0     3200      0      0
 73)=   31    1390      183        1      3       2      0        0      0       0      0      96       0     3200      0      0
 74)=   31    1750      183        2      3       1      0        0      0       0      0     128       0     1500      0      0
 75)=   31    1420      184        1      3       2      0        0      0       0      0     172       0     3200      0      0
 76)=   31    1720      184        2      3       1      0        0      0       0      0     140       0     1500      0      0
 77)=   31    1440      185        2      4       1      0        0      0       0      0      52       0     3200      0      0
 78)=   31    1210      185        1      4       2      0        0      0       0      0      92       0     4000      0      0
 79)=   31    1450      186        2      3       1      0        0      0       0      0     124       0     3200      0      0
 80)=   31    1680      186        1      3       2      0        0      0       0      0     122       0     3200      0      0
 81)=   31    1480      187        2      3       1      0        0      0       0      0      55       0     3200      0      0
 82)=   31     900      187        1      3       2      0        0      0       0      0     100       0     1500      0      0
 83)=   31    1490      188        2      3       1      0        0      0       0      0     110       0     3200      0      0
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Hot CO links with delay weighting of 500 percent

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  84)=  31   1650    188     1     3     2     0     0     0     0     0   122     0  1500     0     0
  85)=  31   1520    189     1     4     2     0     0     0     0     0    82     0  3200     0     0
  86)=  31   1060    189     2     4     1     0     0     0     0     0   100     0  1500     0     0
  87)=  31   2830    193     1     5     2     0     0     0     0     0    88     0  5500     0     0
  88)=  31   1590    193     2     3     1     0     0     0     0     0    50     0  1500     0     0
  89)=  31   1610    194     1    10     2     0     0     0     0     0    96     0  4300     0     0
  90)=  31   1580    194     2    10     1     0     0     0     0     0   100     0  1500     0     0
  91)=  31   1630    195     1     4     2     0     0     0     0     0    52     0  4300     0     0
  92)=  31   1540    195     2     3     1     0     0     0     0     0   108     0  1000     0     0
  93)=  31   1640    196     1     4     2     0     0     0     0     0    80     0  4300   500     0
  94)=  31   1990    196     2     3     1     0     0     0     0     0   188     0  1500     0     0
  95)=  31   1660    197     1     5     2     0     0     0     0     0   112     0  4300   500     0
  96)=  31   1500    197     2     4     1     0     0     0     0     0   108     0  1500     0     0
  97)=  31   1670    198     1     4     2     0     0     0     0     0    50     0  4300     0     0
  98)=  31   1970    198     2     3     1     0     0     0     0     0   208     0  3000     0     0
  99)=  31   1690    199     1     5     2     0     0     0     0     0   118     0  4300   500     0
 100)=  31   1460    199     2     4     1     0     0     0     0     0   110     0  4000     0     0
 101)=  31   1700    200     1     7     2     0     0     0     0     0    62     0  5500     0     0
1PROGRAM TRANSYT8      ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS               PAGE   4  RUN ON 10/ 8/1993

 102)=  31   1920    200     2     4     1     0     0     0     0     0   160     0  3000     0     0
 103)=  31   1730    201     1     0     2     0     0     0     0     0   108     0  5500     0     0
 104)=  31   1740    202     1     6     2     0     0     0     0     0    64     0  5500     0     0
 105)=  31   1900    202     2    12     1     0     0     0     0     0   180     0  2400     0     0
 106)=  31   1760    203     1     4     2     0     0     0     0     0    90     0  5500     0     0
 107)=  31   1400    203     2     3     1     0     0     0     0     0   106     0  1800     0     0
 108)=  31   1770    204     1     4     2     0     0     0     0     0    82     0  5500     0     0
 109)=  31   1860    204     2     3     1     0     0     0     0     0   178     0  1800     0     0
 110)=  31   1800    205     1     4     2     0     0     0     0     0   116     0  5500     0     0
 111)=  31   1360    205     2     3     1     0     0     0     0     0   106     0  1500     0     0
 112)=  31   1810    206     1     7     2     0     0     0     0     0   104     0  5500     0     0
 113)=  31   1830    227     1     3     2     3     0     0     0     0   130     0  3000     0     0
 114)=  31   1831    227     1     3     2     0     0     0     0     0   130     0  3000     0     0
 115)=  31   2200    227     2     6     1     0     0     0     0     0   240     0  4000     0     0
 116)=  31   2225    227     2     0     1     1     0     0     0     0   140     0  4500     0     0
 117)=  31   2215    226     1     4     2     0     0     0     0     0   132     0  8000     0     0
 118)=  31   2205    226     2     4     3     0     0     0     0     0   138     0  2500   250     0
 119)=  31   2206    226     2     4     3     0     0     0     0     0   138     0  4000     0     0
 120)=  31   2170    226     3     4     2     0     0     0     0     0   120     0  1500   500     0
 121)=  31   2171    226     3     4     1     0     0     0     0     0   120     0  4500     0     0
 122)=  31   2190    207     2     0     1     0     0     0     0     0   142     0  9000   500     0
 123)=  31   1840    208     1     5     2     0     0     0     0     0   114     0  9000   500     0
 124)=  31   2140    208     2     4     1     0     0     0     0     0   114     0  2800     0     0
 125)=  31   1870    209     1     5     2     0     0     0     0     0    82     0  9000     0     0
 126)=  31   1780    209     2     4     1     0     0     0     0     0   166     0  2000     0     0
 127)=  31   1880    210     1     5     2     0     0     0     0     0    84     0  9000     0     0
 128)=  31   2110    210     2     4     1     0     0     0     0     0   114     0  2800     0     0
 129)=  31   1910    211     1     4     2     0     0     0     0     0   182     0  9000     0     0
 130)=  31   1930    212     1     5     2     0     0     0     0     0    66     0  7500     0     0
 131)=  31   1710    212     2     4     1     0     0     0     0     0   172     0  3800   500     0
 132)=  31   1940    213     1    10     2     0     0     0     0     0    54     0  7500   500     0
 133)=  31   1950    214     1     7     2     0     0     0     0     0    86     0  7500   500     0
 134)=  31   2040    214     2     7     1     0     0     0     0     0   114     0  1800     0     0
 135)=  31   1980    215     1     5     2     0     0     0     0     0   134     0  7500     0     0
 136)=  31   2010    215     2     3     1     0     0     0     0     0   100     0  1500     0     0
 137)=  31   2000    259     2     7     2     0     0     0     0     0   120     0  7500     0     0
 138)=  31   2805    259     1     4     1     0     0     0     0     0   156     0  4000     0     0
 139)=  31   2790    216     2     4     1     0     0     0     0     0   100     0  5000     0     0
 140)=  31   3730    216     1     6     2     0     0     0     0     0    82     0  5000   500     0
 141)=  31   2020    217     1     8     2     0     0     0     0     0   164     0  5000   500     0
 142)=  31   5800    217     2     4     1     0     0     0     0     0   100     0  1800     0     0
 143)=  31   2050    218     1     8     2     0     0     0     0     0   110     0  5000   500     0
 144)=  31   1960    218     2     4     1     0     0     0     0     0    92     0  2800     0     0
 145)=  31   2060    219     1     7     2     0     0     0     0     0   106     0  5000   500     0
 146)=  31   5930    219     2    10     1     0     0     0     0     0   100     0  1800     0     0
 147)=  31   2080    220     1     0     2     0     0     0     0     0   118     0  7000   500     0
 148)=  31   2090    221     1     0     2     0     0     0     0     0    70     0  5000     0     0
 149)=  31   5940    221     2     6     1     0     0     0     0     0   100     0  1800     0     0
 150)=  31   2120    222     1     4     2     0     0     0     0     0    82     0  5000     0     0
 151)=  31   1890    222     2     4     1     0     0     0     0     0   128     0  1600     0     0
1PROGRAM TRANSYT8      ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS               PAGE   5  RUN ON 10/ 8/1993

 152)=  31   2130    223     1    10     2     0     0     0     0     0    72     0  5000     0     0
 153)=  31   2150    224     1     4     2     0     0     0     0     0   116     0  5000     0     0
 154)=  31   1850    224     2     6     1     0     0     0     0     0    98     0  1600     0     0
 155)=  31   2161    225     3     1     2     0     0     0     0     0    48     0  4500     0     0
 156)=  31   2160    225     3    10     1     0     0     0     0     0    48     0  1500     0     0
 157)=  31   2185    225     2     4     3    10     0     0     0     0   100     0  3000     0     0
0                                                LINK CARDS:   FLOW DATA
                                       ENTRY 1 ...........   ENTRY 2 ...........   ENTRY 3 ...........   ENTRY 4 ...........
  CARD   CARD   LINK   TOTAL  UNIFORM   LINK          CRUISE   LINK          CRUISE   LINK          CRUISE   LINK          CRUISE
   NO.   TYPE    NO.    FLOW    FLOW     NO.    FLOW    TIME    NO.    FLOW    TIME    NO.    FLOW    TIME    NO.    FLOW    TIME
 158)=   32    2846    1755      0        0       0      20      0       0       0      0       0       0      0       0       0
 159)=   32    2845     617      0        0       0      20      0       0       0      0       0       0      0       0       0
 160)=   32    2820     300      0     2800     300      15   1620      30      15      0       0       0      0       0       0
 161)=   32    3850    1000      0        0       0      20      0       0       0      0       0       0      0       0       0
 162)=   32    2825    1700      0     2846    1700      15      0       0       0      0       0       0      0       0       0
 163)=   32    2800     300      0     2000     300      25      0       0       0      0       0       0      0       0       0
 164)=   32    1620     156      0     1590     156      25      0       0       0      0       0       0      0       0       0
 165)=   32    2230     945      0        0       0      22      0       0       0      0       0       0      0       0       0
 166)=   32    1820     550      0     1810     550      26      0       0       0      0       0       0      0       0       0
 167)=   32    1330     995      0     2230     945      11   1820      50      11      0       0       0      0       0       0
 168)=   32    1300     307      0        0       0      18      0       0       0      0       0       0      0       0       0
 169)=   32    1340    1302      0     1330     995      18   1300     307      18      0       0       0      0       0       0
 170)=   32    1280     361      0        0       0      18      0       0       0      0       0       0      0       0       0
 171)=   32    1350    1393      0     1340    1157      25   1280     236      25      0       0       0      0       0       0
 172)=   32    1790     302      0     1860     205      18   1770      97      18      0       0       0      0       0       0
 173)=   32    1380    1147      0     1350    1030      13   1790     117      13      0       0       0      0       0       0
 174)=   32    1390     930      0     1380     900      16      0       0       0      0       0       0      0       0       0
 175)=   32    1750     242      0     1900     182      20   1740      60      20      0       0       0      0       0       0
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Hot CO links with delay weighting of 500 percent

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 176)=  32   1420   1010     0   1390    860   24   1750    150   24     0     0     0     0     0     0
 177)=  32   1720    259     0   1920    159   30   1700    100   30     0     0     0     0     0     0
 178)=  32   1440   1088     0   1420    832    6   1720    256    6     0     0     0     0     0     0
 179)=  32   1210   1094     0      0          17      0      0    0     0     0     0     0     0     0
 180)=  32   1450   1059     0   1440    937   19   1210    122   19     0     0     0     0     0     0
 181)=  32   1680   1228     0   1970    545   30   1670    683   30     0     0     0     0     0     0
 182)=  32   1480    820     0   1450    780   10   1680     40   10     0     0     0     0     0     0
 183)=  32    900    222     0      0      0   18      0      0    0     0     0     0     0     0     0
 184)=  32   1490    849     0   1480    754   24    900     95   24     0     0     0     0     0     0
 185)=  32   1650    605     0   1990    445   26   1640    160   26     0     0     0     0     0     0
 186)=  32   1520   1020     0   1490    805   13   1650    214   13     0     0     0     0     0     0
 187)=  32   1060    142     0      0      0   18      0      0    0     0     0     0     0     0     0
 188)=  32   2830   1847     0      0      0   15      0      0    0     0     0     0     0     0     0
 189)=  32   1590    190     0      0      0    9      0      0    0     0     0     0     0     0     0
 190)=  32   1610   1948     0   2830   1847   12   1590    101   12     0     0     0     0     0     0
 191)=  32   1580     22     0      0      0   18      0      0    0     0     0     0     0     0     0
 192)=  32   1630   1970     0   1610   1948    9   1580     22    9     0     0     0     0     0     0
 193)=  32   1540    230     0   1060     95   22   1520    135   22     0     0     0     0     0     0
 194)=  32   1640   2255     0   1630   2025   13   1540    230   13     0     0     0     0     0     0
 195)=  32   1990    530     0   2010    259   30   1980    271   30     0     0     0     0     0     0
 196)=  32   1660   2452     0   1640   2095   14   1990    357   14     0     0     0     0     0     0
1PROGRAM TRANSYT8    ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS          PAGE   6   RUN ON 10/ 8/1993

 197)=  32   1500    192     0    900    127   22   1480     65   22     0     0     0     0     0     0
 198)=  32   1670   2284     0   1660   2091   11   1500    193   11     0     0     0     0     0     0
 199)=  32   1970    597     0   2040    597   32      0      0    0     0     0     0     0     0     0
 200)=  32   1690   1995     0   1670   1601   21   1970    394   21     0     0     0     0     0     0
 201)=  32   1460   1123     0   1210    972   20   1440    151   20     0     0     0     0     0     0
 202)=  32   1700   2015     0   1690   1467    7   1460    548    7     0     0     0     0     0     0
 203)=  32   1920    740     0   1910    740   30      0      0    0     0     0     0     0     0     0
 204)=  32   1730   1960     0   1700   1789   12   1920    171   12     0     0     0     0     0     0
 205)=  32   1740   1823     0   1730   1823   20      0      0    0     0     0     0     0     0     0
 206)=  32   1900    582     0   2110    373   30   1880    209   30     0     0     0     0     0     0
 207)=  32   1760   2003     0   1740   1848   14   1900    155   14     0     0     0     0     0     0
 208)=  32   1400    370     0   1380    250   20      0      0    0     0     0     0     0     0     0
 209)=  32   1770   2100     0   1760   2000    8   1400     67    8     0     0     0     0     0     0
 210)=  32   1860    511     0   2140    231   28   1840    280   28     0     0     0     0     0     0
 211)=  32   1800   2300     0   1770   1903   13   1860    314   13     0     0     0     0     0     0
 212)=  32   1360    260     0   1280    125   22   1340    135   22     0     0     0     0     0     0
 213)=  32   1810   2400     0   1800   2055   10   1360    260   10     0     0     0     0     0     0
 214)=  32   1831    729     0   1810    729   30      0      0    0     0     0     0     0     0     0
 215)=  32   1830    738     0   1810    738   30      0      0    0     0     0     0     0     0     0
 216)=  32   2200   1043     0   2171    560   25   2215    483   25     0     0     0     0     0     0
 217)=  32   2225   2050     0      0      0   25      0      0    0     0     0     0     0     0     0
 218)=  32   2215   2417     0      0      0   24      0      0    0     0     0     0     0     0     0
 219)=  32   2205    824     0   2225    568   22   1831    256   22     0     0     0     0     0     0
 220)=  32   2206    827     0   2225    357   22   1831    470   22     0     0     0     0     0     0
 221)=  32   2170    955     0   2185    567   22   2160    388   22     0     0     0     0     0     0
 222)=  32   2171    500     0   2185    150   22   2160    350   22     0     0     0     0     0     0
 223)=  32   2190   3300     0   2215   1933   23   2205    833   23  2170   370    23     0     0     0
 224)=  32   1840   2955     0   2190   2955   12      0      0    0     0     0     0     0     0     0
 225)=  32   2140    523     0   2130    373   22      0      0    0     0     0     0     0     0     0
 226)=  32   1870   2725     0   1840   2666    9   2140     59    9     0     0     0     0     0     0
 227)=  32   1780    528     0   1400    182   24   1760    346   24     0     0     0     0     0     0
 228)=  32   1880   2861     0   1870   2500   10   1780    361   10     0     0     0     0     0     0
 229)=  32   2110    590     0   5940     10   20   2090    580   20     0     0     0     0     0     0
 230)=  32   1910   2681     0   1880   2475   17   2110    206   17     0     0     0     0     0     0
 231)=  32   1930   1895     0   1910   1895    7      0      0    0     0     0     0     0     0     0
 232)=  32   1710   1099     0   1460    638   30   1690    214   30     0     0     0     0     0     0
 233)=  32   1940   3000     0   1930   1100    8   1710   1895    8     0     0     0     0     0     0
 234)=  32   1950   2200     0   1940   2200    9      0      0    0     0     0     0     0     0     0
 235)=  32   2040    721     0   5800    307   20   2020    414   20     0     0     0     0     0     0
 236)=  32   1980   2165     0   1950   2095   16   2040     70   16     0     0     0     0     0     0
 237)=  32   2010    268     0   3730    258   18   2790     10   18     0     0     0     0     0     0
 238)=  32   2000   1933     0   1980   1883   22   2010     50   22     0     0     0     0     0     0
 239)=  32   2805   2000     0   2825   1733   28   1620    256   28     0     0     0     0     0     0
 240)=  32   2790   2000     0   2805   1624   25   2000    370   25     0     0     0     0     0     0
 241)=  32   3730   1520     0      0      0   25      0      0    0     0     0     0     0     0     0
 242)=  32   2020   2620     0   2790   1360   20   3730   1260   20     0     0     0     0     0     0
 243)=  32   5800    330     0      0      0   25      0      0    0     0     0     0     0     0     0
 244)=  32   2050   2050     0   2020   2021   18   5800     23   18     0     0     0     0     0     0
 245)=  32   1960    850     0   1940    850   25      0      0    0     0     0     0     0     0     0
 246)=  32   2060   2100     0   2050   1725   30   1960    375   30     0     0     0     0     0     0
1PROGRAM TRANSYT8    ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS          PAGE   7   RUN ON 10/ 8/1993

 247)=  32   5930    420     0      0      0   25      0      0    0     0     0     0     0     0     0
 248)=  32   2080   2600     0   2060   2100   25   5930    500   25     0     0     0     0     0     0
 249)=  32   2090   2038     0   2080   2038   20      0      0    0     0     0     0     0     0     0
 250)=  32   5940     50     0      0      0   25      0      0    0     0     0     0     0     0     0
 251)=  32   2120   1500     0   2090   1424   15   5940     50   15     0     0     0     0     0     0
 252)=  32   1890    570     0   1780    352   25   1870    218   25     0     0     0     0     0     0
 253)=  32   2130   2036     0   2120   1474   12   1890    562   12     0     0     0     0     0     0
 254)=  32   2150   1675     0   2130   1625   25      0      0    0     0     0     0     0     0     0
 255)=  32   1850    200     0   2190    180   25      0      0    0     0     0     0     0     0     0
 256)=  32   2161   2000     0   2150   1900   20   1850    200   20     0     0     0     0     0     0
 257)=  32   2160    600     0   2150    600   20   1850     20   20     0     0     0     0     0     0
 258)=  32   2185    667     0      0      0   15      0      0    0     0     0     0     0     0     0
0*****END OF SUBROUTINE TINPUT*****
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Hot CO links with delay weighting of 500 percent

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1PROGRAM TRANSYT8      ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS                 PAGE  20   RUN ON 10/ 8/1993
0      90 SECOND CYCLE   45 STEPS
0 LINK     FLOW    SAT   DEGREE MEAN TIMES   -------DELAY--------    ----STOPS----    ----QUEUE----   PERFORMANCE    EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF     PER PCU    UNIFORM RANDOM+ COST     MEAN    COST    MEAN               INDEX.      NODE   START  START
           LINK            SAT   CRUISE                OVERSAT  OF    STOPS     OF    MAX.  AVERAGE   WEIGHTED SUM              END      END
                                       DELAY (U+R+O=MEAN Q) DELAY     /PCU   STOPS          EXCESS    OF ( ) VALUES            1ST     2ND
         (PCU/H) (PCU/H)  (%)   (SEC) (SEC)     (PCU-H/H)    ($/H)     (%)    ($/H)   (PCU)   (PCU)       ($/H)                  (SECONDS)

