Modelling real-world driving, fuel consumption and emissions of passenger vehicles: a case study in Johannesburg

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25 January 2008

DECLARATION

I declare that the work contained in this thesis is my own original writing. Sources referred to in the creation of this work have been appropriately acknowledged by explicit references or footnotes. Other assistance received has been acknowledged. I have not knowingly copied or used the words or ideas of others without such acknowledgement.

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ABSTRACT

Quantifying energy consumed and emissions produced by transport is essential for effective policy formulation and urban environmental management. Current first-world methods for determining vehicle emissions factors are technology and resource intensive, and results cannot be applied directly to cities in other parts of the world. There is a need for alternative cost-effective and accurate methods for determining real-world fuel consumption and emissions from vehicles in cities of the developing world.

In this thesis, a new emissions simulation and inventory model is developed and implemented as a software tool. A novel application of low cost on-board diagnostics equipment and Global Positioning System sensors is devised to survey engine-operating parameters, driving conditions and vehicle usage profiles needed by the model. An emissions inventory is produced for the City of Johannesburg using the software tool and surveying method to demonstrate the overall process.

The core contribution of this thesis is the logical development of data structures and software tools which link base engine-operating patterns (of engine speed and engine load), derived from the literature, to measured engine-operating patterns and vehicle activity from real-world driving. A range of real-world driving cycles and emission factors published by the Swiss Institute of Materials Science and Technology are transformed to produce the base engine-operating patterns and their corresponding emissions factors. The calculation of emission factors for real-world driving involves matching measured engine-operating patterns to combinations of the base engine-operating patterns using numerical methods. The method is validated using a cross validation technique. The emissions inventory application integrates measured engine-operating patterns, vehicle activity, fleet structure, fuel sales and the emissions simulation procedure to calculate total emissions.

Fuel consumption and emissions of interest are CO_2, CO, HC, NO_x. Measurements of engine operating parameters and vehicle usage patterns were recorded for 30 privately owned passenger vehicles from the Johannesburg fleet. The selection included Euro-0 (a mixture of pre Euro-1 vehicles), Euro-2 and Euro-3 petrol vehicles, and Euro-2 diesel private passenger vehicles.

Fifteen billion vehicle kilometres were driven in Johannesburg by private passenger vehicles per year consuming 325 million litres of diesel and 1 524 billion litres of petrol.

Total emissions were estimated to be 4.13 Mt CO_2, 82.77 kt CO, 9.15 kt HC, and 24.49 kt NO_x. Between 88 and 93% of the total emissions were from vehicles which fall into the Euro-0 petrol category. Diesel vehicles did not make a significant contribution to CO and HC emissions but contributed 14% of the NO_x and 19% of the CO_2 emissions. During weekdays, 28 to 31% and 25 to 27% of the total fuel consumption and emissions were due to the morning commute and the evening commute periods respectively. Although minibus taxis, buses, freight and vehicle age significantly impact on total fuel consumption and emissions in cities they were not considered within the scope of this study.

Vehicle usage patterns are analysed to produce spatial maps and diurnal charts of congestion on suburban roads, streets and highways within the Johannesburg municipal area. Times and locations of congestion are presented in terms of a standard congestion index, and suggestion given on how and where congestion problems could be addressed.

This study shows that vehicle emissions inventories can be cost effectively produced by surveying engine-operating parameters and vehicle usage profiles using on-board diagnostics and Global Positioning System sensors and simulating emissions factors using a new emissions simulation and emissions inventory model.

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LIST OF ABBREVIATIONS

ACEA	- European Automobile Manufacturers' Association
ADMS	- Atmospheric Dispersion Modelling System
AQIRP	- Air Quality Improvement Research Programme
ARTEMIS	- Assessment and Reliability of Transport Emission Models and Inventory Systems
bmep	- Brake mean effective pressure
BMFT	- Former German Federal Ministry for Education, Science, Research and Technology
BUWAL	- Bundesamt für Umwelt, Wald und Landschaft (Swiss Agency for the Environment, Forests and Landscape)
CADC	- Common ARTEMIS Driving Cycles
CAFÉ	- Clean Air For Europe
CARB	- Californian Air Recourses Board
CECERT	- College of Engineering-Centre for Environmental Research and Technology at the University of California-Riverside
CLRTAP	- Convention on Long Range Trans-boundary Air Pollution
CMEM	- Comprehensive Modal Emissions Model
COPERT	- Computer Program to calculate Emissions from Road Transport
CORINAIR	- COre European INventory of AIR emissions
COST	- European CO-operation in the field of Scientific and Technical Research
COST319	- Part of the COST programme considering transport and environment
DDS	- Decision Support System
DME	- Department of Minerals and Energy
DST	- Department of Science and Technology
EC	- European Commission
ECE	- Economic Commission for Europe
EF	- Emissions Factor
EIA	- Energy Information Agency
EMEP	- European Modelling and Evaluation Program
EMIT	- Emissions Inventory Toolkit
EMME/2	- *Equilibre* Multimodal, Multimodal Equilibrium transport model
EMPA	- Swiss Institute of Materials Science and Technology
eNatis	- electronic National transport information system (South African)
EOBD	- European On-Board Diagnostics
EPA	- US Environmental Protection Agency