   900     222   1500     37    18    14      .6 +    .3  (   .5)     72  (   .2)      2                    .7    187    34  51  79   6
  1060     142   1500     43    18    24      .6 +    .4  (   .5)     97  (   .1)      2                    .7    189    83   2  38  47
  1210    1094   4000     68    17    15     3.4 +   1.1  (  2.5)     80  (   .8)     12                   3.3    185     6  23  51  68
  1280     361   1500     72    18    26     1.3 +   1.3  (  1.4)    104  (   .4)      5                   1.8    180    56  70  11  25
  1300     307   1500     58    18    20     1.0 +    .7  (   .9)     89  (   .3)      4                   1.2    179    43  58  88  13
  1330     994   3200     61    11     4      .3 +    .8  (   .6)     17  (   .3)      4                    .9    179    17  39  62  84
  1340    1301   3200     70    18     7     1.3 +   1.2  (  1.4)     38  (   .8)      8                   2.2    180    73   8  28  53
  1350    1392   3200     72    25     7     1.5 +   1.3  (  1.5)     43  (   .4)     10                   1.9    181     2  28  47  73
  1360     260   1500     65    22    28     1.1 +    .9  (  1.1)    110  (   .2)      4                   1.3    205    59  70  14  25
  1380    1146   3200     52    13     3      .4 +    .5  (   .5)     16  (   .2)      3                    .7    182    12  42  57  87
  1390     928   3200     47    16     3      .4 +    .4  (   .4)     19  (   .2)      3                    .6    183    72   9  27  54
  1400     369   1800     58    20    14      .8 +    .7  (   .8)     72  (   .3)      4                   1.1    203    40  55  85  10
  1420    1006   3200     51    24     8     1.7 +    .5  (  1.2)     58  (  1.0)      9                   2.2    184    28  55  73  10
  1440    1082   3200     72     6    10     1.8 +   1.3  (  1.7)     55  (  1.5)      9                   3.3    185    27  47  72   2
  1450    1055   3200     78    19    12     1.6 +   1.8  (  1.9)     64  (  1.0)     12                   2.8    186    47  65   2  20
  1460    1121   4000     90    20    23     2.9 +   4.4  (  4.0)    106  (  1.2)     18                   5.1    199    30  43  75  88
  1480     816   3200     50    10     3      .3 +    .5  (   .4)     12  (   .1)      1                    .5    187    54  76   9  31
  1490     846   3200     70    24    12     1.7 +   1.2  (  1.6)     77  (   .4)     10                   2.0    188    41  57  86  12
  1500     192   1500     82    22    57      .8 +   2.2  (  1.7)    157  (   .2)      4                   1.9    197    58  64  13  19
  1520    1008<  3200     49    13     3      .4 +    .5  (   .5)     16  (   .2)      3                    .7    189    51  79   6  34
  1540     228   1000     68    22    29      .8 +   1.1  (  1.0)    112  (   .2)      4                   1.2    195    32  46  77   1
  1580      22   1500     33    18    82      .3 +    .2  (   .3)    134  (   .0)      1                    .3    194    27  30
  1590     190   1500     60     9    46     1.7 +    .7  (  1.3)    101  (   .2)      5                   1.5    193    52  70
  1610    1948   4300     60    12     6     2.6 +    .7  (  1.8)     40  (  1.7)     21                   3.5    194    40  17
  1620     156   1800     60    25    70     2.3 +    .7  (  1.7)    118  (   .0)      5                   1.7    260    44  56
  1630    1970   4300     82     9     6     1.0 +   2.3  (  1.9)     33  (   .7)     23     +             2.5    195     5  29  50  74
  1640    2253   4300     94    13    16     2.1 +   7.9  (  5.5)*    54  (  1.6)     30                  29.0    196    13  37  58  82
  1650     578<  1500     72    26    13      .7 +   1.3  (  1.1)     53  (   .2)      5                   1.3    188    15  38  60  83
  1660    2433<  4300     82    14     5     1.1 +   2.3  (  1.8)*    25  (  1.3)     11                  10.5    197    24  54  69   9
  1670    2266<  4300     85    11     8     2.6 +   2.7  (  2.9)     43  (   .7)     16                   3.6    198    28  55  73  10
  1680    1224   3200     78    30    15     3.4 +   1.8  (  2.9)     81  (   .5)     14                   3.4    186    23  44  68  89
  1690    1980<  4300     86    21    13     3.9 +   3.1  (  3.9)*    75  (  1.6)     24                  21.0    199     3  26  48  71
  1700    2004<  5500     75     7     9     3.5 +   1.5  (  2.7)     53  (  2.7)     17                   5.4    200     7  28  52  73
  1710    1094   3800     72    30    24     6.0 +   1.3  (  4.0)*    72  (   .8)     20                  20.8    212    87  32
  1720     257   1500     59    30    22      .8 +    .7  (   .8)     85  (   .2)      3                   1.0    184    58  70  13  25
  1730    1949<  5500     44    12     1      .1 +    .4  (   .3)      4  (   .2)      1                    .5    201    62   7  17  52
  1740    1813   5500     87    20    15     4.2 +   3.4  (  4.2)     93  (   .6)     24                   4.7    202    45  61   0  16
  1750     239   1500     55    20    19      .7 +    .6  (   .7)     92  (   .3)      3                   1.0    183    12  24  57  69
  1760    1993   5500     68    14     4     1.0 +   1.1  (  1.1)     26  (   .7)     18                   1.9    203    14  37  59  82
  1770    2088<  5500     74     8     4      .7 +   1.4  (  1.2)     13  (  1.0)      5                   2.1    204    20  42  65  87
  1780     524   2000     76    24    35     3.5 +   1.6  (  2.8)     88  (   .7)     12                   3.5    209    65   5
  1790     298   1500     64    18    23     1.0 +    .9  (  1.0)    101  (   .4)      5                   1.5    181    76  89  31  44
  1800    2284<  5500     67    13     3     1.1 +   1.0  (  1.2)     19  (  1.2)     10                   2.4    205    29  56  74  11
  1810    2384<  5500     53    10     2      .6 +    .6  (   .6)      9  (   .8)      7                   1.4    206    36  19
  1820     548   2000     62    26    14     1.3 +    .8  (  1.2)     84  (   .4)      7                   1.6    178    31  50  76   5
  1830     734   3000     65    30    26     4.4 +    .9  (  2.9)     74  (   .3)     14                   3.2    227    52  85
  1831     725   3000     70    30    31     5.0 +   1.2  (  3.4)     81  (   .4)     15                   3.7    227    52  82
  1840    2906<  9000     46    12     3     2.0 +    .4  (  1.3)*    18  (  1.6)     18                   8.2    208    11  73
  1850     195   1600     52    25    33     1.3 +    .5  (  1.0)     86  (   .1)      5                   1.1    224    38  58
  1860     503   1800     74    28    24     2.0 +   1.4  (  1.9)     99  (   .7)      9                   2.5    204    45  61   0  16
  1870    2680<  9000     52     9     7     4.4 +    .5  (  2.7)     22  (  1.6)     15                   4.4    209    10  61
  1880    2818<  9000     56    10     7     4.6 +    .6  (  2.9)     22  (  1.5)     16                   4.4    210    13  62
  1890     563   1600     72    25    20     1.8 +   1.3  (  1.7)     52  (   .3)      8                   2.0    222    75  28
  1900     581   2400     91    30    51     3.7 +   4.5  (  4.5)    149  (  1.0)     15                   5.5    202    73  84  28  39
1PROGRAM TRANSYT8      ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS                 PAGE  21   RUN ON 10/ 8/1993
0      90 SECOND CYCLE   45 STEPS
0 LINK     FLOW    SAT   DEGREE MEAN TIMES   -------DELAY--------    ----STOPS----    ----QUEUE----   PERFORMANCE    EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF     PER PCU    UNIFORM RANDOM+ COST     MEAN    COST    MEAN               INDEX.      NODE   START  START
           LINK            SAT   CRUISE                OVERSAT  OF    STOPS     OF    MAX.  AVERAGE   WEIGHTED SUM              END      END
                                       DELAY (U+R+O=MEAN Q) DELAY     /PCU   STOPS          EXCESS    OF ( ) VALUES            1ST     2ND
         (PCU/H) (PCU/H)  (%)   (SEC) (SEC)     (PCU-H/H)    ($/H)     (%)    ($/H)   (PCU)   (PCU)       ($/H)                  (SECONDS)

  1910    2647<  9000     34    17     0      .1 +    .3  (   .2)      1  (   .1)      1                    .3    211    27  13
  1920     730   3000     78    30    23     2.9 +   1.8  (  2.6)    103  (   .7)     12                   3.3    200    32  45  77   0
  1930    1869<  7500     48     7     6     2.8 +    .5  (  1.8)     24  (  1.4)     15                   3.2    212    37  83
  1940    2977<  7500     50     8     2     1.3 +    .5  (  1.0)*    14  (   .7)     12                   5.7    213    73  53
  1950    2185<  7500     67     9    15     8.2 +   1.0  (  5.1)*    78  (  5.3)     47                  30.7    214    21  59
  1960     846   2800     91    25    54     8.1 +   4.6  (  7.0)    111  (   .4)     24                   7.4    218    72  11
  1970     596   3000     75    32    25     2.6 +   1.5  (  2.2)     90  (   .8)     10                   3.0    198    58  69  13  24
  1980    2151<  7500     48    16     1      .4 +    .5  (   .5)      4  (   .2)      3                    .7    215    33  86
  1990     532   1500    106    30   285     3.1 +  39.0  ( 23.1)    283  (  1.9)     47     +            25.1    196    40  54  85   9
  2000    1922<  7500     27    22     0      .0 +    .2  (   .1)      1  (   .0)      0                    .1    259    46  39
  2010     270   1500     54    18    26     1.4 +    .6  (  1.1)    102  (   .3)      7                   1.4    215    89  28
  2020    2617   5000     77    20    12     6.7 +   1.7  (  4.6)*    55  (  3.3)     39                  26.4    217    85  55
  2040     720   1800     92    20    49     4.3 +   5.5  (  5.4)    117  (   .9)     23     +             6.3    214    66  14
  2050    2049   5000     74    18     8     3.0 +   1.4  (  2.4)*    51  (  1.3)     34                  13.5    218    19  68
  2060    2099   5000     73    30     9     4.0 +   1.3  (  2.9)*    40  (   .3)     27                  14.9    219    42   3
  2080    2598   7000     41    25     1      .1 +    .4  (   .3)*     4  (   .1)      3                   1.4    220    37  27
  2090    2037   5000     46    20     2      .6 +    .4  (   .6)     16  (   .1)      9                    .7    221    40  29
  2110     589   2800     57    20    31     4.4 +    .7  (  2.8)     89  (   .6)     14                   3.3    210    66   8
  2120    1501   5000     68    15    19     7.0 +   1.0  (  4.4)     76  (  1.1)     30                   5.5    222    32  71
  2130    2030   5000     51    12     2      .7 +    .5  (   .7)     10  (   .3)      7                    .9    223    40  20
  2140     520   2800     84    22    40     3.3 +   2.5  (  3.2)    103  (   .5)     15                   3.6    208    77   6
  2150    1669   5000     49    25     3     1.1 +    .5  (   .9)     15  (   .2)      7                   1.0    224    62  32
  2160     596   1500     74    20    15     1.1 +   1.5  (  1.4)     65  (   .1)     11     +             1.5    225    83  40
  2161    1987<  4500     59    20     3      .9 +    .7  (   .9)     13  (   .0)      7                    .9    225    74  50
  2170     952   1500    102    22   138     3.6 +  33.0  ( 20.1)*   174  (  1.6)     51     +           102.3    226    50  15
  2171     497   4500     66    22    39     4.4 +   1.0  (  3.0)    101  (   .5)     13                   3.4    226    50  64
  2185     667   3000     67    15    31     4.8 +   1.0  (  3.2)     87  (   .9)     15                   4.1    225    54  83
  2190    3243<  9000     40    23     1      .1 +    .3  (   .3)*     2  (   .1)      3                   1.4    207    81  71
  2200    1041   4000     45    25     9     2.3 +    .4  (  1.5)     63  (  2.0)     19                   3.5    227    88  49
  2205     825   2500    106    22   269     6.8 +  54.8  ( 33.9)*   240  (  2.6)     76     +            87.3    226    19  46
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Hot CO links with delay weighting of 500 percent

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  2206    823  4000     66    22    29    5.8 +  1.0  (  3.7)     91  (  1.0)       19                     4.7   226     19  46
  2215   2417  8000     72    24    23   14.5 +  1.3  (  8.6)     79  (  1.9)       51                    10.5   226     68  15
  2225   2050  4500     69    25    12    5.6 +  1.1  (  3.7)     58  (  1.3)       32                     5.0   227     82  50
  2230    945  3200     66    22    14    2.6 +  1.0  (  2.0)     76  (   .7)       10                     2.7   178      8  27  53  72
  2790   1998  5000     86    25    28   12.8 +  2.9  (  8.6)     88  (   .9)       46                     9.6   216     89  40
  2800    300  1800     25    25     4     .2 +   .2  (   .2)     14  (   .1)        1                      .3   260     60  30
  2805   2001  4000     52    28     1     .0 +   .5  (   .3)      1  (   .0)        1                      .3   259     89  85
  2820    300  1800     88    15    78    3.1 +  3.5  (  3.6)    137  (   .9)       11                     4.4   261     51  67
  2825   1699  5000     47    15     1     .2 +   .4  (   .3)      4  (   .0)        2                      .4   260     66  40
  2830   1847  5500     46    15     6    2.7 +   .4  (  1.7)     37  (   .8)       19                     2.5   193     75  49
  2845    617  1600     83    20    34    3.6 +  2.3  (  3.2)*    98  (   .1)       16      +             16.4   261     73  24
  2846   1755  3500     74    20    12    4.6 +  1.4  (  3.3)*    63  (   .2)       30      +             16.7   261     51  21
  3730   1520  5000     68    25    23    8.4 +  1.1  (  5.2)*    78  (   .4)       31                    26.5   216     46  85
  3850   1000  5000     95    20    63    9.7 +  7.9  (  9.7)    123  (  1.5)       32                    11.1   261     28  46
  5800    330  1800     87    25    68    3.1 +  3.1  (  3.4)    127  (   .2)       11                     3.7   217     59  77
  5930    420  1800     91    25    73    3.8 +  4.7  (  4.7)    133  (   .3)       15                     5.0   219     13  35
  5940     50  1800     42    25    66     .6 +   .4  (   .5)    119  (   .0)        2                      .5   221     35  40
1PROGRAM TRANSYT8    ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS                    PAGE  22   RUN ON 10/ 8/1993
0     90 SECOND CYCLE  45 STEPS
0  TOTAL         TOTAL       MEAN            TOTAL     TOTAL     TOTAL        TOTAL          PENALTY       TOTAL
 DISTANCE         TIME      JOURNEY         UNIFORM   RANDOM+     COST         COST            FOR       PERFORMANCE
TRAVELLED        SPENT       SPEED           DELAY    OVERSAT      OF           OF            EXCESS        INDEX
                                                       DELAY     DELAY        STOPS           QUEUES
 (PCU-KM/H)    (PCU-H/H)    (KM/H)        (PCU-H/H) (PCU-H/H)    ($/H)        ($/H)           ($/H)         ($/H)
0 13281.2       1160.5       11.4           271.1     265.7     ( 606.1) + (    74.6)  +  (       .0)   =      680.7        TOTALS
0**********************************************************************************************************************************
*
0                                     CRUISE              DELAY              STOPS               TOTALS
                                  LITRES PER HOUR    LITRES PER HOUR    LITRES PER HOUR     LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS        1243.4       +       751.5        +      214.2        =     2209.2
0
 NO. OF ENTRIES TO SUBPT:      125
 NO. OF LINKS RECALCULATED: 2543
 SYSTEM TIME:           19:25:29

 EXECUTION TIME:    451 SECONDS
 PROGRAM TRANSYT8 FINISHED
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Hot CO links with delay and stop weighting of 500 percent

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0CARD   CARD
 NO.    TYPE
 (  1)= TITLE:- ATHENS * Central Arteries * ADDED DELAY & STOP WT OF 500 TO HOT CO LINKS
0CARD   CARD   CYCLE  NO. OF   TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW   CRUISE-SPEEDS   OPTIMISE EXTRA    HILL-    DELAY    STOP
 NO.    TYPE   TIME   STEPS  PERIOD DISPLACEMENTS  SETTINGS  INFO.    SCALE   SCALE  CARD32  0=NONE  COPIES   CLIMB    VALUE    VALUE
                       PER   1-1200  START    END     0=NO  2=CYCLE  10-200  50-200 0=TIMES  1=O/SET  FINAL   OUTPUT   P PER    P PER
               (SEC)  CYCLE  MINS.  (SEC)   (SEC)    1=YES  CHOICE     %       %    1=SPEEDS 2=FULL  OUTPUT   1=FULL   PCU-H     100
  2)=    1      90     45     120     2       3        1       0        0       0       0       2       0        0       55       50
1PROGRAM TRANSYT8     ATHENS * Central Arteries * ADDED DELAY & STOP WT OF 500 TO HOT CO LINKS             PAGE  20   RUN ON 29/ 8/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK     FLOW    SAT   DEGREE  MEAN TIMES  -------DELAY--------   ----STOPS----   ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF     PER PCU    UNIFORM RANDOM+ COST     MEAN   COST    MEAN              INDEX.      NODE   START  START
           LINK           SAT   CRUISE               OVERSAT  OF     STOPS    OF     MAX.  AVERAGE  WEIGHTED SUM            END     END
                                      DELAY  (U+R+O=MEAN Q) DELAY     /PCU   STOPS           EXCESS  OF ( ) VALUES         1ST     2ND
         (PCU/H) (PCU/H)  (%)   (SEC) (SEC)    (PCU-H/H)    ($/H)     (%)    ($/H)    (PCU)  (PCU)      ($/H)              (SECONDS)

    900      222   1500     37    18    14     .6 +   .3  (   .5)     72  (   .2)     2                      .7    187    35  52  80   7
   1060      142   1500     47    18    27     .6 +   .4  (   .6)    104  (   .2)     2                      .7    189    84   2  39  47
   1210     1094   4000     72    17    16    3.6 +  1.3  (  2.7)     85  (   .9)    13                     3.6    185    12  28  57  73
   1280      361   1500     72    18    26    1.3 +  1.3  (  1.4)    104  (   .4)     5                     1.8    180    55  69  10  24
   1300      307   1500     58    18    20    1.0 +   .7  (   .9)     89  (   .3)     4                     1.2    179    43  58  88  13
   1330      994   3200     61    11     4     .4 +   .8  (   .6)     18  (   .3)     4                      .9    179    17  39  62  84
   1340     1301   3200     70    18     7    1.4 +  1.2  (  1.4)     38  (   .8)     7                     2.2    180    72   7  27  52
   1350     1392   3200     70    25     8    1.9 +  1.2  (  1.7)     47  (   .4)     9                     2.1    181    39  66  84  21
   1360      260   1500     65    22    28    1.1 +   .9  (  1.1)    110  (   .2)     4                     1.3    205    58  69  13  24
   1380     1146   3200     50    13     3     .4 +   .5  (   .5)     16  (   .2)     3                      .7    182    48  79   3  34
   1390      928   3200     47    16     4     .6 +   .4  (   .6)     23  (   .3)     3                      .8    183    16  43  61  88
   1400      369   1800     58    20    16     .9 +   .7  (   .9)     84  (   .3)     4                     1.2    203    39  54  84   9
   1420     1006   3200     52    24     6    1.2 +   .5  (  1.0)     39  (   .7)     6                     1.6    184    33  59  78  14
   1440     1082   3200     69     6    11    2.1 +  1.1  (  1.8)     57  (  1.6)    10                     3.3    185    32  53  77   8
   1450     1055   3200     78    19    13    2.1 +  1.8  (  2.1)     55  (   .8)     9                     3.0    186    47  65   2  20
   1460     1121   4000     90    20    23    2.9 +  4.4  (  4.0)    108  (  1.2)    18                     5.2    199    37  50  82   5
   1480      816   3200     50    10     3     .3 +   .5  (   .4)     13  (   .1)     2                      .5    187    55  77  10  32
   1490      846   3200     70    24    13    1.8 +  1.2  (  1.6)     76  (   .4)    10                     2.1    188    41  57  86  12
   1500      192   1500     82    22    57     .8 +  2.2  (  1.7)    156  (   .2)     4                     1.9    197    58  64  13  19
   1520     1008<  3200     47    13     3     .3 +   .4  (   .4)     14  (   .2)     2                      .6    189    51  80   6  35
   1540      228   1000     68    22    29     .7 +  1.1  (  1.0)    112  (   .2)     4                     1.2    195    32  46  77   1
   1580       22   1500     33    18    82     .3 +   .2  (   .3)    133  (   .0)     1                      .3    194    26  29
   1590      190   1500     60     9    46    1.7 +   .7  (  1.3)    101  (   .2)     5                     1.5    193    51  69
   1610     1948   4300     60    12     6    2.6 +   .7  (  1.8)     41  (  1.7)    20                     3.5    194    39  16
   1620      156   1800     46    25    69    2.6 +   .4  (  1.6)    111  (   .0)     4                     1.7    260    49  65
   1630     1970   4300     82     9     7    1.3 +  2.3  (  2.0)     47  (  1.0)    23        +            3.0    195     5  29  50  74
   1640     2253   4300     94    13    16    2.0 +  7.9  (  5.4)*    51  (  1.5)    21                    34.6    196    13  37  58  82
   1650      578<  1500     72    26    13     .7 +  1.3  (  1.1)     53  (   .2)     5                     1.3    188    15  38  60  83
   1660     2433<  4300     82    14     5    1.1 +  2.3  (  1.8)*    25  (  1.3)    11                    15.6    197    24  54  69   9
   1670     2266<  4300     82    11     8    2.7 +  2.2  (  2.7)     69  (  1.1)    27        +            3.8    198    39  67  84  22
   1680     1224   3200     78    30    15    3.3 +  1.8  (  2.8)     87  (   .6)    15                     3.3    186    23  44  68  89
   1690     1980<  4300     86    21    12    3.3 +  3.1  (  3.6)*    64  (  1.4)    21                    24.6    199    10  33  55  78
   1700     2004<  5500     75     7    10    3.9 +  1.5  (  3.0)     54  (  2.8)    17                     5.8    200    12  33  57  78
   1710     1094   3800     56    30    20    5.6 +   .6  (  3.4)*    76  (   .9)    22                    21.6    212    21  66
   1720      257   1500     55    30    19     .8 +   .6  (   .8)     79  (   .1)     3                      .9    184    62  75  17  30
   1730     1949<  5500     44    12     1     .1 +   .4  (   .3)      4  (   .2)     1                      .5    201    67  12  22  57
   1740     1813   5500     87    20    15    4.4 +  3.4  (  4.3)     83  (   .5)    24                     4.7    202    45  61   0  16
   1750      239   1500     55    20    19     .6 +   .6  (   .7)     67  (   .2)     2                      .9    183    46  58   1  13
   1760     1993   5500     68    14     3     .9 +  1.1  (  1.1)     19  (   .5)     8                     1.6    203    13  36  58  81
   1770     2088<  5500     71     8     3     .6 +  1.2  (  1.0)     12  (   .9)     4                     1.9    204    19  42  64  87
   1780      524   2000     67    24    28    3.1 +  1.0  (  2.3)     80  (   .6)    11                     2.9    209    63   7
   1790      298   1500     69    18    24     .9 +  1.1  (  1.1)    102  (   .4)     5                     1.5    181    24  36  69  81
   1800     2284<  5500     67    13     3    1.2 +  1.0  (  1.2)     20  (  1.3)     9                     2.5    205    28  55  73  10
   1810     2384<  5500     53    10     2     .6 +   .6  (   .7)      9  (   .8)     7                     1.5    206    34  17
   1820      548   2000     65    26    16    1.6 +   .9  (  1.4)     92  (   .4)     7                     1.8    178    32  50  77   5
   1830      734   3000     65    30    26    4.4 +   .9  (  2.9)     74  (   .3)    14                     3.3    227    50  83
   1831      725   3000     70    30    31    5.0 +  1.2  (  3.4)     81  (   .4)    15                     3.8    227    50  80
   1840     2906<  9000     45    12     3    2.0 +   .4  (  1.3)*    13  (  1.2)    11                    12.7    208     5  68
   1850      195   1600     52    25    33    1.2 +   .5  (  1.0)     87  (   .1)     5                     1.1    224    38  58
   1860      503   1800     79    28    27    1.9 +  1.8  (  2.1)     99  (   .7)     9                     2.7    204    45  60   0  15
   1870     2680<  9000     56     9     7    4.8 +   .6  (  3.0)     27  (  2.0)    23                     5.0    209    12  59
   1880     2818<  9000     53    10     4    2.6 +   .6  (  1.8)     17  (  1.2)    19                     2.9    210    19  71
   1890      564   1600     69    25    19    1.8 +  1.1  (  1.6)     51  (   .3)     7                     1.9    222    71  26
   1900      581   2400     91    30    46    2.9 +  4.5  (  4.1)    147  (  1.0)    14                     5.1    202    73  84  28  39
1PROGRAM TRANSYT8     ATHENS * Central Arteries * ADDED DELAY & STOP WT OF 500 TO HOT CO LINKS             PAGE  21   RUN ON 29/ 8/1993
0      90 SECOND CYCLE  45 STEPS
0 LINK     FLOW    SAT   DEGREE  MEAN TIMES  -------DELAY--------   ----STOPS----   ----QUEUE----  PERFORMANCE   EXIT   GREEN TIMES
 NUMBER    INTO    FLOW    OF     PER PCU    UNIFORM RANDOM+ COST     MEAN   COST    MEAN              INDEX.      NODE   START  START
           LINK           SAT   CRUISE               OVERSAT  OF     STOPS    OF     MAX.  AVERAGE  WEIGHTED SUM            END     END
                                      DELAY  (U+R+O=MEAN Q) DELAY     /PCU   STOPS           EXCESS  OF ( ) VALUES         1ST     2ND
         (PCU/H) (PCU/H)  (%)   (SEC) (SEC)    (PCU-H/H)    ($/H)     (%)    ($/H)    (PCU)  (PCU)      ($/H)              (SECONDS)

   1910     2647<  9000     34    17     1     .5 +   .3  (   .4)      8  (   .8)     6                     1.2    211     4  80
   1920      731   3000     78    30    22    2.7 +  1.8  (  2.5)    102  (   .7)    13                     3.2    200    37  50  82   5
   1930     1869<  7500     61     7    20    9.6 +   .8  (  5.7)     87  (  4.8)    42                    10.5    212    71  17
   1940     2977<  7500     50     8     2     .8 +   .5  (   .7)*     9  (   .4)     9                     5.6    213    26   6
   1950     2185<  7500     66     9    13    6.9 +  1.0  (  4.3)*    42  (  2.9)    24                    36.1    214    26  65
   1960      846   2800     94    25    57    6.7 +  6.7  (  7.4)    119  (   .5)    27        +            7.8    218    87  25
   1970      596   3000     81    32    28    2.5 +  2.1  (  2.6)    106  (   .9)     9                     3.5    198    70  80  25  35
   1980     2151<  7500     50    16     2     .5 +   .5  (   .5)      5  (   .3)     4                      .8    215    39   0
   1990      532   1500    106    30   285    3.1 + 39.1  ( 23.2)    282  (  1.9)    48        +           25.1    196    40  54  85   9
   2000     1922<  7500     27    22     0     .0 +   .2  (   .1)      1  (   .0)     0                      .1    259    49  42
   2010      270   1500     51    18    49    3.1 +   .5  (  2.0)    106  (   .3)     7                     2.3    215     3  34
   2020     2617   5000     77    20    10    5.3 +  1.7  (  3.9)*    56  (  3.3)    40                    35.7    217    13  73
   2040      720   1800     95    20    60    4.3 +  7.6  (  6.6)    109  (   .8)    22        +            7.4    214    72  19
   2050     2049   5000     72    18     6    2.4 +  1.3  (  2.0)*    33  (   .9)    25                    14.5    218    33  83
   2060     2099   5000     73    30    10    4.2 +  1.3  (  3.1)*    46  (   .4)    31                    17.1    219    57  18
   2080     2598   7000     41    25     1     .1 +   .4  (   .3)*     4  (   .1)     3                     1.7    220    53  43
   2090     2037   5000     48    20     2     .7 +   .5  (   .7)     22  (   .2)    16                      .8    221    15   1
   2110      589   2800     63    20    32    4.4 +   .9  (  2.9)     92  (   .6)    14                     3.5    210    75  14
   2120     1501   5000     71    15    17    5.7 +  1.2  (  3.8)     67  (  1.0)    29                     4.8    222    30  67
   2130     2030   5000     51    12     2     .6 +   .5  (   .6)      9  (   .2)     6                      .9    223    38  18
   2140      520   2800     88    22    49    3.6 +  3.5  (  3.9)    109  (   .5)    15                     4.4    208    72   0
   2150     1669   5000     49    25     3    1.0 +   .5  (   .8)     15  (   .2)     9                     1.0    224    62  32
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Hot CO links with delay and stop weighting of 500 percent

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  2160     596   1500      75     20     16    1.2 +  1.5  (  1.4)     70  (   .1)     12       +           1.5    225     83  40
  2161    1987<  4500      59     20      3     .9 +   .7  (   .9)     13  (   .0)      6                    .9    225     74  50
  2170     952   1500     102     22    138    3.6 + 33.0  ( 20.1)*   175  (  1.6)     51       +         108.8    226     50  15
  2171     497   4500      71     22     41    4.4 +  1.2  (  3.1)    104  (   .5)     13                   3.6    226     50  63
  2185     667   3000      67     15     31    4.8 +  1.0  (  3.2)     87  (   .9)     15                   4.1    225     54  83
  2190    3243<  9000      43     23      1     .4 +   .4  (   .4)*     5  (   .2)      6                   3.3    207     86  70
  2200    1041   4000      45     25      8    2.0 +   .4  (  1.3)     59  (  1.9)     17                   3.2    227     86  47
  2205     825   2500     106     22    269    6.9 + 54.8  ( 33.9)*   240  (  2.6)     76       +          91.2    226     19  46
  2206     823   4000      66     22     30    6.0 +  1.0  (  3.8)     93  (  1.0)     20                   4.8    226     19  46
  2215    2417   8000      70     24     22   13.9 +  1.2  (  8.3)     78  (  1.8)     49                  10.1    226     67  15
  2225    2050   4500      69     25     12    5.6 +  1.1  (  3.7)     58  (  1.3)     32                   5.0    227     80  48
  2230     945   3200      63     22     12    2.4 +   .9  (  1.8)     72  (   .7)     10                   2.4    178      8  28   53   73
  2790    1997   5000      92     25     32   12.3 +  5.7  (  9.9)    100  (  1.0)     52       +          11.0    216     69  17
  2800     300   1800      26     25      6     .3 +   .2  (   .3)     18  (   .1)      1                    .3    260     69  35
  2805    2001   4000      52     28      1     .0 +   .5  (   .3)      1  (   .0)      1                    .3    259      1  87
  2820     300   1800      88     15     82    3.4 +  3.5  (  3.7)    139  (   .9)     11                   4.6    261     61  77
  2825    1699   5000      50     15      2     .4 +   .5  (   .5)      6  (   .1)      3                    .6    260     75  45
  2830    1847   5500      46     15      6    2.7 +   .4  (  1.7)     37  (   .8)     19                   2.5    193     74  48
  2845     617   1600      83     20     34    3.6 +  2.3  (  3.2)*    98  (   .1)     16       +          16.9    261     83  34
  2846    1755   3500      74     20     12    4.6 +  1.4  (  3.3)*    63  (   .2)     30       +          17.7    261     61  31
  3730    1520   5000      64     25     20    7.4 +   .9  (  4.6)*    73  (   .4)     29                  24.7    216     23  65
  3850    1000   5000      95     20     63    9.7 +  7.9  (  9.7)    123  (  1.5)     32                  11.1    261     38  56
  5800     330   1800      87     25     68    3.1 +  3.1  (  3.4)    127  (   .2)     11                   3.7    217     77   5
  5930     420   1800      91     25     73    3.8 +  4.7  (  4.7)    133  (   .3)     15                   5.0    219     28  50
  5940      50   1800      28     25     51     .5 +   .2  (   .4)    104  (   .0)      1                    .4    221      7  15
1PROGRAM TRANSYT8     ATHENS * Central Arteries * ADDED DELAY & STOP WT OF 500 TO HOT CO LINKS              PAGE  22   RUN ON 29/ 8/1993
0     90 SECOND CYCLE  45 STEPS
0  TOTAL            TOTAL      MEAN          TOTAL    TOTAL     TOTAL          TOTAL           PENALTY       TOTAL
  DISTANCE           TIME    JOURNEY        UNIFORM  RANDOM+    COST           COST             FOR       PERFORMANCE
 TRAVELLED          SPENT     SPEED          DELAY   OVERSAT     OF             OF             EXCESS        INDEX
                                                      DELAY     DELAY          STOPS           QUEUES
  (PCU-KM/H)      (PCU-H/H)    (KM/H)      (PCU-H/H)(PCU-H/H)   ($/H)          ($/H)            ($/H)         ($/H)
0 13281.2          1167.7      11.4         271.2    272.8    ( 596.1) + (  146.2)  +  (       .0)   =      742.2       TOTALS
0************************************************************************************************************************************
*
0                                     CRUISE              DELAY              STOPS                 TOTALS
                                 LITRES PER HOUR    LITRES PER HOUR    LITRES PER HOUR      LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS         1243.4        +       761.6       +       216.6          =      2221.7
0
 NO. OF ENTRIES TO SUBPT:      138
 NO. OF LINKS RECALCULATED: 2604
 SYSTEM TIME:             17:37:14

 EXECUTION TIME:    441 SECONDS
 PROGRAM TRANSYT8 FINISHED
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Hot NOx links with stop weighting of -200 percent

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0CARD   CARD
 NO.    TYPE
 (  1)= TITLE:- ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200
0CARD   CARD    CYCLE  NO. OF    TIME EFFECTIVE-GREEN  EQUISAT 1=CYCLE   FLOW   CRUISE-SPEEDS    OPTIMISE EXTRA    HILL-   DELAY   STOP
 NO.    TYPE    TIME   STEPS   PERIOD DISPLACEMENTS  SETTINGS  INFO.    SCALE   SCALE  CARD32  0=NONE  COPIES   CLIMB   VALUE   VALUE
                        PER    1-1200  START    END     0=NO  2=CYCLE  10-200  50-200 0=TIMES  1=O/SET  FINAL   OUTPUT   P PER   P PER
               (SEC)   CYCLE   MINS.  (SEC)   (SEC)    1=YES  CHOICE     %       %   1=SPEEDS 2=FULL  OUTPUT   1=FULL   PCU-H    100
   2)=   1      90      45     120      2       3        1      0        0       0       0       2       0        0      55      50
0CARD   CARD                                           LIST  OF  NODES  TO  BE  OPTIMISED
 NO.    TYPE
   3)=   2     261     260     178     179     180     181     182     183     184     185     186     187     188     189     193
   4)=   2     194     195     196     197     198     199     200     201     202     203     204     205     206     227     226
   5)=   2     207     208     209     210     211     212     213     214     215     259     216     217     218     219     220
   6)=   2     221     222     223     224     225       0       0       0       0       0       0       0       0       0       0
0                                  NODE  CARDS:   STAGE  CHANGE  TIMES  AND  MINIMUM  STAGE  TIMES
 CARD   CARD   NODE         STAGE 1          STAGE 2          STAGE 3          STAGE 4          STAGE 5          STAGE 6          STAGE 7
 NO.    TYPE    NO.     CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN    CHANGE    MIN
   7)=  13     261        35      10       64      10       90      10        0       0        0       0        0       0        0       0
   8)=  14     260        44      10       55      10       66      10       33      10        0       0        0       0        0       0
   9)=  22     178         7      10       26      10        0       0        0       0        0       0        0       0        0       0
  10)=  22     179        14      10       33      10        0       0        0       0        0       0        0       0        0       0
  11)=  22     180        39      10       13      10        0       0        0       0        0       0        0       0        0       0
  12)=  22     181        16      10       34      10        0       0        0       0        0       0        0       0        0       0
  13)=  22     182        28      10       39      10        0       0        0       0        0       0        0       0        0       0
  14)=  22     183         9      10       38      10        0       0        0       0        0       0        0       0        0       0
  15)=  22     184        17      10       43      10        0       0        0       0        0       0        0       0        0       0
  16)=  22     185         3      10       21      10        0       0        0       0        0       0        0       0        0       0
  17)=  22     186        19      10       40      10        0       0        0       0        0       0        0       0        0       0
  18)=  22     187        31      10        4      10        0       0        0       0        0       0        0       0        0       0
  19)=  22     188        12      10       32      10        0       0        0       0        0       0        0       0        0       0
  20)=  22     189        35      10       20      10        0       0        0       0        0       0        0       0        0       0
  21)=  12     193        30      10       89      10        0       0        0       0        0       0        0       0        0       0
  22)=  12     194        30      10        9      10        0       0        0       0        0       0        0       0        0       0
  23)=  22     195         0      10       31      10        0       0        0       0        0       0        0       0        0       0
  24)=  22     196        10      10       36      10        0       0        0       0        0       0        0       0        0       0
  25)=  22     197        16      10        1      10        0       0        0       0        0       0        0       0        0       0
  26)=  22     198        13      10       40      10        0       0        0       0        0       0        0       0        0       0
  27)=  22     199        31      10       11      10        0       0        0       0        0       0        0       0        0       0
  28)=  22     200        31      10       16      10        0       0        0       0        0       0        0       0        0       0
  29)=  22     201         2      10       37      10        0       0        0       0        0       0        0       0        0       0
  30)=  22     202        40      10       19      10        0       0        0       0        0       0        0       0        0       0
  31)=  22     203        10      10       37      10        0       0        0       0        0       0        0       0        0       0
  32)=  22     204        16      10       43      10        0       0        0       0        0       0        0       0        0       0
  33)=  22     205        22      10        9      10        0       0        0       0        0       0        0       0        0       0
  34)=  12     206        28      10       17      10        0       0        0       0        0       0        0       0        0       0
  35)=  12     227        75      10       41      10        0       0        0       0        0       0        0       0        0       0
  36)=  13     226        49      10       80      10       25      10        0       0        0       0        0       0        0       0
  37)=  12     207        65      10       76      10        0       0        0       0        0       0        0       0        0       0
  38)=  12     208        80      10       57      10        0       0        0       0        0       0        0       0        0       0
  39)=  12     209        83      10       55      10        0       0        0       0        0       0        0       0        0       0
  40)=  12     210        85      10       60      10        0       0        0       0        0       0        0       0        0       0
  41)=  12     211        11      10        1      10        0       0        0       0        0       0        0       0        0       0
  42)=  12     212        33      10       88      10        0       0        0       0        0       0        0       0        0       0
  43)=  12     213        15      10       85      10        0       0        0       0        0       0        0       0        0       0
  44)=  12     214        26      10       82      10        0       0        0       0        0       0        0       0        0       0
  45)=  12     215        46      10       26      10        0       0        0       0        0       0        0       0        0       0
  46)=  12     259        85      10       45      10        0       0        0       0        0       0        0       0        0       0
  47)=  12     216        86      10       41      10        0       0        0       0        0       0        0       0        0       0
  48)=  12     217         7      10       76      10        0       0        0       0        0       0        0       0        0       0
  49)=  12     218        12      10       72      10        0       0        0       0        0       0        0       0        0       0
  50)=  12     219        43      10       21      10        0       0        0       0        0       0        0       0        0       0
  51)=  12     220        23      10       12      10        0       0        0       0        0       0        0       0        0       0
  52)=  12     221        35      10       18      10        0       0        0       0        0       0        0       0        0       0
  53)=  12     222        35      10        4      10        0       0        0       0        0       0        0       0        0       0
  54)=  12     223        29      10       11      10        0       0        0       0        0       0        0       0        0       0
  55)=  12     224        59      10       33      10        0       0        0       0        0       0        0       0        0       0
  56)=  13     225        40      10       59      10       74      10        0       0        0       0        0       0        0       0
1PROGRAM TRANSYT8     ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200                  PAGE    3   RUN ON 30/ 8/1993

0                                            LINK  CARDS:   FIXED  DATA
                                     FIRST  GREEN                    SECOND  GREEN
 CARD   CARD   LINK     EXIT       START            END            START            END         LINK    STOP      SAT    DELAY   DISPSN
 NO.    TYPE    NO.     NODE    STAGE    LAG    STAGE    LAG    STAGE    LAG    STAGE    LAG  LENGTH  WT.X100   FLOW  WT.X100   X100
  57)=  31    2846      261       2       5       1       0       0       0       0       0      54       0     3500      0       0
  58)=  31    2845      261       3       6       1       3       0       0       0       0      54       0     1600      0       0
  59)=  31    2820      261       2       5       3       0       0       0       0       0     120       0     1800      0       0
  60)=  31    3850      261       1       7       2       0       0       0       0       0     120       0     5000      0       0
  61)=  31    2825      260       3       0       1       0       0       0       0       0      68       0     5000      0       0
  62)=  31    2800      260       2       4       4       0       0       0       0       0     156       0     1800      0       0
  63)=  31    1620      260       1       4       2       0       0       0       0       0      64       0     1800      0       0
  64)=  31    1820      178       2       4       1       0       0       0       0       0     130       0     2000      0       0
  65)=  31    2230      178       1       3       2       0       0       0       0       0     118       0     3200      0       0
  66)=  31    1330      179       1       4       2       0       0       0       0       0      75       0     3200      0       0
  67)=  31    1300      179       2       4       1       0       0       0       0       0     100       0     1500      0       0
  68)=  31    1340      180       2       3       1       0       0       0       0       0     124       0     3200      0       0
  69)=  31    1280      180       1       3       2       0       0       0       0       0      98       0     1500      0       0
  70)=  31    1350      181       2       3       1       0       0       0       0       0     114       0     3200      0       0
  71)=  31    1790      181       1       3       2       0       0       0       0       0     116       0     1500      0       0
  72)=  31    1380      182       2       4       1       0       0       0       0       0      81       0     3200      0       0
  73)=  31    1390      183       1       3       2       0       0       0       0       0      96       0     3200      0       0
  74)=  31    1750      183       2       3       1       0       0       0       0       0     128       0     1500      0       0
  75)=  31    1420      184       1       3       2       0       0       0       0       0     172       0     3200      0       0
  76)=  31    1720      184       2       3       1       0       0       0       0       0     140       0     1500      0       0
  77)=  31    1440      185       2       4       1       0       0       0       0       0      52       0     3200      0       0
  78)=  31    1210      185       1       4       2       0       0       0       0       0      92       0     4000      0       0
  79)=  31    1450      186       2       3       1       0       0       0       0       0     124       0     3200      0       0
  80)=  31    1680      186       1       3       2       0       0       0       0       0     122       0     3200      0       0
  81)=  31    1480      187       2       3       1       0       0       0       0       0      55       0     3200      0       0
  82)=  31     900      187       1       3       2       0       0       0       0       0     100       0     1500      0       0
  83)=  31    1490      188       2       3       1       0       0       0       0       0     110       0     3200      0       0
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Hot NOx links with stop weighting of -200 percent

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  84)=  31   1650    188     1      3      2      0      0      0      0      0    122      0   1500      0      0
  85)=  31   1520    189     1      4      2      0      0      0      0      0     82      0   3200      0      0
  86)=  31   1060    189     2      4      1      0      0      0      0      0    100      0   1500      0      0
  87)=  31   2830    193     1      5      2      0      0      0      0      0     88      0   5500      0      0
  88)=  31   1590    193     2      3      1      0      0      0      0      0     50      0   1500      0      0
  89)=  31   1610    194     1     10      2      0      0      0      0      0     96      0   4300      0      0
  90)=  31   1580    194     2     10      1      0      0      0      0      0    100      0   1500      0      0
  91)=  31   1630    195     1      4      2      0      0      0      0      0     52      0   4300      0      0
  92)=  31   1540    195     2      3      1      0      0      0      0      0    108      0   1000      0      0
  93)=  31   1640    196     1      4      2      0      0      0      0      0     80      0   4300      0      0
  94)=  31   1990    196     2      3      1      0      0      0      0      0    188      0   1500      0      0
  95)=  31   1660    197     1      5      2      0      0      0      0      0    112   -200   4300      0      0
  96)=  31   1500    197     2      4      1      0      0      0      0      0    108      0   1500      0      0
  97)=  31   1670    198     1      4      2      0      0      0      0      0     50      0   4300      0      0
  98)=  31   1970    198     2      3      1      0      0      0      0      0    208      0   3000      0      0
  99)=  31   1690    199     1      5      2      0      0      0      0      0    118   -200   4300      0      0
 100)=  31   1460    199     2      4      1      0      0      0      0      0    110      0   4000      0      0
 101)=  31   1700    200     1      7      2      0      0      0      0      0     62      0   5500      0      0
1PROGRAM TRANSYT8     ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200          PAGE   4   RUN ON 30/ 8/1993
 102)=  31   1920    200     2      4      1      0      0      0      0      0    160      0   3000      0      0
 103)=  31   1730    201     1      0      2      0      0      0      0      0    108      0   5500      0      0
 104)=  31   1740    202     1      6      2      0      0      0      0      0     64      0   5500      0      0
 105)=  31   1900    202     2     12      1      0      0      0      0      0    180      0   2400      0      0
 106)=  31   1760    203     1      4      2      0      0      0      0      0     90      0   5500      0      0
 107)=  31   1400    203     2      3      1      0      0      0      0      0    106      0   1800      0      0
 108)=  31   1770    204     1      4      2      0      0      0      0      0     82      0   5500      0      0
 109)=  31   1860    204     2      3      1      0      0      0      0      0    178      0   1800      0      0
 110)=  31   1800    205     1      4      2      0      0      0      0      0    116   -200   5500      0      0
 111)=  31   1360    205     2      3      1      0      0      0      0      0    106      0   1500      0      0
 112)=  31   1810    206     1      7      2      0      0      0      0      0    104   -200   5500      0      0
 113)=  31   1830    227     1      3      2      3      0      0      0      0    130      0   3000      0      0
 114)=  31   1831    227     1      3      2      0      0      0      0      0    130      0   3000      0      0
 115)=  31   2200    227     2      6      1      0      0      0      0      0    240   -150   4000      0      0
 116)=  31   2225    227     2      0      1      1      0      0      0      0    140   -200   4500      0      0
 117)=  31   2215    226     1      4      2      0      0      0      0      0    132   -200   8000      0      0
 118)=  31   2205    226     2      4      3      0      0      0      0      0    138   -150   2500      0      0
 119)=  31   2206    226     2      4      3      0      0      0      0      0    138   -150   4000      0      0
 120)=  31   2170    226     3      4      2      0      0      0      0      0    120      0   1500      0      0
 121)=  31   2171    226     3      4      1      0      0      0      0      0    120      0   4500      0      0
 122)=  31   2190    207     2      0      1      0      0      0      0      0    142   -200   9000      0      0
 123)=  31   1840    208     1      5      2      0      0      0      0      0    114   -200   9000      0      0
 124)=  31   2140    208     2      4      1      0      0      0      0      0    114      0   2800      0      0
 125)=  31   1870    209     1      5      2      0      0      0      0      0     82   -200   9000      0      0
 126)=  31   1780    209     2      4      1      0      0      0      0      0    166      0   2000      0      0
 127)=  31   1880    210     1      5      2      0      0      0      0      0     84   -200   9000      0      0
 128)=  31   2110    210     2      4      1      0      0      0      0      0    114      0   2800      0      0
 129)=  31   1910    211     1      4      2      0      0      0      0      0    182   -200   9000      0      0
 130)=  31   1930    212     1      5      2      0      0      0      0      0     66      0   7500      0      0
 131)=  31   1710    212     2      4      1      0      0      0      0      0    172      0   3800      0      0
 132)=  31   1940    213     1     10      2      0      0      0      0      0     54      0   7500      0      0
 133)=  31   1950    214     1      7      2      0      0      0      0      0     86      0   7500      0      0
 134)=  31   2040    214     2      7      1      0      0      0      0      0    114      0   1800      0      0
 135)=  31   1980    215     1      5      2      0      0      0      0      0    134   -200   7500      0      0
 136)=  31   2010    215     2      3      1      0      0      0      0      0    100      0   1500      0      0
 137)=  31   2000    259     2      7      2      0      0      0      0      0    120   -150   7500      0      0
 138)=  31   2805    259     1      4      1      0      0      0      0      0    156   -200   4000      0      0
 139)=  31   2790    216     2      4      1      0      0      0      0      0    100      0   5000      0      0
 140)=  31   3730    216     1      6      2      0      0      0      0      0     82      0   5000      0      0
 141)=  31   2020    217     1      8      2      0      0      0      0      0    164   -200   5000      0      0
 142)=  31   5800    217     2      4      1      0      0      0      0      0    100      0   1800      0      0
 143)=  31   2050    218     1      8      2      0      0      0      0      0    110      0   5000      0      0
 144)=  31   1960    218     2      4      1      0      0      0      0      0     92      0   2800      0      0
 145)=  31   2060    219     1      7      2      0      0      0      0      0    106   -200   5000      0      0
 146)=  31   5930    219     2     10      1      0      0      0      0      0    100      0   1800      0      0
 147)=  31   2080    220     1      0      2      0      0      0      0      0    118   -200   7000      0      0
 148)=  31   2090    221     1      0      2      0      0      0      0      0     70      0   5000      0      0
 149)=  31   5940    221     2      6      1      0      0      0      0      0    100      0   1800      0      0
 150)=  31   2120    222     1      4      2      0      0      0      0      0     82      0   5000      0      0
 151)=  31   1890    222     2      4      1      0      0      0      0      0    128      0   1600      0      0
1PROGRAM TRANSYT8     ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200          PAGE   5   RUN ON 30/ 8/1993
 152)=  31   2130    223     1     10      2      0      0      0      0      0     72      0   5000      0      0
 153)=  31   2150    224     1      4      2      0      0      0      0      0    116      0   5000      0      0
 154)=  31   1850    224     2      6      1      0      0      0      0      0     98      0   1600      0      0
 155)=  31   2161    225     3      1      2      0      0      0      0      0     48      0   4500      0      0
 156)=  31   2160    225     3     10      1      0      0      0      0      0     48      0   1500      0      0
 157)=  31   2185    225     2      4      3     10      0      0      0      0    100      0   3000      0      0
0                                                   LINK CARDS:   FLOW DATA
                                          ENTRY 1 ............   ENTRY 2 ............   ENTRY 3 ............   ENTRY 4 ............
 CARD   CARD   LINK   TOTAL  UNIFORM   LINK           CRUISE   LINK           CRUISE   LINK           CRUISE   LINK           CRUISE
  NO.   TYPE    NO.    FLOW    FLOW     NO.    FLOW    TIME     NO.    FLOW    TIME     NO.    FLOW    TIME     NO.    FLOW    TIME
 158)=  32    2846    1755      0        0       0      20        0       0       0        0       0       0        0       0       0
 159)=  32    2845     617      0        0       0      20        0       0       0        0       0       0        0       0       0
 160)=  32    2820     300      0     2800     300      15     1620      30      15        0       0       0        0       0       0
 161)=  32    3850    1000      0        0       0      20        0       0       0        0       0       0        0       0       0
 162)=  32    2825    1700      0     2846    1700      15        0       0       0        0       0       0        0       0       0
 163)=  32    2800     300      0     2000     300      25        0       0       0        0       0       0        0       0       0
 164)=  32    1620     156      0     1590     156      25        0       0       0        0       0       0        0       0       0
 165)=  32    2230     945      0        0       0      22        0       0       0        0       0       0        0       0       0
 166)=  32    1820     550      0     1810     550      26        0       0       0        0       0       0        0       0       0
 167)=  32    1330     995      0     2230     945      11     1820      50      11        0       0       0        0       0       0
 168)=  32    1300     307      0        0       0      18        0       0       0        0       0       0        0       0       0
 169)=  32    1340    1302      0     1330     995      18     1300     307      18        0       0       0        0       0       0
 170)=  32    1280     361      0        0       0      18        0       0       0        0       0       0        0       0       0
 171)=  32    1350    1393      0     1340    1157      25     1280     236      25        0       0       0        0       0       0
 172)=  32    1790     302      0     1860     205      18     1770      97      18        0       0       0        0       0       0
 173)=  32    1380    1147      0     1350    1030      13     1790     117      13        0       0       0        0       0       0
 174)=  32    1390     930      0     1380     900      16        0       0       0        0       0       0        0       0       0
 175)=  32    1750     242      0     1900     182      20     1740      60      20        0       0       0        0       0       0
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Hot NOx links with stop weighting of -200 percent

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 176)=  32  1420  1010    0  1390   860  24  1750   150  24     0     0     0     0     0     0
 177)=  32  1720   259    0  1920   159  30  1700   100  30     0     0     0     0     0     0
 178)=  32  1440  1088    0  1420   832   6  1720   256   6     0     0     0     0     0     0
 179)=  32  1210  1094    0     0     0  17     0     0   0     0     0     0     0     0     0
 180)=  32  1450  1059    0  1440   937  19  1210   122  19     0     0     0     0     0     0
 181)=  32  1680  1228    0  1970   545  30  1670   683  30     0     0     0     0     0     0
 182)=  32  1480   820    0  1450   780  10  1680    40  10     0     0     0     0     0     0
 183)=  32   900   222    0     0     0  18     0     0   0     0     0     0     0     0     0
 184)=  32  1490   849    0  1480   754  24   900    95  24     0     0     0     0     0     0
 185)=  32  1650   605    0  1990   445  26  1640   160  26     0     0     0     0     0     0
 186)=  32  1520  1020    0  1490   805  13  1650   214  13     0     0     0     0     0     0
 187)=  32  1060   142    0     0     0  18     0     0   0     0     0     0     0     0     0
 188)=  32  2830  1847    0     0     0  15     0     0   0     0     0     0     0     0     0
 189)=  32  1590   190    0     0     0   9     0     0   0     0     0     0     0     0     0
 190)=  32  1610  1948    0  2830  1847  12  1590   101  12     0     0     0     0     0     0
 191)=  32  1580    22    0     0     0  18     0     0   0     0     0     0     0     0     0
 192)=  32  1630  1970    0  1610  1948   9  1580    22   9     0     0     0     0     0     0
 193)=  32  1540   230    0  1060    95  22  1520   135  22     0     0     0     0     0     0
 194)=  32  1640  2255    0  1630  2025  13  1540   230  13     0     0     0     0     0     0
 195)=  32  1990   530    0  2010   259  30  1980   271  30     0     0     0     0     0     0
 196)=  32  1660  2452    0  1640  2095  14  1990   357  14     0     0     0     0     0     0
1PROGRAM TRANSYT8      ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200               PAGE    6   RUN ON 30/ 8/1993

 197)=  32  1500   192    0   900   127  22  1480    65  22     0     0     0     0     0     0
 198)=  32  1670  2284    0  1660  2091  11  1500   193  11     0     0     0     0     0     0
 199)=  32  1970   597    0  2040   597  32     0     0   0     0     0     0     0     0     0
 200)=  32  1690  1995    0  1670  1601  21  1970   394  21     0     0     0     0     0     0
 201)=  32  1460  1123    0  1210   972  20  1440   151  20     0     0     0     0     0     0
 202)=  32  1700  2015    0  1690  1467   7  1460   548   7     0     0     0     0     0     0
 203)=  32  1920   740    0  1910   740  30     0     0   0     0     0     0     0     0     0
 204)=  32  1730  1960    0  1700  1789  12  1920   171  12     0     0     0     0     0     0
 205)=  32  1740  1823    0  1730  1823  20     0     0   0     0     0     0     0     0     0
 206)=  32  1900   582    0  2110   373  30  1880   209  30     0     0     0     0     0     0
 207)=  32  1760  2003    0  1740  1848  14  1900   155  14     0     0     0     0     0     0
 208)=  32  1400   370    0  1380   250  20     0     0   0     0     0     0     0     0     0
 209)=  32  1770  2100    0  1760  2000   8  1400    67   8     0     0     0     0     0     0
 210)=  32  1860   511    0  2140   231  28  1840   280  28     0     0     0     0     0     0
 211)=  32  1800  2300    0  1770  1903  13  1860   314  13     0     0     0     0     0     0
 212)=  32  1360   260    0  1280   125  22  1340   135  22     0     0     0     0     0     0
 213)=  32  1810  2400    0  1800  2055  10  1360   260  10     0     0     0     0     0     0
 214)=  32  1831   729    0  1810   729  30     0     0   0     0     0     0     0     0     0
 215)=  32  1830   738    0  1810   738  30     0     0   0     0     0     0     0     0     0
 216)=  32  2200  1043    0  2171   560  25  2215   483  25     0     0     0     0     0     0
 217)=  32  2225  2050    0     0     0  25     0     0   0     0     0     0     0     0     0
 218)=  32  2215  2417    0     0     0  24     0     0   0     0     0     0     0     0     0
 219)=  32  2205   824    0  2225   568  22  1831   256  22     0     0     0     0     0     0
 220)=  32  2206   827    0  2225   357  22  1831   470  22     0     0     0     0     0     0
 221)=  32  2170   955    0  2185   567  22  2160   388  22     0     0     0     0     0     0
 222)=  32  2171   500    0  2185   150  22  2160   350  22     0     0     0     0     0     0
 223)=  32  2190  3300    0  2215  1933  23  2205   833  23  2170   370    23     0     0     0
 224)=  32  1840  2955    0  2190  2955  12     0     0   0     0     0     0     0     0     0
 225)=  32  2140   523    0  2130   373  22     0     0   0     0     0     0     0     0     0
 226)=  32  1870  2725    0  1840  2666   9  2140    59   9     0     0     0     0     0     0
 227)=  32  1780   528    0  1400   182  24  1760   346  24     0     0     0     0     0     0
 228)=  32  1880  2861    0  1870  2500  10  1780   361  10     0     0     0     0     0     0
 229)=  32  2110   590    0  5940    10  20  2090   580  20     0     0     0     0     0     0
 230)=  32  1910  2681    0  1880  2475  17  2110   206  17     0     0     0     0     0     0
 231)=  32  1930  1895    0  1910  1895   7     0     0   0     0     0     0     0     0     0
 232)=  32  1710  1099    0  1460   638  30  1690   214  30     0     0     0     0     0     0
 233)=  32  1940  3000    0  1930  1100   8  1710  1895   8     0     0     0     0     0     0
 234)=  32  1950  2200    0  1940  2200   9     0     0   0     0     0     0     0     0     0
 235)=  32  2040   721    0  5800   307  20  2020   414  20     0     0     0     0     0     0
 236)=  32  1980  2165    0  1950  2095  16  2040    70  16     0     0     0     0     0     0
 237)=  32  2010   268    0  3730   258  18  2790    10  18     0     0     0     0     0     0
 238)=  32  2000  1933    0  1980  1883  22  2010    50  22     0     0     0     0     0     0
 239)=  32  2805  2000    0  2825  1733  28  1620   256  28     0     0     0     0     0     0
 240)=  32  2790  2000    0  2805  1624  25  2000   370  25     0     0     0     0     0     0
 241)=  32  3730  1520    0     0     0  25     0     0   0     0     0     0     0     0     0
 242)=  32  2020  2620    0  2790  1360  20  3730  1260  20     0     0     0     0     0     0
 243)=  32  5800   330    0     0     0  25     0     0   0     0     0     0     0     0     0
 244)=  32  2050  2050    0  2020  2021  18  5800    23  18     0     0     0     0     0     0
 245)=  32  1960   850    0  1940   850  25     0     0   0     0     0     0     0     0     0
 246)=  32  2060  2100    0  2050  1725  30  1960   375  30     0     0     0     0     0     0
1PROGRAM TRANSYT8      ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200               PAGE    7   RUN ON 30/ 8/1993

 247)=  32  5930   420    0     0     0  25     0     0   0     0     0     0     0     0     0
 248)=  32  2080  2600    0  2060  2100  25  5930   500  25     0     0     0     0     0     0
 249)=  32  2090  2038    0  2080  2038  20     0     0   0     0     0     0     0     0     0
 250)=  32  5940    50    0     0     0  25     0     0   0     0     0     0     0     0     0
 251)=  32  2120  1500    0  2090  1424  15  5940    50  15     0     0     0     0     0     0
 252)=  32  1890   570    0  1780   352  25  1870   218  25     0     0     0     0     0     0
 253)=  32  2130  2036    0  2120  1474  12  1890   562  12     0     0     0     0     0     0
 254)=  32  2150  1675    0  2130  1625  25     0     0   0     0     0     0     0     0     0
 255)=  32  1850   200    0  2190   180  25     0     0   0     0     0     0     0     0     0
 256)=  32  2161  2000    0  2150  1900  20  1850   200  20     0     0     0     0     0     0
 257)=  32  2160   600    0  2150   600  20  1850    20  20     0     0     0     0     0     0
 258)=  32  2185   667    0     0     0  15     0     0   0     0     0     0     0     0     0
0*****END OF SUBROUTINE TINPUT*****
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Hot NOx links with stop weighting of -200 percent

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1PROGRAM TRANSYT8    ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200          PAGE  20   RUN ON 30/ 8/1993
0       90 SECOND CYCLE  45 STEPS
0 LINK    FLOW    SAT  DEGREE  MEAN TIMES  -------DELAY--------  ----STOPS----  ----QUEUE----  PERFORMANCE  EXIT   GREEN TIMES
 NUMBER   INTO   FLOW    OF     PER PCU    UNIFORM RANDOM+ COST   MEAN   COST   MEAN              INDEX.    NODE   START  START
          LINK           SAT   CRUISE              OVERSAT  OF    STOPS   OF    MAX.  AVERAGE  WEIGHTED SUM            END     END
                                     DELAY (U+R+O=MEAN Q) DELAY   /PCU   STOPS          EXCESS  OF ( ) VALUES           1ST    2ND
        (PCU/H) (PCU/H)  (%)  (SEC) (SEC)    (PCU-H/H)    ($/H)   (%)    ($/H)   (PCU)  (PCU)      ($/H)                (SECONDS)

   900     222   1500    37    18    14     .6 +   .3  (   .5)    72  (   .2)     2                   .7     187    34  51  79   6
  1060     142   1500    47    18    27     .6 +   .4  (   .6)   104  (   .2)     2                   .7     189    84   2  39  47
  1210    1094   4000    68    17    15    3.4 +  1.1  (  2.5)    80  (   .8)    12                  3.3     185     3  20  48  65
  1280    1361   1500    72    18    26    1.3 +  1.3  (  1.4)   104  (   .4)     5                  1.8     180    55  69  10  24
  1300     307   1500    58    18    20    1.0 +   .7  (   .9)    89  (   .3)     4                  1.2     179    43  58  88  13
  1330     995   3200    61    11     4     .4 +   .8  (   .6)    18  (   .3)     5                   .9     179    17  39  62  84
  1340    1302   3200    70    18     7    1.4 +  1.2  (  1.4)    38  (   .8)     7                  2.2     180    72   7  27  52
  1350    1392   3200    72    25     7    1.5 +  1.3  (  1.6)    44  (   .4)    10                  2.0     181     1  27  46  72
  1360     260   1500    43    22    14     .7 +   .4  (   .6)    69  (   .1)     3                   .7     205    75   2  30  47
  1380    1146   3200    50    13     3     .3 +   .5  (   .5)    14  (   .2)     2                   .7     182    11  42  56  87
  1390     929   3200    47    16     3     .4 +   .4  (   .4)    21  (   .2)     3                   .7     183    72   9  27  54
  1400     369   1800    58    20    14     .8 +   .7  (   .8)    74  (   .3)     4                  1.1     203    41  56  86  11
  1420    1007   3200    49    24     7    1.5 +   .5  (  1.1)    54  (   .9)     8                  2.0     184    27  55  72  10
  1440    1084   3200    73     6    10    1.8 +  1.3  (  1.7)    54  (  1.5)     8                  3.2     185    24  44  69  89
  1450    1057   3200    78    19    12    1.7 +  1.8  (  1.9)    63  (   .9)    12                  2.9     186    44  62  89  17
  1460    1121   4000    84    20    17    2.7 +  2.6  (  2.9)    72  (   .8)    14                  3.7     199    65  79  20  34
  1480     818   3200    50    10     3     .2 +   .5  (   .4)    15  (   .1)     2                   .5     187    54  76   9  31
  1490     847   3200    70    24    13    2.0 +  1.2  (  1.7)    86  (   .5)    11                  2.2     188    42  58  87  13
  1500     192   1500    64    22    35    1.0 +   .9  (  1.0)   122  (   .2)     3                  1.2     197    37  45  82   0
  1520    1019   3200    48    13     3     .3 +   .5  (   .4)    14  (   .2)     2                   .6     189    51  80   6  35
  1540     230   1000    74    22    36     .9 +  1.4  (  1.3)   128  (   .2)     4                  1.5     195    37  50  82   5
  1580      22   1500    33    18    82     .3 +   .2  (   .3)   134  (   .0)     1                   .3     194    31  34
  1590     190   1500    63     9    49    1.7 +   .9  (  1.4)   105  (   .2)     5                  1.6     193    14  31
  1610    1948   4300    60    12     3     .8 +   .7  (   .9)    14  (   .6)    13                  1.4     194    44  21
  1620     156   1800    56    25    34     .9 +   .6  (   .8)   113  (   .0)     4                   .9     260    62  75
  1630    1970   4300    79     9     7    2.2 +  1.9  (  2.2)    43  (   .9)    19                  3.2     195     9  34  54  79
  1640    2255   4300    98    13    36    3.1 + 19.5  ( 12.4)   113  (  3.3)    48     +           15.7     196    64  87  19  42
  1650     606   1500    76    26    14     .9 +  1.5  (  1.3)    58  (   .2)     5                  1.6     188    16  39  61  84
  1660    2456   4300    89    14    17    7.8 +  3.9  (  6.4)   100  (  5.1)    33                 -3.9     197     5  33  50  78
  1670    2286   4300    85    11     7    1.8 +  2.9  (  2.6)    33  (   .5)    11                  3.1     198    10  37  55  82
  1680    1230   3200    79    30    14    3.0 +  1.8  (  2.6)    85  (   .5)    16                  3.2     186    20  41  65  86
  1690    1994   4300    91    21    17    4.8 +  4.8  (  5.3)    94  (  2.0)    30                  1.2     199    39  61  84  16
  1700    2015   5500    75     7     9    3.3 +  1.5  (  2.6)    54  (  2.8)    18                  5.4     200     1  22  46  67
  1710    1096   3800    76    30    26    6.3 +  1.6  (  4.3)    76  (   .9)    23                  5.2     212    32  65
  1720     258   1500    65    30    25     .9 +   .9  (  1.0)   103  (   .2)     4                  1.2     184    58  69  13  24
  1730    1960   5500    45    12     1     .1 +   .4  (   .3)     4  (   .2)     1                   .5     201    56   1  11  46
  1740    1823   5500    88    20    18    5.8 +  3.5  (  5.1)   107  (   .6)    26                  5.7     202    47  63   2  18
  1750     240   1500    55    20    19     .6 +   .6  (   .7)    90  (   .3)     3                  1.0     183    12  24  57  69
  1760    2003   5500    68    14     3     .8 +  1.1  (  1.1)    19  (   .5)     8                  1.6     203    15  38  60  83
  1770    2099   5500    72     8     3     .6 +  1.3  (  1.0)    12  (   .9)     4                  1.9     204    21  44  66  89
  1780     526   2000    48    24    15    1.8 +   .5  (  1.2)    57  (   .5)     8                  1.7     209    71  29
  1790     300   1500    64    18    22    1.0 +   .9  (  1.0)   101  (   .4)     4                  1.5     181    75  88  30  43
  1800    2295   5500    85    13    18    8.7 +  2.9  (  6.4)   102  (  6.4)    31                 -6.5     205    51  72   6  27
  1810    2395   5500    69    10    11    6.0 +  1.1  (  3.9)    53  (  4.7)    32                 -5.4     206    34   0
  1820     551   2000    65    26    19    1.9 +   .9  (  1.6)    96  (   .5)    10                  2.0     178    32  50  77   5
  1830     738   3000    58    30    12    1.8 +   .7  (  1.4)    59  (   .3)    12                  1.6     227    80  27
  1831     728   3000    62    30    14    2.1 +   .8  (  1.6)    64  (   .3)    13                  1.9     227    80  24
  1840    2927<  9000    75    12    15   11.1 +  1.5  (  6.9)    81  (  7.5)    66                 -8.0     208    13  51
  1850     196   1600    55    25    33    1.2 +   .6  (  1.0)    94  (   .1)     5                  1.1     224    36  55
  1860     505   1800    79    28    24    1.5 +  1.8  (  1.9)    99  (   .7)     8                  2.5     204    47  62   2  17
  1870    2698<  9000    79     9    12    7.1 +  1.9  (  5.0)    88  (  6.6)    68                 -8.2     209    34  67
  1880    2837<  9000    79    10    13    8.4 +  1.9  (  5.7)    86  (  6.0)    70                 -6.3     210    51  86
  1890     566   1600    74    25    22    2.1 +  1.4  (  1.9)    66  (   .3)    10                  2.3     222    75  27
  1900     582   2400    91    30    45    2.5 +  4.7  (  4.0)   141  (  1.0)    13                  4.9     202    75  86  30  41
1PROGRAM TRANSYT8      ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200          PAGE  21   RUN ON 30/ 8/1993
0       90 SECOND CYCLE  45 STEPS
0 LINK    FLOW    SAT  DEGREE  MEAN TIMES  -------DELAY--------  ----STOPS----  ----QUEUE----  PERFORMANCE  EXIT   GREEN TIMES
 NUMBER   INTO   FLOW    OF     PER PCU    UNIFORM RANDOM+ COST   MEAN   COST   MEAN              INDEX.    NODE   START  START
          LINK           SAT   CRUISE              OVERSAT  OF    STOPS   OF    MAX.  AVERAGE  WEIGHTED SUM            END     END
                                     DELAY (U+R+O=MEAN Q) DELAY   /PCU   STOPS          EXCESS  OF ( ) VALUES           1ST    2ND
        (PCU/H) (PCU/H)  (%)  (SEC) (SEC)    (PCU-H/H)    ($/H)   (%)    ($/H)   (PCU)  (PCU)      ($/H)                (SECONDS)

  1910    2663<  9000    72    17    15    9.4 +  1.3  (  5.9)    92  (  9.5)    65                -13.2     211    83  29
  1920     735   3000    79    30    21    2.5 +  1.8  (  2.4)    81  (   .6)    10                  3.0     200    26  39  71  84
  1930    1880<  7500    46     7     3    1.0 +   .4  (   .8)     6  (   .3)     3                  1.1     212    70  28
  1940    2988<  7500    51     8     5    3.4 +   .5  (  2.2)    34  (  1.6)    33                  3.7     213    29   8
  1950    2193   7500    71     9     8    3.5 +  1.2  (  2.6)    29  (  2.0)    23                  4.6     214    40  76
  1960     849   2800    80    25    20    2.7 +  2.0  (  2.6)    95  (   .4)    21                  3.0     218    68  11
  1970     597   3000    75    32    23    2.3 +  1.5  (  2.1)   102  (   .9)    12                  2.9     198    40  51  85   6
  1980    2158   7500    55    16    10    5.5 +   .6  (  3.3)    83  (  4.3)    51                 -5.4     215    67  23
  1990     533   1500   100    30   126    2.4 + 16.2  ( 10.3)   224  (  1.5)    23                 11.8     196     0  15  45  60
  2000    1928   7500    28    22     0     .0 +   .2  (   .1)     1  (   .0)     0                   .1     259    73  66
  2010     270   1500    44    18    11     .4 +   .4  (   .4)    58  (   .2)     5                   .6     215    26  62
  2020    2618   5000    86    20    19   10.8 +  3.0  (  7.6)    84  (  5.0)    63                 -2.3     217     1  55
  2040     721   1800    88    20    41    4.7 +  3.5  (  4.5)   105  (   .8)    20     +            5.3     214    83  33
  2050    2049   5000    80    18     8    2.5 +  2.0  (  2.5)    26  (   .7)    20                  3.2     218    19  64
  2060    2101   5000    79    30    13    5.5 +  1.8  (  4.0)    67  (   .5)    40                  3.0     219    51   8
  2080    2600   7000    41    25     2    1.0 +   .4  (   .7)    20  (   .3)    16                   .0     220    19   9
  2090    2039   5000    47    20     1     .3 +   .4  (   .4)     8  (   .1)     5                   .5     221     3  80
  2110     589   2800    40    20    17    2.4 +   .3  (  1.5)    56  (   .4)     9                  1.8     210     0  46
  2120    1502   5000    66    15    16    5.5 +  1.0  (  3.6)    67  (  1.0)    27                  4.5     222    31  71
  2130    2034   5000    52    12     2     .6 +   .5  (   .6)    10  (   .2)     6                   .9     223    39  19
  2140     521   2800    38    22    11    1.2 +   .3  (   .8)    30  (   .1)     4                  1.0     208    55   8
  2150    1672   5000    49    25     4    1.2 +   .5  (   .9)    14  (   .2)     6                  1.1     224    59  30
  2160     597   1500    75    20    17    1.4 +  1.5  (  1.6)    42  (   .0)     7                  1.6     225    70  27
  2161    1992   4500    59    20     4    1.3 +   .7  (  1.1)    19  (   .1)    10                  1.2     225    61  37
  2170     953   1500   104    22   191    4.2 + 46.4  ( 27.8)   206  (  1.9)    71     +           29.7     226    35  89
  2171     498   4500    77    22    43    4.3 +  1.6  (  3.3)   104  (   .5)    14                  3.8     226    35  47
  2185     667   3000    67    15    31    4.8 +  1.0  (  3.2)    87  (   .9)    15                  4.1     225    41  70
  2190    3266<  9000    48    23     5    4.4 +   .5  (  2.7)    51  (  2.2)    50                 -1.7     207    83  60
  2200    1041   4000    49    25    16    4.3 +   .5  (  2.6)    48  (  1.5)    13                   .3     227    30  77
  2205     826   2500   103    22   177    7.5 + 33.1  ( 22.3)   206  (  2.2)    54     +           19.0     226     3  31
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Hot NOx links with stop weighting of -200 percent

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  2206     826   4000      64    22    26   5.1 +  .9  ( 3.3)   67  (  .7)      14                        2.2   226     3  31
  2215    2417   8000      70    24    22  13.9 + 1.2  ( 8.3)   78  ( 1.8)      49                        4.6   226    51  89
  2225    2050   4500      75    25    15   7.1 + 1.5  ( 4.7)   67  ( 1.5)      37                        1.8   227    24  78
  2230     945   3200      63    22    12   2.4 +  .9  ( 1.8)   72  (  .7)      10                        2.4   178     8  28   53   73
  2790    1999   5000      80    25    15   6.3 + 2.0  ( 4.5)   64  (  .7)      37                        5.2   216    39  83
  2800     301   1800      25    25     7    .5 +  .2  (  .3)   27  (  .1)       2                         .4   260    79  48
  2805    2001   4000      52    28     2    .7 +  .5  (  .7)   30  (  .6)      26                        -.6   259    27  23
  2820     301   1800      84    15    60   2.6 + 2.4  ( 2.8)  126  (  .8)      10                        3.6   261    61  78
  2825    1699   5000      48    15     3   1.1 +  .5  (  .9)   37  (  .4)      22                        1.3   260    85  58
  2830    1847   5500      46    15     6   2.5 +  .4  ( 1.6)   35  (  .8)      19                        2.4   193    36  11
  2845     617   1600      89    20    46   4.0 + 3.8  ( 4.3)  112  (  .1)      18        +               4.5   261    84  32
  2846    1755   3500      76    20    14   5.2 + 1.6  ( 3.8)   68  (  .3)      32        +               4.0   261    61  29
  3730    1520   5000      74    25    26   9.5 + 1.4  ( 6.0)   84  (  .4)      34                        6.4   216    89  35
  3850    1000   5000      86    20    44   9.2 + 2.9  ( 6.7)  103  ( 1.2)      27                        7.9   261    36  56
  5800     330   1800      66    25    39   2.6 + 1.0  ( 2.0)   96  (  .2)       8                        2.1   217    59  83
  5930     420   1800      78    25    44   3.4 + 1.7  ( 2.8)  103  (  .2)      11                        3.0   219    18  44
  5940      50   1800      31    25    55    .5 +  .2  (  .4)  109  (  .0)       1                         .4   221    86   3
1PROGRAM TRANSYT8     ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200              PAGE  22   RUN ON 30/ 8/1993
0      90 SECOND CYCLE  45 STEPS
0  TOTAL         TOTAL      MEAN          TOTAL    TOTAL     TOTAL        TOTAL          PENALTY       TOTAL
  DISTANCE        TIME     JOURNEY       UNIFORM  RANDOM+     COST         COST            FOR      PERFORMANCE
 TRAVELLED       SPENT      SPEED         DELAY   OVERSAT      OF           OF            EXCESS       INDEX
                                                   DELAY     DELAY        STOPS           QUEUES
 (PCU-KM/H)     (PCU-H/H)  (KM/H)      (PCU-H/H) (PCU-H/H)   ($/H)        ($/H)           ($/H)        ($/H)
0 13281.2        1167.7      11.4        304.8    239.2     ( 299.2) + (   -88.6)  + (      .0)   =    210.6      TOTALS
0**************************************************************************************************************************************
*
0                                  CRUISE            DELAY                     STOPS              TOTALS
                               LITRES PER HOUR   LITRES PER HOUR         LITRES PER HOUR     LITRES PER HOUR
0FUEL CONSUMPTION PREDICTIONS      1243.4      +      761.6        +        330.3        =      2335.3
0
 NO. OF ENTRIES TO SUBPT:     147
 NO. OF LINKS RECALCULATED: 2865
 SYSTEM TIME:          19:26: 0

 EXECUTION TIME:    474 SECONDS
 PROGRAM TRANSYT8 FINISHED
```

Appendix C
PREMIT EMISSIONS DATA

The predictions of the PREMIT emissions model are included in this appendix. Files have been included for emissions corresponding to the scenarios included in the TRANSYT Data appendix.

These files contain three components:

- header;
- link data; and
- network totals.

The header contains the name and version of the program, the time the results were generated by PREMIT, the title of the scenario and the driving modes modelled. The line following "Emissions based on:" corresponds to the scenario title included in the TRANSYT file. The following line is a title specified at PREMIT run time and also indicates the name of a control file, used to define which files were used in the run.

The driving modes modelled are also reported in the header. The default is to model all modes, namely cruise, acceleration, deceleration and idling. The link and total network emissions are derived by adding emissions from each mode modelled. It is possible to specify any combination of driving modes, or even just one driving mode.

The link data in the emissions file lists, for each uni-directional road segment between two nodes, the node numbers, total delay, number of vehicles in the queue, mean stops per pcu, average speed and emission rates, in grams per minute, for each pollutant.

The total delay and number of vehicles in the queue are derived by adding up the corresponding values on each TRANSYT link representing a particular segment of road. The mean stops per pcu and average speed are derived by obtaining the average of the corresponding values on each TRANSYT link. Although the average is derived by weighting link values by the corresponding link flow. These weighted values are then totalled and divided by the total flow on the segment of road.

Average speed is derived by dividing the link length by the total journey time over the link. Hence, this does not represent a cruise speed as such, because it includes the time spent idling.

The delay, queue, stops and average speed columns were, primarily, provided for feedback to the assignment model in the PREDICT model suite.

The end of the file contains the total network emissions of each pollutant in grams per minute.

Base Case Scenario

```
PREMIT EMISSIONS MODEL  Version 3.07
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Run time: 19 Jul 93 20:56
Emissions based on:
ATHENS * CENTRAL ARTERIES * Optimisation ON
BASECASE.ctl ** BASE CASE **
Modes modelled are: cruising acceleration deceleration idling

  A      B    total    number of      mean     average    Carbon     Hydrocarbons   Nitrogen
 node   node  delay   vehicles in     stops     speed     Monoxide   (THC)          Oxides
                       the queue     per PCU              (CO)                      (NOx)
             (PCU-h/h)   (PCU)         (%)      (km/h)    (g/min)    (g/min)        (g/min)

 151    187     0.9       2           72       11     15.76        1.68          0.71
 160    189     1.0       2          104        8     13.05        1.38          0.47
 171    185     4.5      12           80       10     76.62        7.95          3.10
 175    180     2.6       5          104        7     32.33        3.44          1.10
 176    179     1.7       4           89        9     24.83        2.59          0.95
 178    179     1.2       4           18       17     33.65        3.76          2.31
 179    180     2.6       7           38       17     75.80        8.18          4.89
 180    181     3.0       9           45       12     86.98       10.43          5.08
 180    205     2.0       4          111        7     24.83        2.77          0.92
 181    182     0.9       3           16       17     38.83        4.53          2.88
 182    183     1.0       3           23       16     39.32        4.60          2.78
 182    203     1.6       4           84       10     28.33        2.98          1.21
 183    184     1.9       6           40       20     73.09        7.87          5.24
 184    185     3.7      10           61       10     62.03        5.68          2.12
 185    186     3.5      11           58       14     73.42        7.76          3.89
 185    199     7.1      18          101        9     99.93       10.53          3.70
 186    187     0.8       2           13       14     21.69        2.67          1.45
 187    188     2.9       9           72       10     61.44        6.92          2.96
 187    197     2.1       3          123        6     21.25        2.49          0.74
 188    189     0.8       3           15       17     34.52        4.06          2.60
 189    195     2.2       4          125        6     23.93        2.75          0.85
 191    194     0.7       1          153        2      4.31        0.57          0.11
 192    193     2.4       5          101        3     18.35        2.05          0.35
 193    194     1.4      23           15       22     68.72        7.27          5.51
 193    260     1.4       5          114        3     12.77        1.66          0.39
 194    195     4.1      19           43       11     72.85        7.38          2.94
 195    196    22.6      47          108        5    198.28       20.79          3.90
 196    188     2.3       6           60       10     45.42        5.39          2.35
 196    197     4.3      14           30       19    121.54       12.56          8.11
 197    198     3.7      18           39       10     77.96        8.42          3.48
 198    186     5.7      17           93        9    103.21       11.71          4.52
 198    199     7.3      25           73       12    143.07       15.12          6.68
 199    200     5.8      19           60       12    111.99       10.05          4.12
 199    212     8.5      24           79       10    118.39       13.85          5.78
 200    184     1.4       3           83        9     24.81        2.90          1.20
 200    201     0.5       2            4       29     62.22        6.86          6.45
 201    202     7.5      25           90        6    108.29       12.42          3.68
 202    183     1.3       3           69       11     20.17        2.18          0.96
 202    203     2.0       9           19       18     76.40        8.70          5.56
 203    204     1.9       5           12       26     65.82        6.86          5.47
 203    209     4.0      11           81       11     54.44        5.94          2.48
 204    181     2.0       5          105        9     28.14        2.85          1.02
 204    205     2.2       8           21       24    101.02       10.23          7.97
 205    206     1.2       8           10       30     79.48        8.44          7.67
 206    178     2.3       7           90       11     46.35        4.96          2.11
 206    227    10.3      30           78        8    139.28       16.84          6.17
 207    208     3.9      17           19       24    129.29       13.35         10.14
 207    224     1.9       5           93        5     19.38        2.34          0.68
 208    204     3.7       8          111       11     57.48        6.20          2.63
 208    209     5.7      21           22       17    109.35       11.42          6.86
 209    210     3.8      11           16       20     99.32       10.51          7.22
 209    222     3.1      10           59       10     45.36        5.40          2.21
 210    202     8.5      14          146        7     84.65       10.11          3.40
 210    211     0.4       1            1       38    115.84       14.01         14.86
 211    200     5.1      15          105       10     79.08        8.78          3.54
 211    212     2.6      21           36       19     79.30        7.05          4.11
 212    213     5.9      40           47       12    118.99       11.12          4.65
 213    214     9.4      30           50       12    145.34       13.96          6.16
 213    218     7.1      22          102        5     73.04        8.58          2.30
 214    198     5.9      13          108       10     80.30        8.97          3.79
 214    215     1.0       2            4       26     88.72        9.77          8.83
 215    196    18.4      23          227        4    116.40       15.34          3.25
 215    259     0.2       1            1       19     79.61       10.82          7.29
 216    215     0.7       2           22       13     13.45        1.68          0.87
 216    217     7.0      44           49       19    185.05       18.59         11.50
 217    214     6.3      18           96        7     64.80        6.99          1.92
```

Base Case Scenario

```
217  218   7.4    34          50      12  126.66    13.88          6.38
218  219   6.3    34          52       8  137.00    17.68          6.88
219  220   0.5     3           3      15  120.33    16.57          9.95
220  221   1.5    23          35      10   80.31    10.11          4.45
221  210   4.1    14          89       9   52.53     5.71          2.01
221  222   5.8    21          47       9   83.27     9.51          3.79
222  223   1.0     5           8      18   55.98     6.98          4.57
223  208   3.8    11          71       8   45.85     5.41          1.94
223  224   1.6     8          15      14   86.33    11.38          6.32
224  225   4.1    17          24       6   89.05    13.24          4.48
225  226  71.4    99         185       3  369.82    51.41          7.04
226  207   1.2    26          16      21  167.09    20.08         14.24
226  227   1.1     4          11      29   74.07     8.29          7.64
227  226  32.4    58         130       6  243.93    29.87          7.24
228  178   3.3    10          72      12   69.39     7.50          3.39
228  227   7.6    35          63      13  153.46    17.10          8.10
259  216   6.2    32          55       9  122.39    14.57          6.03
259  260   0.6     2          27      17   19.83     2.37          1.47
260  259   0.5     1           2      19  104.40    14.03          9.74
260  261   5.3    10         126       5   41.30     4.79          1.09
261  193   3.1    19          37      15   84.44     9.23          4.89
261  260   0.8    12          16      14   53.44     6.68          3.69
262  261  14.6    49          79       4  120.91    14.90          2.98
331  216  15.4    39         100       4  131.24    16.33          3.64
338  261  12.1    27         102       6  114.13    12.98          3.66
463  217   5.4    10         118       4   40.76     5.16          1.17
470  219   5.6    12         108       4   45.71     5.62          1.33
471  221   1.0     2         119       3    7.34     0.96          0.22
473  225   6.0    16          89       7   62.26     6.65          1.93
491  226  16.4    51          81       9  219.25    24.81          9.33


Total pollution emission rates for this network (g/min) :

         Carbon Monoxide (CO) :                 7772.1
         Hydrocarbons (THC) :                    889.8
         Nitrogen Oxides (NOx) :                 404.7
```

Delay:stop weighting ratio of 0.01

```
PREMIT EMISSIONS MODEL Version 3.07
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Run time: 30 Jul 93 21:06
Emissions based on:
ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 0.01
codelstl.ctl Delay:stop ratio 0.01
Modes modelled are: cruising acceleration deceleration idling

  A     B    total   number of     mean    average   Carbon     Hydrocarbons  Nitrogen
node  node   delay  vehicles in   stops    speed    Monoxide   (THC)         Oxides
                     the queue   per PCU            (CO)                     (NOx)
           (PCU-h/h)   (PCU)       (%)     (km/h)   (g/min)    (g/min)       (g/min)

 151   187    1.1       2          79       10      17.06       1.82          0.71
 160   189    1.3       2         112        7      14.30       1.57          0.49
 171   185    4.5      12          80       10      76.62       7.95          3.10
 175   180    3.1       6         115        7      34.11       3.72          1.11
 176   179    2.1       4         100        8      27.46       2.87          0.96
 178   179    0.8       3          12       18      30.00       3.45          2.30
 179   180    2.1       7          34       18      71.96       7.80          4.88
 180   181    4.7      13          69       10      99.87      11.34          4.90
 180   205    4.4       6         166        4      34.37       4.26          1.03
 181   182    0.8       3          13       19      37.22       4.43          2.88
 182   183    0.8       3          18       17      36.95       4.42          2.77
 182   203    1.6       5          89       10      28.50       2.94          1.17
 183   184    1.6       5          37       20      70.79       7.65          5.24
 184   185    3.8      10          62        9      62.65       5.75          2.12
 185   186    2.5       8          41       15      64.05       7.04          3.96
 185   199    6.9      12          78        9      94.20      10.54          3.96
 186   187    0.6       1          11       14      20.27       2.52          1.43
 187   188    2.0       7          56       11      54.69       6.33          2.98
 187   197    3.1       4         153        4      25.25       3.12          0.79
 188   189    0.6       1          10       19      29.95       3.64          2.42
 189   195    2.0       4         117        6      22.46       2.57          0.81
 191   194    1.2       1         207        1       6.40       0.89          0.14
 192   193    2.8       5         109        2      20.02       2.31          0.38
 193   194    1.4      10          12       22      67.64       7.31          5.65
 193   260    3.6       7         157        2      21.54       3.02          0.50
 194   195    4.2      19          42       10      72.74       7.44          2.96
 195   196    2.3       9          18       16      78.51       9.11          5.55
 196   188    1.5       3          41       10      29.23       3.67          1.66
 196   197    2.8      10          22       21     102.67      10.80          7.68
 197   198    4.2      18          42        9      77.52       8.37          3.27
 198   186    6.8      19          95        8     104.26      11.97          4.33
 198   199    8.1      24          74       11     141.61      15.17          6.44
 199   200    4.2      14          45       14      89.20       8.19          3.89
 199   212   12.9      27          97        8     139.68      16.49          5.76
 200   184    1.4       3          92        9      25.00       2.87          1.18
 200   201    0.5       2           4       29      60.14       6.64          6.22
 201   202   12.0      27         112        5     125.71      14.82          3.70
 202   183    1.3       2          69       11      20.11       2.18          0.96
 202   203    2.4       9          22       17      77.77       8.78          5.39
 203   204    1.6       3          10       26      60.14       6.38          5.27
 203   209    4.0      11          82       11      53.79       5.87          2.43
 204   181    1.4       3          69       11      22.93       2.42          1.06
 204   205    1.4       6          15       27      89.59       9.28          7.79
 205   206    1.1       7          10       30      77.23       8.18          7.47
 206   178    1.9       6          76       12      42.41       4.67          2.12
 206   227   17.0      40         103        6     166.87      20.37          6.00
 207   208    3.2      12          15       25     120.12      12.66         10.13
 207   224    3.0       6         117        4      23.98       3.02          0.73
 208   204    3.5       8         108       11      56.40       6.05          2.60
 208   209    6.0      16          21       17     108.89      11.53          6.85
 209   210    5.3      14          19       17     107.74      11.51          7.19
 209   222    3.4      13          84        9      47.76       5.32          1.97
 210   202    5.1      10         108       10      71.23       8.01          3.27
 210   211    0.4       1           1       38     114.95      13.90         14.74
 211   200    5.8      14         114        9      81.84       9.23          3.58
 211   212    3.5      11          22       16      68.65       6.96          4.08
 212   213    2.3      14          17       17      74.56       7.96          4.84
 213   214    6.7      18          28       15     107.66      11.12          6.01
 213   218   13.0      24         103        4      96.23      12.23          2.59
 214   198    4.5      12          94       12      73.55       8.07          3.74
 214   215    0.7       2           4       28      86.57       9.48          8.72
 215   196  240.2     245         257        0    1025.68     157.23         16.03
 215   259    0.3       3           4       18      80.89      10.81          7.21
 216   215    2.0       7         106        8      24.13       2.53          0.79
 216   217    5.6      28          34       20     172.09      17.94         12.39
 217   214    9.8      22         117        5      77.50       8.92          1.87
```

Delay:stop weighting ratio of 0.01

```
217  218    6.3   20      35      13   117.11   13.53        6.88
218  219   10.0   48      86       7   149.17   17.68        5.74
219  220    0.5    2       3      15   120.07   16.54        9.93
220  221    1.0   16      20      10    75.04   10.14        4.67
221  210    2.4    9      55      11    40.81    4.65        2.09
221  222    7.0   19      47       9    88.51   10.33        3.90
222  223    0.8    3       6      18    53.65    6.78        4.55
223  208    5.5   10      77       6    53.71    6.52        2.04
223  224    0.9    6      10      14    80.98   10.85        6.26
224  225    8.1   28      40       5   104.27   14.71        4.23
225  226  100.2  127     198       3   488.61   70.07        8.92
226  207    0.9   17      11      21   160.35   19.72       14.26
226  227    0.5    1       4      31    67.72    7.75        7.61
227  226   19.3   44     105       7   191.80   21.83        6.79
228  178    4.0   11      81      11    74.24    7.94        3.36
228  227    4.1   25      43      15   132.08   15.28        8.52
259  216    5.1   24      41      10   115.91   14.37        6.37
259  260    0.6    4      46      17    21.24    2.37        1.41
260  259    0.5    1       1      19   103.77   14.02        9.74
260  261    3.3    5      66       7    30.51    3.51        1.15
261  193    2.7   18      34      15    81.30    8.96        4.91
261  260    1.0    3       8      14    51.47    6.83        3.79
262  261   21.3   56      90       4   147.13   18.88        3.25
331  216   20.2   44     113       3   148.25   18.98        3.73
338  261   11.1   25      98       7   109.97   12.40        3.66
463  217    7.9   13     144       3    50.18    6.64        1.25
470  219    4.4   11      97       5    40.96    4.91        1.30
471  221    1.0    2     120       3     7.34    0.96        0.22
473  225    4.5   13      76       9    54.11    5.71        1.96
491  226   18.8   56      87       8   230.69   26.09        9.19


Total pollution emission rates for this network (g/min) :

         Carbon Monoxide (CO) :               8536.8
         Hydrocarbons (THC) :                 1036.3
         Nitrogen Oxides (NOx) :               418.8
```

PAGE
MISSING
IN
ORIGINAL

Delay:stop weighting ratio of 100

```
PREMIT EMISSIONS MODEL  Version 3.07
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Run time: 30 Jul 93 21:17
Emissions based on:
ATHENS * Central Arteries * Opt on; DELAY:STOP WEIGHTS = 100
codelst4.ctl Delay:stop ratio 100
Modes modelled are: cruising acceleration deceleration idling

 A     B      total    number of      mean     average    Carbon     Hydrocarbons  Nitrogen
node  node    delay   vehicles in    stops     speed     Monoxide   (THC)          Oxides
                       the queue    per PCU               (CO)                     (NOx)
           (PCU-h/h)    (PCU)        (%)      (km/h)     (g/min)    (g/min)        (g/min)

 151   187     0.8        2          69         11        15.14       1.61          0.70
 160   189     1.0        2          97          8        12.92       1.37          0.47
 171   185     4.5       12          80         10        76.62       7.95          3.10
 175   180     2.2        5          97          8        30.38       3.17          1.08
 176   179     1.7        4          89          9        24.83       2.59          0.95
 178   179     1.3        9          27         17        36.52       3.85          2.22
 179   180     2.9       10          43         16        78.49       8.35          4.81
 180   181     2.7       11          47         12        85.75      10.16          5.00
 180   205     2.1        4         113          7        25.25       2.84          0.92
 181   182     0.8        3          15         17        38.05       4.46          2.88
 182   183     1.1        6          35         16        42.84       4.71          2.72
 182   203     1.7        4          74         10        27.74       3.03          1.23
 183   184     2.4       10          68         18        83.43       8.34          5.02
 184   185     2.8       13          53         12        54.19       4.89          2.04
 185   186     3.4       11          55         14        72.06       7.68          3.90
 185   199     7.5       18         111          8       101.60      10.79          3.73
 186   187     0.8        3          17         13        22.61       2.69          1.44
 187   188     3.1       10          83         10        64.09       7.02          2.91
 187   197     2.1        4         127          6        21.08       2.47          0.73
 188   189     0.9        4          20         17        36.50       4.16          2.58
 189   195     2.2        4         124          6        23.93       2.75          0.85
 191   194     0.5        1         134          3         3.48       0.44          0.10
 192   193     2.6        5         105          3        19.19       2.18          0.37
 193   194     1.5       13          14         22        69.18       7.39          5.61
 193   260     1.2        4         109          4        12.14       1.57          0.39
 194   195     4.1       19          43         11        72.85       7.38          2.94
 195   196    22.7       49         106          5       197.52      20.70          3.79
 196   188     2.3        6          62         10        45.68       5.39          2.35
 196   197     4.3       14          31         19       122.35      12.59          8.09
 197   198     3.9       20          45         10        81.10       8.46          3.36
 198   186     5.3       17          90          9       100.95      11.47          4.52
 198   199     7.3       23          71         12       142.83      15.22          6.79
 199   200     5.8       19          61         12       112.88      10.09          4.12
 199   212     7.9       25          83         10       116.75      13.43          5.68
 200   184     1.4        4          83          9        24.61       2.88          1.19
 200   201     0.5        2           4         29        62.22       6.86          6.45
 201   202     7.6       25          91          6       108.95      12.48          3.67
 202   183     1.1        3          88         12        20.78       2.09          0.93
 202   203     1.9       15          24         18        78.66       8.66          5.45
 203   204     2.2       20          19         24        76.58       7.47          5.54
 203   209     4.1       11          80         11        54.72       6.00          2.49
 204   181     2.0        4         103         10        28.37       2.88          1.05
 204   205     2.2       15          25         24       104.25      10.30          7.83
 205   206     1.1        7           8         30        75.94       8.26          7.66
 206   178     2.1        7          82         11        44.49       4.83          2.13
 206   227    11.0       33          84          8       142.93      17.14          6.09
 207   208     8.1       50          55         18       193.54      17.23          9.12
 207   224     1.7        5          87          6        18.31       2.21          0.68
 208   204     3.1        8         103         12        54.98       5.81          2.59
 208   209     1.8       14          10         26        78.89       8.35          6.76
 209   210     3.6       21          18         20        99.92      10.39          7.11
 209   222     3.2        8          55         10        45.85       5.55          2.29
 210   202     8.0       14         152          8        82.57       9.78          3.37
 210   211     0.4        4           3         38       119.46      14.13         14.85
 211   200     3.9       14          99         11        74.21       8.04          3.49
 211   212     2.3       16          25         21        67.08       6.35          4.05
 212   213     3.0       46          45         16       104.97       9.18          4.50
 213   214    12.1       51          84         10       196.06      17.28          6.20
 213   218     7.3       22         101          5        73.87       8.71          2.31
 214   198     4.8       11         101         12        76.17       8.32          3.77
 214   215     1.0        3           4         26        88.70       9.77          8.83
 215   196    18.1       24         226          4       114.66      15.08          3.18
 215   259     0.2        0           1         19        79.61      10.82          7.29
 216   215     0.9        5          60         11        16.99       1.83          0.82
 216   217     8.0       46          61         18       196.72      19.24         10.99
 217   214     5.9       18          95          8        63.01       6.74          1.90
```

Delay:stop weighting ratio of 100

```
217  218   6.8   41       67      13   130.15   13.13        5.72
218  219   6.9   38       55       8   138.35   17.73        6.73
219  220   0.5    3        3      15   120.33   16.57        9.95
220  221   1.4   22       31      10    79.04   10.14        4.51
221  210   4.8   14       91       8    55.75    6.16        2.05
221  222   6.2   27       57       9    87.22    9.59        3.59
222  223   1.2    6       11      18    58.67    7.15        4.56
223  208   2.6    6       44      10    37.87    4.67        1.98
223  224   1.7    7       16      13    87.24   11.47        6.33
224  225   3.7   13       19       6    88.20   13.40        4.64
225  226  71.2   98      184       3   368.99   51.28        7.03
226  207   0.6    4        4      21   153.19   19.50       14.45
226  227   1.0   11       26      30    81.13    8.46        7.51
227  226  31.5   58      130       6   240.18   29.29        7.18
228  178   3.3   10       72      12    69.39    7.50        3.39
228  227   6.7   33       59      13   148.53   16.63        8.19
259  216   7.2   31       57       9   127.50   15.24        6.09
259  260   0.6    2       24      17    19.54    2.36        1.47
260  259   0.5    1        1      19   103.77   14.02        9.74
260  261   5.2   10      126       5    40.88    4.73        1.08
261  193   2.9   19       35      15    82.54    9.08        4.90
261  260   0.8   11       16      14    53.53    6.69        3.70
262  261  14.6   50       79       4   120.13   14.77        2.93
331  216  13.3   36       93       5   123.62   15.42        3.74
338  261  12.1   27      103       6   114.13   12.98        3.66
463  217   4.8    9      111       4    38.59    4.81        1.15
470  219   5.1   11      103       5    44.05    5.35        1.33
471  221   1.0    2      120       3     7.34    0.96        0.22
473  225   6.3   16       91       7    63.89    6.85        1.93
491  226  16.4   51       81       9   219.25   24.81        9.33


Total pollution emission rates for this network (g/min) :

         Carbon Monoxide (CO) :                  7842.0
         Hydrocarbons (THC) :                     886.6
         Nitrogen Oxides (NOx) :                  401.0
```

Cycle time of 140 seconds

```
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Run time: 31 Jul 93 18:04
Emissions based on:
ATHENS * Central Arteries * Opt on; CYCLE TIME = 140 with 60 steps
cocyc.ctl Cruise time 140
Modes modelled are: cruising acceleration deceleration idling
  A     B     total    number of      mean      average    Carbon      Hydrocarbons    Nitrogen
 node  node   delay   vehicles in       stops    speed     Monoxide    (THC)           Oxides
                       the queue     per PCU               (CO)                        (NOx)
            (PCU-h/h)     (PCU)         (%)      (km/h)    (g/min)     (g/min)         (g/min)

 151   187         0.9       3            63          10     15.05        1.65            0.70
 160   189         1.3       3            92           7     13.85        1.55            0.48
 171   185         5.7      17            76           9     79.26        8.55            3.08
 175   180         2.9       7            92           7     32.26        3.55            1.09
 176   179         2.0       5            80           8     25.09        2.75            0.96
 178   179         1.1       3            12          17     31.30        3.65            2.33
 179   180         3.0      11            35          16     75.53        8.32            4.86
 180   181         2.7      10            30          12     80.73       10.17            5.12
 180   205         2.9       6           109           6     28.11        3.29            0.93
 181   182         0.5       2             6          19     33.51        4.17            2.89
 182   183         1.7       7            34          14     44.94        5.07            2.75
 182   203         1.7       6            77          10     27.57        2.97            1.18
 183   184         1.7      10            36          20     70.38        7.64            5.19
 184   185         4.2      12            50           9     58.54        5.73            2.13
 185   186         4.0      19            62          13     74.79        7.86            3.69
 185   199         7.1      19            63           9     89.11       10.41            3.92
 186   187         0.9       2            10          13     21.40        2.72            1.46
 187   188         3.0      14            73          10     60.59        6.78            2.84
 187   197         2.4       5           119           5     22.15        2.64            0.73
 188   189         0.8       3            12          17     33.54        4.04            2.61
 189   195         2.1       4            94           6     23.17        2.68            0.85
 191   194         0.5       1           109           3      3.48        0.44            0.10
 192   193         3.6       8           100           2     23.01        2.78            0.40
 193   194         1.4      21            14          22     68.24        7.27            5.55
 193   260         0.5       4            45           5      8.16        1.15            0.37
 194   195         4.9      31            41          10     74.00        7.73            2.90
 195   196        11.6      45            52           9    130.29       14.32            4.76
 196   188         2.7       6            49          10     45.65        5.65            2.41
 196   197         3.1      13            19          20    107.71       11.52            8.26
 197   198         4.1      25            35          10     75.88        8.44            3.40
 198   186         5.5      19            67           9     96.36       11.62            4.66
 198   199         6.9      33            62          12    133.29       14.49            6.57
 199   200         5.7      19            46          12     99.08        9.41            4.12
 199   212        10.1      37            82           9    122.74       14.47            5.55
 200   184         2.2       5            90           8     28.15        3.37            1.21
 200   201         0.4       2             2          29     60.10        6.73            6.46
 201   202         6.7      25            58           6     97.32       12.27            3.92
 202   183         1.0       2            43          13     17.07        1.95            0.98
 202   203         2.9       7            17          16     79.03        9.27            5.65
 203   204         1.9       5             8          26     60.41        6.63            5.44
 203   209         5.5      17            79           9     58.52        6.67            2.40
 204   181         2.9       6           102           8     31.73        3.41            1.06
 204   205         1.9       8            14          26     93.02        9.80            8.05
 205   206         0.9       6             6          33     72.02        8.01            7.65
 206   178         2.2       6            54          11     41.61        4.93            2.26
 206   227        15.4      46            77           6    155.77       19.54            6.15
 207   208         8.6      37            29          18    162.14       16.74           10.09
 207   224         2.7       7            94           4     22.43        2.81            0.71
 208   204         3.5      10            86          11     54.12        5.97            2.61
 208   209         3.3      19            10          22     85.41        9.35            6.88
 209   210         8.1      24            21          15    121.73       13.42            7.33
 209   222         4.2      18            81           8     49.37        5.63            1.89
 210   202         4.5      11            76          11     64.80        7.55            3.30
 210   211         0.2       1             1          38    115.35       13.92           14.89
 211   200         5.5      19            98          10     79.32        8.89            3.47
 211   212         4.3      12            16          15     66.59        7.25            4.15
 212   213         0.9       7             5          21     58.03        6.83            4.99
 213   214        10.4      37            43          11    141.52       14.30            6.26
 213   218        11.2      32            95           4     85.36       10.66            2.27
 214   198         5.0      13            92          11     75.16        8.37            3.77
 214   215         1.5       4             5          25     91.68       10.14            8.86
 215   196        11.4      19           156           6     88.89       11.01            2.96
 215   259         0.2       0             1          19     79.69       10.83            7.30
 216   215         1.4       2            24           9     16.53        2.14            0.91
 216   217        10.9      68            63          16    201.56       20.17           10.16
 217   214         9.3      22            77           6     73.15        8.83            2.14
```

Cycle time of 140 seconds

```
 217   218    5.1  41        35          14    108.30     12.25           6.43
 218   219    7.8  59        65           8    132.96     16.38           5.77
 219   220    0.4   3         2          15    119.26     16.49           9.95
 220   221    2.4  36        40          10     81.46     10.03           4.15
 221   210    3.5  16        61           9     45.43      5.24           2.05
 221   222    8.0  31        49           8     91.12     10.66           3.72
 222   223    0.6   4         4          19     51.84      6.66           4.57
 223   208    4.4  11        51           7     45.77      5.77           2.03
 223   224    2.0  29        32          13     91.54     11.28           5.97
 224   225    4.7  43        31           6     86.08     12.34           3.98
 225   226   51.0  94       146           3    283.70     38.03           5.62
 226   207    0.4   2         2          21    150.81     19.38          14.51
 226   227    1.8   5        12          27     77.48      8.76           7.68
 227   226   34.3  67        99           5    241.34     30.63           7.27
 228   178    4.4  14        73          10     73.06      8.06           3.34
 228   227   10.2  52        61          11    157.65     18.03           7.76
 259   216   11.4  56        69           7    136.84     16.14           5.21
 259   260    0.3   1        10          19     17.03      2.14           1.47
 260   259    0.5   3         2          19    104.38     14.03           9.74
 260   261    7.2  11        96           4     48.72      6.00           1.20
 261   193    3.6  26        33          14     83.55      9.40           4.88
 261   260    0.8   2         3          14     48.42      6.65           3.78
 262   261   17.3  68        72           4    126.54     15.96           2.88
 331   216   19.0  56        91           4    136.24     17.48           3.35
 338   261   15.7  38        95           5    125.09     14.94           3.67
 463   217    5.5  13        97           4     40.05      5.09           1.10
 470   219    6.7  16        96           4     48.45      6.12           1.29
 471   221    1.3   2       113           3      8.59      1.15           0.24
 473   225    9.3  24        91           5     74.55      8.57           1.94
 491   226   20.2  72        74           8    225.03     26.46           9.14


Total pollution emission rates for this network (g/min) :

        Carbon Monoxide (CO) :              7517.6
        Hydrocarbons (THC) :                 883.0
        Nitrogen Oxides (NOx) :              399.7
```

Hot CO links with delay weighting of 500 percent

```
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Run time: 10 Aug 93 19:38
Emissions based on:
ATHENS * Central Arteries * ADDED DELAY WT OF 500 TO HOT CO LINKS
cohot.ctl Hot CO links with delay weighting of 500
Modes modelled are: cruising acceleration deceleration idling

 A     B     total    number of     mean     average   Carbon     Hydrocarbons   Nitrogen
node  node   delay   vehicles in   stops      speed    Monoxide   (THC)          Oxides
                     the queue    per PCU              (CO)                      (NOx)
          (PCU-h/h)   (PCU)         (%)      (km/h)    (g/min)    (g/min)        (g/min)

 151   187    0.9       2            72        11        15.76       1.68          0.71
 160   189    1.0       2            97         8        12.92       1.37          0.47
 171   185    4.5      12            80        10        76.62       7.95          3.10
 175   180    2.6       5           104         7        32.33       3.44          1.10
 176   179    1.7       4            89         9        24.83       2.59          0.95
 178   179    1.1       4            17        17        32.88       3.69          2.30
 179   180    2.5       8            38        17        75.15       8.09          4.86
 180   181    2.8      10            43        12        85.22      10.26          5.05
 180   205    2.0       4           110         7        24.83       2.77          0.92
 181   182    0.9       3            16        17        38.80       4.53          2.88
 182   183    0.8       3            19        17        37.28       4.43          2.77
 182   203    1.5       4            72        11        26.71       2.89          1.22
 183   184    2.2       9            58        18        79.58       8.16          5.09
 184   185    3.1       9            55        11        56.34       5.13          2.06
 185   186    3.4      12            64        14        74.46       7.68          3.80
 185   199    7.3      18           106         9       100.76      10.66          3.71
 186   187    0.8       1            12        14        21.44       2.67          1.45
 187   188    2.9      10            77        10        61.99       6.87          2.91
 187   197    3.0       4           157         4        24.83       3.05          0.79
 188   189    0.9       3            16        17        34.90       4.10          2.57
 189   195    1.9       4           112         7        22.55       2.55          0.83
 191   194    0.5       1           134         3         3.48       0.44          0.10
 192   193    2.4       5           101         3        18.35       2.05          0.35
 193   194    3.3      21            40        18        92.07       8.91          5.18
 193   260    3.0       5           118         2        19.44       2.70          0.49
 194   195    3.3      23            33        12        63.56       6.71          2.94
 195   196   10.0      30            54         9       129.29      13.87          5.07
 196   188    2.0       5            53        10        41.93       5.05          2.28
 196   197    3.4      11            25        20       113.19      11.81          8.12
 197   198    5.3      16            43         9        86.62       9.49          3.56
 198   186    5.2      14            81         9        99.87      11.63          4.69
 198   199    7.0      24            75        12       142.42      14.91          6.63
 199   200    5.0      17            53        13       101.96       9.21          4.05
 199   212    7.3      20            72        11       112.14      13.17          5.83
 200   184    1.5       3            85         9        25.21       2.96          1.20
 200   201    0.5       1             4        29        61.87       6.82          6.41
 201   202    7.6      24            93         6       109.50      12.49          3.68
 202   183    1.3       3            92        11        21.85       2.22          0.93
 202   203    2.1      18            26        17        80.04       8.74          5.39
 203   204    2.1       5            13        24        67.67       7.02          5.46
 203   209    5.1      12            88         9        59.50       6.60          2.47
 204   181    1.9       5           101        10        27.59       2.77          1.01
 204   205    2.1      10            19        26        98.00      10.03          7.93
 205   206    1.2       7             9        30        77.52       8.34          7.63
 206   178    2.1       7            84        11        44.55       4.81          2.11
 206   227   11.5      29            77         8       143.75      17.61          6.25
 207   208    2.4      18            18        27       120.23      12.20          9.94
 207   224    1.8       5            86         6        18.58       2.26          0.68
 208   204    3.4       9            99        12        55.37       5.92          2.56
 208   209    4.9      15            22        18       105.04      10.82          6.73
 209   210    5.2      16            22        17       109.95      11.52          7.09
 209   222    3.1       8            52        10        44.83       5.46          2.28
 210   202    8.2      15           149         7        83.00       9.87          3.35
 210   211    0.4       1             1        38       114.73      13.88         14.71
 211   200    4.7      12           103        10        77.71       8.59          3.56
 211   212    3.3      15            24        17        69.71       6.91          4.07
 212   213    1.8      12            14        19        70.11       7.61          4.89
 213   214    9.2      47            78        12       176.31      15.07          6.01
 213   218   12.7      24           111         4        95.28      12.06          2.58
 214   198    4.1      10            90        13        71.60       7.85          3.77
 214   215    0.9       3             4        28        87.90       9.66          8.79
 215   196   42.1      47           283         2       205.05      29.40          3.78
 215   259    0.2       0             1        19        79.25      10.77          7.26
 216   215    2.0       7           102         8        24.13       2.53          0.79
 216   217    8.4      39            55        18       196.66      19.73         11.52
 217   214    9.8      23           117         5        76.92       8.84          1.82
```

Hot CO links with delay weighting of 500 percent

```
217  218   4.4   34          51        15   114.65      11.93          6.16
218  219   5.3   27          40         9   132.62      17.69          7.20
219  220   0.5    3           4        15   120.89      16.57          9.94
220  221   1.0    9          16        10    74.70      10.31          4.78
221  210   5.1   14          89         7    56.70       6.36          2.07
221  222   8.0   30          76         8   100.26      10.58          3.38
222  223   1.2    7          10        18    57.85       7.11          4.55
223  208   5.8   15         103         6    56.95       6.60          1.91
223  224   1.6    7          15        14    86.22      11.37          6.31
224  225   4.2   18          25         6    88.73      13.15          4.42
225  226  42.0   64         149         3   247.12      32.33          5.14
226  207   0.4    3           2        21   148.45      19.08         14.28
226  227   2.7   19          63        25   105.90      10.06          7.23
227  226  68.4   95         166         5   380.73      51.62          8.38
228  178   3.6   10          76        11    71.64       7.71          3.39
228  227   6.7   32         158        13   148.38      16.68          8.24
259  216  15.7   46          88         6   162.86      19.02          5.38
259  260   0.4    1         114        19    17.73       2.21          1.46
260  259   0.5    1           1        19   103.77      14.02          9.74
260  261   6.6   11         137         4    46.44       5.61          1.15
261  193   3.1   19          37        15    84.44       9.23          4.89
261  260   0.6    2           4        15    48.04       6.53          3.77
262  261  11.9   46          72         4   112.25      13.81          3.10
331  216   9.5   31          78         5   108.68      13.70          3.89
338  261  17.6   32         123         5   135.73      16.37          3.89
463  217   6.2   11         127         3    43.76       5.63          1.19
470  219   8.5   15         133         3    56.53       7.32          1.42
471  221   1.0    2         119         3     7.34       0.96          0.22
473  225   5.8   15          87         7    61.27       6.54          1.95
491  226  15.8   51          79         9   215.68      24.44          9.34


Total pollution emission rates for this network (g/min) :

          Carbon Monoxide (CO) :              7880.2
          Hydrocarbons (THC) :                 910.4
          Nitrogen Oxides (NOx) :              404.2
```

Hot CO links with delay and stop weighting of 500 percent

```
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Run time: 30 Aug 93 14:00
Emissions based on:
ATHENS * Central Arteries * ADDED DELAY & STOP WT OF 500 TO HOT CO LINKS
cohot.ctl Hot CO links with stop&delay wt of 500
Modes modelled are: cruising acceleration deceleration idling

  A     B    total   number of     mean    average   Carbon     Hydrocarbons  Nitrogen
node  node  delay  vehicles in   stops    speed    Monoxide   (THC)         Oxides
                    the queue   per PCU            (CO)                     (NOx)
          (PCU-h/h)   (PCU)       (%)      (km/h)   (g/min)    (g/min)       (g/min)

 151   187    0.9       2          72        11     15.76       1.68          0.71
 160   189    1.0       2         104         8     13.05       1.38          0.47
 171   185    4.9      13          85         9     79.52       8.20          3.08
 175   180    2.6       5         104         7     32.33       3.44          1.10
 176   179    1.7       4          89         9     24.83       2.59          0.95
 178   179    1.2       4          18        17     33.62       3.76          2.30
 179   180    2.6       7          38        17     75.75       8.17          4.88
 180   181    3.1       9          47        12     88.03      10.50          5.07
 180   205    2.0       4         110         7     24.83       2.77          0.92
 181   182    0.9       3          16        17     38.80       4.53          2.88
 182   183    1.0       3          23        16     39.28       4.60          2.77
 182   203    1.6       4          84        10     28.33       2.98          1.21
 183   184    1.7       6          39        20     71.86       7.73          5.23
 184   185    3.2      10          57        10     57.78       5.24          2.08
 185   186    3.9       9          55        13     74.43       8.04          3.97
 185   199    7.3      18         108         9    100.76      10.66          3.71
 186   187    0.8       2          13        14     21.64       2.67          1.44
 187   188    3.0      10          76        10     62.21       6.93          2.92
 187   197    3.0       4         156         4     24.83       3.05          0.79
 188   189 0.7  2          14        17     33.47       3.95          2.57
 189   195    1.8       4         112         7     22.14       2.48          0.82
 191   194 0.5  1         133         3      3.48       0.44          0.10
 192   193 2.4  5         101         3     18.35       2.05          0.35
 193   194 3.3 20          41        18     92.87       8.95          5.18
 193   260    3.0       4         111         2     19.64       2.73          0.50
 194   195    3.6      23          47        11     71.86       6.94          2.76
 195   196    9.9      21          51         9    129.86      14.16          5.39
 196   188    2.0       5          53        10     41.93       5.05          2.28
 196   197    3.4      11          25        20    113.19      11.81          8.12
 197   198    4.9      27          69         9     92.62       8.52          2.80
 198   186    5.1      15          87         9    100.21      11.47          4.60
 198   199    6.4      21          64        12    135.43      14.64          6.85
 199   200    5.4      17          54        12    104.52       9.51          4.08
 199   212    6.2      22          76        12    108.26      12.40          5.68
 200   184    1.4       3          79         9     24.41       2.88          1.20
 200   201    0.5       1           4        29     61.87       6.82          6.41
 201   202    7.8      24          83         6    107.90      12.72          3.77
 202   183    1.2       2          67        11     19.66       2.12          0.96
 202   203    2.0       8          19        18     76.10       8.67          5.53
 203   204    1.8       4          12        26     65.07       6.77          5.43
 203   209    4.1      11          80        11     54.58       5.99          2.49
 204   181    2.0       5         102         9     28.01       2.84          1.02
 204   205    2.2       9          20        26     99.46      10.14          7.93
 205   206    1.2       7           9        30     77.52       8.34          7.63
 206   178    2.5       7          92        11     47.24       5.07          2.11
 206   227   11.5      29          77         8    143.75      17.61          6.25
 207   208    2.4      11          13        27    113.33      11.99         10.06
 207   224    1.7       5          87         6     18.20       2.20          0.67
 208   204    3.7       9          99        11     56.62       6.12          2.58
 208   209    5.4      23          27        18    112.98      11.37          6.70
 209   210    3.2      19          17        21     96.50      10.02          7.05
 209   222    2.9       7          51        10     44.17       5.37          2.30
 210   202    7.4      14         147         8     79.90       9.38          3.32
 210   211    0.8       6           8        35    128.93      14.57         14.70
 211   200    4.5      13         102        11     76.65       8.42          3.52
 211   212   10.4      42          87         8    161.58      14.36          4.79
 212   213    1.3       9           9        19     63.27       7.16          4.94
 213   214    7.9      24          42        14    129.31      12.58          6.07
 213   218   13.4      27         119         4     96.84      12.31          2.52
 214   198    4.6       9         106        12     75.71       8.24          3.79
 214   215    1.0       4           5        26     89.08       9.76          8.78
 215   196   42.2      48         282         2    205.05      29.41          3.75
 215   259    0.2       0           1        19     79.25      10.77          7.26
 216   215    3.6       7         106         5     30.81       3.57          0.89
 216   217    7.0      40          56        19    191.19      18.79         11.36
 217   214   11.9      22         109         5     86.26      10.28          2.01
```

Hot CO links with delay and stop weighting of 500 percent

```
 217   218   3.7  25       33         16   104.32     11.72            6.66
 218   219   5.5  31       46          9   133.50     17.48            7.02
 219   220   0.5   3        4         15   120.89     16.57            9.94
 220   221   1.2  16       22         10    76.63     10.27            4.68
 221   210   5.3  14       92          7    57.99      6.49            2.07
 221   222   6.9  29       67          9    92.95      9.94            3.46
 222   223   1.1   6        9         18    56.86      7.04            4.55
 223   208   7.1  15      109          5    62.37      7.45            1.99
 223   224   1.5   9       15         14    85.64     11.28            6.29
 224   225   4.3  18       26          6    88.73     13.08            4.37
 225   226  42.2  64      151          3   247.96     32.46            5.15
 226   207   0.8   6        5         21   153.25     19.43           14.28
 226   227   2.4  17       59         25   102.94      9.84            7.28
 227   226  68.7  96      167          5   382.25     51.80            8.37
 228   178   3.3  10       72         12    69.39      7.50            3.39
 228   227   6.7  32       58         13   148.38     16.68            8.24
 259   216  18.0  52      100          6   170.58     19.58            4.90
 259   260   0.5   1       18         17    18.54      2.28            1.47
 260   259   0.5   1        1         19   103.77     14.02            9.74
 260   261   6.9  11      139          4    47.69      5.80            1.16
 261   193   3.1  19       37         15    84.44      9.23            4.89
 261   260   0.9   3        6         14    50.16      6.74            3.78
 262   261  11.9  46       72          4   112.25     13.81            3.10
 331   216   8.3  29       73          6   103.92     13.16            3.94
 338   261  17.6  32      123          5   135.73     16.37            3.89
 463   217   6.2  11      127          3    43.76      5.63            1.19
 470   219   8.5  15      133          3    56.53      7.32            1.42
 471   221   0.7   1      104          4     6.14      0.77            0.21
 473   225   5.8  15       87          7    61.27      6.54            1.95
 491   226  15.1  49       78         10   212.87     24.08            9.37


Total pollution emission rates for this network (g/min) :

         Carbon Monoxide (CO) :               7928.4
         Hydrocarbons (THC) :                  915.0
         Nitrogen Oxides (NOx) :               405.1
```

Hot NOx links with stop weighting of -200 percent

```
PREMIT EMISSIONS MODEL  Version 3.07
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Run time: 30 Aug 93 19:38
Emissions based on:
ATHENS * Central Arteries * HOT NOx LINKS WITH STOP WEIGHTING OF -200
cohot.ctl Hot NOx links with stop wt of -200
Modes modelled are: cruising acceleration deceleration idling

  A     B    total   number of     mean     average    Carbon    Hydrocarbons   Nitrogen
 node  node  delay  vehicles in    stops     speed    Monoxide   (THC)          Oxides
                     the queue    per PCU             (CO)                      (NOx)
          (PCU-h/h)    (PCU)        (%)      (km/h)   (g/min)    (g/min)        (g/min)

 151   187    0.9        2          72        11      15.76       1.68           0.71
 160   189    1.0        2         104         8      13.05       1.38           0.47
 171   185    4.5       12          80        10      76.62       7.95           3.10
 175   180    2.6        5         104         7      32.33       3.44           1.10
 176   179    1.7        4          89         9      24.83       2.59           0.95
 178   179    1.2        5          18        17      33.58       3.75           2.30
 179   180    2.6        7          38        17      75.80       8.18           4.89
 180   181    2.8       10          44        12      85.53      10.26           5.05
 180   205    1.1        3          69        10      19.25       2.18           0.90
 181   182    0.8        2          14        17      37.71       4.45           2.89
 182   183    0.8        3          21        17      37.90       4.45           2.77
 182   203    1.5        4          74        11      26.91       2.90           1.21
 183   184    2.0        8          54        19      77.74       8.02           5.13
 184   185    3.1        8          54        11      55.91       5.11           2.06
 185   186    3.5       12          63        14      74.68       7.75           3.82
 185   199    5.3       14          72        10      85.29       9.42           3.85
 186   187    0.7        2          15        14      21.76       2.62           1.44
 187   188    3.2       11          86        10      64.67       7.03           2.87
 187   197    1.9        3         122         6      20.42       2.36           0.73
 188   189    0.8        2          14        17      34.22       4.06           2.60
 189   195    2.3        4         128         6      24.35       2.82           0.86
 191   194    0.5        1         134         3       3.48       0.44           0.10
 192   193    2.6        5         105         3      19.19       2.18           0.37
 193   194    1.5       13          14        22      69.18       7.39           5.61
 193   260    1.5        4         113         3      13.39       1.76           0.41
 194   195    4.1       19          43        11      72.85       7.38           2.94
 195   196   22.6       48         113         5     197.69      20.71           3.85
 196   188    2.4        5          58        10      45.91       5.50           2.39
 196   197   11.7       33         100        12     198.03      17.80           6.05
 197   198    4.7       11          33         9      80.80       9.30           3.75
 198   186    4.8       16          85         9      98.39      11.25           4.57
 198   199    9.6       30          94        11     160.61      16.30           6.27
 199   200    4.8       18          54        13     102.47       9.16           4.06
 199   212    7.9       23          76        10     115.28      13.49           5.78
 200   184    1.8        4         103         8      27.23       3.14           1.19
 200   201    0.5        1           4        29      62.21       6.86           6.44
 201   202    9.3       26         107         5     117.65      13.40           3.66
 202   183    1.2        3          90        11      21.35       2.16           0.93
 202   203    1.9        8          19        18      76.02       8.64           5.55
 203   204    1.9        4          12        26      65.79       6.86           5.47
 203   209    2.3        8          57        14      44.73       4.90           2.58
 204   181    1.9        4         101        10      27.96       2.81           1.04
 204   205   11.6       31         102        13     208.26      18.12           6.46
 205   206    7.1       32          53        17     170.97      14.76           7.99
 206   178    2.8       10          96        10      47.82       5.09           2.00
 206   227    5.4       25          61        10     115.22      13.88           6.10
 207   208   12.6       66          81        15     245.94      21.02           8.53
 207   224    1.8        5          94         6      18.94       2.27           0.67
 208   204    3.3        8          99        12      55.51       5.92           2.60
 208   209    9.0       68          88        13     200.46      16.52           6.21
 209   210   10.3       70          86        13     191.60      16.78           5.71
 209   222    3.5       10          66         9      47.79       5.64           2.20
 210   202    7.2       13         141         8      79.38       9.29           3.34
 210   211   10.7       65          92        20     308.46      24.61          13.09
 211   200    4.3       10          81        11      73.36       8.40           3.68
 211   212    1.4        3           6        23      44.22       4.89           3.90
 212   213    3.9       33          34        14      98.04       9.48           4.71
 213   214    4.7       23          29        18     101.25       9.94           5.94
 213   218    4.7       21          95         7      62.92       7.12           2.21
 214   198    3.8       12         102        13      71.77       7.64           3.68
 214   215    6.1       51          83        18     160.04      14.18           6.86
 215   196   18.6       23         224         4     117.16      15.46           3.26
 215   259    0.2        0           1        19      79.49      10.80           7.28
 216   215    0.8        5          58        12      16.42       1.77           0.81
 216   217   13.8       63          84        15     227.58      22.13           9.42
 217   214    8.2       20         105         6      72.05       8.04           1.88
```

Hot NOx links with stop weighting of -200 percent

```
217   218     4.5       20              26         15    104.52     12.30            6.90
218   219     7.3       40              67          8    140.90     17.44            6.42
219   220     1.4       16              20         14    134.55     17.28            9.86
220   221     0.7        5               8         11     70.72     10.15            4.82
221   210     2.7        9              56         10     42.28      4.85            2.11
221   222     6.5       27              67          9     91.90      9.76            3.48
222   223     1.1        6              10         18     57.59      7.07            4.56
223   208     1.5        4              30         12     31.45      3.94            1.95
223   224     1.7        6              14         13     86.43     11.46            6.34
224   225     4.9       17              24          6     94.06     14.04            4.64
225   226    56.5       85             171          3    307.55     41.72            6.07
226   207     4.9       50              51         18    210.69     22.41           13.31
226   227     4.8       13              48         20    107.91     11.27            7.58
227   226    46.6       68             136          6    292.33     38.44            7.89
228   178     3.3       10              72         12     69.39      7.50            3.39
228   227     8.6       37              67         12    158.72     17.62            8.01
259   216     8.3       37              64          8    131.50     15.48            5.83
259   260     0.7        2              27         17     20.25      2.44            1.47
260   259     1.2       26              30         18    120.93     14.46            9.32
260   261     5.0       10             126          5     40.05      4.60            1.07
261   193     2.9       19              35         15     82.54      9.08            4.90
261   260     1.6       22              37         13     63.17      7.01            3.45
262   261    14.6       50              79          4    120.13     14.77            2.93
331   216    10.9       34              84          5    113.76     14.25            3.79
338   261    12.1       27             103          6    114.13     12.98            3.66
463   217     3.6        8              96          5     33.70      4.09            1.11
470   219     5.1       11             103          5     44.05      5.35            1.33
471   221     0.7        1             109          4      6.14      0.77            0.21
473   225     5.8       15              87          7     61.27      6.54            1.95
491   226    15.1       49              78         10    212.87     24.08            9.37

Total pollution emission rates for this network (g/min) :

        Carbon Monoxide (CO) :                8538.7
        Hydrocarbons (THC) :                   930.7
        Nitrogen Oxides (NOx) :                388.9
```

Appendix D

LINK-NODE CROSS REFERENCE TABLE

A link-node cross reference table is required to map links numbers to node numbers and combine those TRANSYT links which are part of the same stretch of road.

The TRANSYT program refers to each stretch of road as a link which has an associated link number. Sometimes multiple TRANSYT links may be used to represent the same physical stretch of road between two intersections. The PREMIT emissions model produces one set of emissions data for a physical stretch of road. It refers to the section of road by listing the numbers of the nodes at each end of a given section of road. The link-node cross reference table maps between link numbers and node numbers.

The node layout is shown in Figure D.1. The TRANSYT link number refers to the section of road between nodes A and B, with traffic flowing from A to B. On leaving the link the traffic will turn into another link defined by the node numbers B and Cx, where Cx is C1 up to C4.

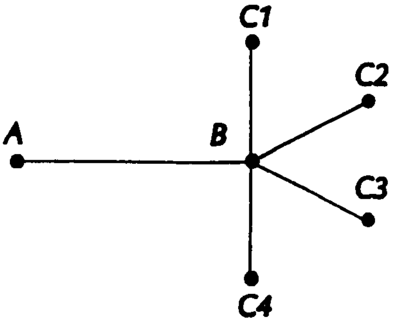

Figure D.1 Link nodes

The columns in the link-node cross reference file are: TRANSYT link number, and the nodes A, B, C1, C2, C3, C4. The contents of this file have been presented in two columns in this appendix. In the actual file there is only one column.

90	104	131	135	132	0	0
110	105	130	137	131	0	0
230	112	238	239	237	0	0
240	113	239	240	530	238	0
300	117	247	246	0	0	0
330	119	244	241	245	0	0
360	121	233	232	0	0	0
370	121	236	235	237	0	0
420	124	232	234	231	0	0
440	125	231	521	230	0	0
490	128	129	139	130	0	0
500	129	130	131	137	0	0
510	129	139	142	140	0	0
520	130	131	132	135	0	0
530	130	137	138	0	0	0
540	131	132	244	103	0	0
550	131	135	145	136	0	0
570	132	249	248	250	0	0
580	133	132	103	249	0	0
590	133	134	135	146	0	0
600	134	135	136	145	0	0
620	135	136	137	0	0	0
640	136	137	138	0	0	0
650	137	138	139	143	0	0
660	138	139	140	142	0	0
680	139	140	171	0	0	0
700	140	171	185	172	0	0
710	141	140	171	0	0	0
770	144	136	137	0	0	0
820	146	251	133	250	252	0
840	148	252	251	253	0	0
900	151	187	188	197	0	0
1060	160	189	195	190	0	0
1110	163	257	256	258	0	0
1130	164	258	257	295	269	0
1170	166	264	265	341	263	0
1190	170	171	185	172	0	0
1200	171	172	173	129	0	0
1210	171	185	199	186	0	0
1220	172	129	130	139	0	0
1280	175	180	181	205	0	0
1300	176	179	180	0	0	0
1310	177	229	228	0	0	0
1311	177	229	523	230	0	0
1330	178	179	180	0	0	0
1340	179	180	181	205	0	0
1350	180	181	182	174	0	0
1360	180	205	206	0	0	0
1380	181	182	203	0	0	0
1390	182	183	173	184	0	0
1400	182	203	209	204	0	0
1420	183	184	172	185	0	0
1430	184	172	129	173	0	0
1440	184	185	199	186	0	0
1450	185	186	170	187	0	0
1460	185	199	212	200	0	0
1480	186	187	188	197	0	0
1490	187	188	152	189	0	0
1500	187	197	198	0	0	0
1520	188	189	190	195	0	0
1540	189	195	196	0	0	0
1580	191	194	195	0	0	0
1590	192	193	260	0	0	0
1600	192	262	339	261	0	0
1610	193	194	195	0	0	0
1620	193	260	259	0	0	0
1630	194	195	196	0	0	0
1640	195	196	197	188	0	0
1650	196	188	152	189	0	0
1660	196	197	198	0	0	0
1670	197	198	199	186	0	0
1680	198	186	170	187	0	0
1690	198	199	200	212	0	0
1700	199	200	201	184	0	0
1710	199	212	213	0	0	0
2770	258	269	270	0	0	0
2771	258	269	268	0	0	0
2775	269	258	295	0	0	0
1720	200	184	172	185	0	0
1730	200	201	202	0	0	0
1740	201	202	203	183	0	0
1750	202	183	173	184	0	0
1760	202	203	204	209	0	0
1770	203	204	205	181	0	0
1780	203	209	222	210	0	0
1790	204	181	174	182	0	0
1800	204	205	206	0	0	0
1810	205	206	227	178	0	0
1820	206	178	177	179	0	0
1830	206	227	228	0	0	0
1831	206	227	226	0	0	0
1840	207	208	204	209	0	0
1850	207	224	225	0	0	0
1860	208	204	205	181	0	0
1870	208	209	212	222	0	0
1880	209	210	202	211	0	0
1890	209	222	223	0	0	0
1900	210	202	203	183	0	0
1910	210	211	200	212	0	0
1920	211	200	201	184	0	0
1930	211	212	213	0	0	0
1940	212	213	214	218	0	0
1950	213	214	198	215	0	0
1960	213	218	468	219	0	0
1970	214	198	199	186	0	0
1980	214	215	196	259	0	0
1990	215	196	197	188	0	0
2000	215	259	260	330	216	0
2010	216	215	196	259	0	0
2020	216	217	218	214	0	0
2040	217	214	198	215	0	0
2050	217	218	468	219	0	0
2060	218	219	220	0	0	0
2080	219	220	471	221	0	0
2090	220	221	222	210	0	0
2110	221	210	202	211	0	0
2120	221	222	223	0	0	0
2130	222	223	224	208	0	0
2140	223	208	204	209	0	0
2150	223	224	225	0	0	0
2160	224	225	226	0	0	0
2161	224	225	473	0	0	0
2170	225	226	227	491	0	0
2171	225	226	207	0	0	0
2180	225	473	474	0	0	0
2185	473	225	226	0	0	0
2190	226	207	224	0	0	0
2200	226	227	228	0	0	0
2205	227	226	207	0	0	0
2206	227	226	491	0	0	0
2210	226	491	474	492	0	0
2215	491	226	227	207	0	0
2220	227	228	229	0	0	0
2225	228	227	226	0	0	0
2230	228	178	179	177	0	0
2240	228	229	523	0	0	0
2241	228	229	230	0	0	0
2245	229	228	227	178	0	0
2250	229	230	231	0	0	0
2255	230	229	228	0	0	0
2260	229	523	517	524	0	0
2280	230	231	521	232	0	0
2285	231	230	126	229	0	0
2290	231	232	234	0	0	0
2295	232	231	125	230	0	0
2300	231	521	520	623	0	0
2305	521	231	232	125	230	0
2315	233	232	231	0	0	0
2320	232	234	522	525	235	0
2325	234	233	121	232	0	0
2330	234	235	236	0	0	0
2335	235	234	525	0	0	0
2336	235	234	522	0	0	0
6190	492	475	476	0	0	0
6200	492	493	494	0	0	0
6205	493	492	475	0	0	0
2340	234	522	617	0	0	0
2341	234	522	521	0	0	0
2345	522	234	235	525	0	0
2355	525	234	235	233	522	0
2360	235	233	121	232	0	0
2370	235	236	121	0	0	0
2371	235	236	237	0	0	0
2375	236	235	233	234	0	0
2380	236	237	238	0	0	0
2385	237	236	121	235	0	0
2390	237	238	112	0	0	0
2391	237	238	239	0	0	0
2395	238	237	236	0	0	0
2400	238	239	244	0	0	0
2401	238	239	530	240	0	0
2405	239	238	237	112	0	0
2410	239	240	241	0	0	0
2415	240	239	238	0	0	0
2420	239	244	241	245	0	0
2440	240	241	242	0	0	0
2445	241	240	239	0	0	0
2450	241	242	533	537	0	0
2451	241	242	243	0	0	0
2455	242	241	240	0	0	0
2460	242	243	245	0	0	0
2461	242	243	570	537	0	0
2465	243	242	241	0	0	0
2485	537	242	241	243	0	0
2490	243	245	119	0	0	0
2491	243	245	246	563	0	0
2495	245	243	570	0	0	0
2496	245	243	242	0	0	0
2497	245	243	537	0	0	0
2505	537	243	570	245	0	0
2515	570	243	537	0	0	0
2516	570	243	245	0	0	0
2517	570	243	242	0	0	0
2520	244	241	242	240	0	0
2530	244	245	243	563	246	0
2550	245	246	247	0	0	0
2555	246	245	243	119	0	0
2565	563	245	246	0	0	0
2566	563	245	119	243	0	0
2580	246	247	248	0	0	0
2585	247	246	245	116	0	0
2590	247	248	118	0	0	0
2591	247	248	562	249	0	0
2595	248	247	246	0	0	0
2610	248	249	250	0	0	0
2615	249	248	562	0	0	0
2616	249	248	247	118	0	0
2625	562	248	247	118	249	0
2630	249	250	133	0	0	0
2631	249	250	251	0	0	0
2635	250	249	248	0	0	0
2640	250	133	134	132	0	0
2650	250	251	252	0	0	0
2655	251	250	249	133	0	0
2660	251	133	134	132	0	0
2670	251	252	253	0	0	0
2675	252	251	250	133	0	0
2680	252	253	254	302	0	0
2685	253	252	251	0	0	0
2690	253	254	255	0	0	0
2695	254	253	302	0	0	0
2696	254	253	252	0	0	0
2710	254	255	155	0	0	0
2711	254	255	256	0	0	0
2715	255	254	253	0	0	0
2730	255	256	257	0	0	0
2735	256	255	254	155	0	0
2750	256	257	258	0	0	0
2755	257	256	255	0	0	0
2760	257	258	269	295	0	0
2765	258	257	256	0	0	0
6700	521	522	525	234	0	0
6705	522	521	623	0	0	0
6706	522	521	520	0	0	0

2776	269	258	257	0	0	0
2790	259	216	463	217	215	0
2800	259	260	261	0	0	0
2805	260	259	216	330	0	0
2810	259	330	335	0	0	0
2820	260	261	262	193	0	0
2825	261	260	259	0	0	0
2830	261	193	194	0	0	0
2840	261	262	263	0	0	0
2845	262	261	193	0	0	0
2846	262	261	260	0	0	0
2850	262	263	264	0	0	0
2855	263	262	261	339	0	0
2860	262	339	340	0	0	0
2870	263	264	265	0	0	0
2875	264	263	262	0	0	0
2880	264	265	266	0	0	0
2885	265	264	263	341	0	0
2890	264	341	342	365	0	0
2900	265	266	267	0	0	0
2905	266	265	264	342	0	0
2910	265	342	343	364	0	0
2920	266	267	268	164	0	0
2925	267	266	265	0	0	0
2940	267	268	269	0	0	0
2945	268	267	266	0	0	0
2950	268	269	270	0	0	0
2951	268	269	258	0	0	0
2955	269	268	344	0	0	0
2956	269	268	267	0	0	0
2960	268	344	345	362	0	0
2975	270	269	258	0	0	0
2976	270	269	268	0	0	0
3390	302	254	253	255	0	0
3720	330	335	336	0	0	0
3730	331	216	463	217	215	0
3740	331	330	335	0	0	0
3820	335	336	337	0	0	0
3830	336	337	338	0	0	0
3840	337	338	261	339	0	0
3850	338	261	193	0	0	0
3860	338	339	340	0	0	0
3870	339	340	341	0	0	0
3880	340	341	342	0	0	0
3890	341	342	266	343	0	0
3910	342	266	267	265	0	0
3920	342	343	344	267	0	0
3940	343	267	164	268	266	0
3950	343	344	345	0	0	0
3960	344	345	346	0	0	0
4290	363	343	267	344	0	0
4330	365	342	266	343	364	0
5080	420	336	337	0	0	0
5100	421	338	261	339	0	0
5800	463	217	218	214	0	0
5890	467	476	494	493	0	0
5930	470	219	220	0	0	0
5940	471	221	210	222	0	0
5970	472	473	474	225	0	0
5980	473	474	475	0	0	0
5985	474	473	225	0	0	0
6000	474	475	476	0	0	0
6010	475	476	494	493	0	0
6020	476	493	484	482	0	0
6030	476	494	495	0	0	0
6060	477	496	497	0	0	0
6061	477	496	495	0	0	0
6140	487	499	500	512	498	0
6170	491	474	473	475	0	0
6180	491	492	475	493	0	0
6185	492	491	474	0	0	0
6186	492	491	226	0	0	0
6206	493	492	491	0	0	0
6210	493	494	495	0	0	0
6215	494	493	492	0	0	0
6220	494	495	516	0	0	0
6221	494	495	496	0	0	0
6225	495	494	493	0	0	0
6230	495	496	477	0	0	0
6231	495	496	497	0	0	0
6235	496	495	516	0	0	0
6236	496	495	494	0	0	0
6240	495	516	515	0	0	0
6241	495	516	517	0	0	0
6245	516	495	494	0	0	0
6246	516	495	496	0	0	0
6250	496	497	514	0	0	0
6251	496	497	498	0	0	0
6255	497	496	495	0	0	0
6260	497	498	499	0	0	0
6265	498	497	514	496	0	0
6270	497	514	513	636	0	0
6275	514	497	496	0	0	0
6290	498	499	512	0	0	0
6291	498	499	500	0	0	0
6295	499	498	497	0	0	0
6300	499	500	510	0	0	0
6301	499	500	501	0	0	0
6305	500	499	512	498	0	0
6310	499	512	511	636	513	0
6325	501	500	510	499	0	0
6330	500	510	680	670	511	0
6335	510	500	499	501	0	0
6490	510	511	512	0	0	0
6495	511	510	670	0	0	0
6496	511	510	500	680	0	0
6505	670	510	511	500	680	0
6515	680	510	670	0	0	0
6516	680	510	500	0	0	0
6517	680	510	511	0	0	0
6520	511	512	513	0	0	0
6525	512	511	510	0	0	0
6530	512	513	514	0	0	0
6535	513	512	511	0	0	0
6550	513	498	497	480	499	0
6560	513	514	515	636	0	0
6565	514	513	498	512	0	0
6570	514	515	516	0	0	0
6590	515	516	495	0	0	0
6591	515	516	517	0	0	0
6600	516	514	636	0	0	0
6601	516	514	497	0	0	0
6602	516	514	513	0	0	0
6610	516	517	518	0	0	0
6615	517	516	495	0	0	0
6616	517	516	514	0	0	0
6620	517	518	625	0	0	0
6621	517	518	519	0	0	0
6625	518	517	516	0	0	0
6630	518	519	524	0	0	0
6631	518	519	520	0	0	0
6635	519	518	517	0	0	0
6645	625	518	519	517	0	0
6650	519	520	524	0	0	0
6651	519	520	521	0	0	0
6655	520	519	524	518	0	0
6660	519	524	520	523	0	0
6670	520	521	624	522	0	0
6671	520	521	231	0	0	0
6675	521	520	524	0	0	0
6676	521	520	624	0	0	0
6680	520	524	230	523	0	0
6685	524	520	624	521	0	0
6695	624	520	521	524	519	0
6715	623	521	522	231	0	0
6725	525	522	521	0	0	0
6740	523	517	516	0	0	0
6750	523	524	520	0	0	0
6755	524	523	517	0	0	0
6760	524	230	231	126	229	0
6830	529	236	237	121	235	0
6860	531	240	241	239	0	0
6880	532	241	242	240	0	0
7210	561	250	249	133	251	0
7760	626	514	515	497	513	0

Appendix E

TRAFFIC REROUTING RESULTS

The PREDICT project, evaluated the impact of the traffic rerouting strategy on pollutant concentrations. This appendix shows the results of the strategy's impact in the environmentally sensitive area and on the peripheral links. The pollutant concentrations corresponded to a property line at a height of 1.5 metres. The average pollutant concentration within the environmentally sensitive area and on the peripheral links was reported.

Table E.1 shows the results of the pollutant concentration analysis for carbon monoxide, hydrocarbons and nitrogen oxides, before and after implementation of the strategy. These results corresponded to 30 percent of vehicles complying with the traffic rerouting instructions.

Table E.1 shows the average pollutant concentrations in the environmentally sensitive area. It clearly illustrates that the strategy is very effective at reducing the pollutant concentrations of all three pollutants in the environmentally sensitive area.

The strategy caused average pollutant concentrations to increase on the peripheral links. However, the increases on the peripheral links were much lower than the size of the decrease in the environmentally sensitive area.

Pollutant	Before (ppm)	After (ppm)	Change (%)
Environmental area			
CO	16.45	8.57	-47.9
HC	4.69	2.72	-42.0
NOx	0.67	0.35	-47.8
Peripheral links			
CO	12.67	16.02	+26.4
HC	3.37	4.60	+23.3
NOx	0.53	0.67	+26.4

Table E.1 Pollutant concentrations within environmental area