EPEFE	-	European Programme on Emissions, Fuels and Engine Technologies
ERI	-	Energy Research Institute, University of Cape Town
ESASTAP	-	European – South African Science and Technology Advancement Program
EU	-	European Union
EUROPIA	-	European Petroleum Industry Association
FC	-	Fuel Consumption
FTP	-	US Federal testing procedure
FTP75	-	A variant of the US Federal testing procedure
GDP	-	Gross domestic product
GIS	-	Geographical Information Systems
GPS	-	Global Positioning System
HBEFA	-	HandBook of Emission FActors
HC	-	Emissions of Hydrocarbons
IEA	-	International Energy Agency
IER	-	Institute for Energy Economics and Rational Use of Energy, University of Stuttgart
IKARUS	-	Instruments for Climate change gases Reduction Strategies
ISO	-	International Standards Organisation
ITM	-	IKARUS Transport Model
LDV	-	Light duty vehicle
MI	-	Matching Index
MEET	-	Methods for Estimating Emissions from Transport
MOBILE	-	US EPA mobile emissions model
MOBILE6	-	last version of US EPA mobile emissions model, replaced by MOVES
MOVES	-	Current vehicle emissions modelling system used by EPA
NAAMSA	-	National Association of Automobile manufacturers of South Africa
NATIS	-	National Transport Information System
NDOT	-	National Department of Transport (South Africa)
NEDC	-	New European Driving Cycle
NEMO	-	Network EMissions Model
NEMS	-	US National Energy Modelling System
NRF	-	National Research Foundation
OBD	-	International standards for vehicle on-board diagnostics (ISO and SAE)
OECD	-	Organisation for Economic Co-operation and Development
PHEM	-	Passenger car and Heavy duty vehicle Emissions Model

SAE - Society of Automotive engineers
SAEFL - Swiss Agency for Environment, Forestry and Landscape
SANERI - South African National Energy Research Institute
SANEA - South African National Energy Association
SDS - Sum of Differences Squared
SEA - Sustainable Energy Africa
SMP - Sustainable Mobility Project
SUV - Sports Utility Vehicle
TRAN - Transport module of NEMS
TREMOD - TRansport Emissions MODel
TREMOVE - The name of a transport and emissions model developed by Transport and Mobility Leuven for the European Commission
UNECE - United Nations Economic Commission for Europe
UNFCCC - United Nations Framework Convention on Climate Change
US - United States of America
UTP - Urban Transport Planning
VESIM - Vehicle Emissions SImulation Model
VEHSIME - VEHicle SIMulation Emissions
VSIME - Vehicle SIMulation Emissions (previous version of VEHSIME)
WEC - World Energy Council
WBCSD - World Business Council for Sustainable Development

1. INTRODUCTION

Economic development of industrialised society has largely depended on finite fossil fuel reserves. To sustain current economic growth and social development, energy resources and the environmental impacts of their use need to be monitored and carefully managed. The transport sector is one of the single largest consumers of energy, emitters of greenhouse gases and sources of air pollution. Quantifying the energy consumed and emissions produced by transport is essential for effective policy formulation and management of energy resources as well as global and local air quality. This thesis considers methods used to quantify fuel consumption and emissions from private passenger road transport within the context of urban energy and environmental management.

1.1. Background

1.1.1. The international context

Transport consumes a quarter of the global energy production and generates approximately one fifth of the worlds CO_2 emissions (IEA, 2000c). It also emits between one third and one half of regulated pollutants in developed countries on a national scale, depending on the species of pollutant (Ekström *et al.*, 2004; Pokharel *et al.*, 2002; Vasconcellos, 2001:187), and a larger proportion in urban environments in both developed and developing countries (Vasconcellos, 2001:186; Chin, 1996; Owen, 2000; Bose, 1998).

Crude oil provides 97% of the worlds transport energy (IEA, 2000a). The rate of discovery of conventional crude oil deposits is decreasing (Campbell, 1997; Deffeyes, 2005) and it is expected that oil demand will surpass global production within the next 25 years (Hirsch *et al.*, 2006). As the scarcity of oil increases, fuel prices are likely to increase and become more volatile as evident following recent fuel price increases. Increasing international oil demand and the consequent higher oil price are of concern for most countries as imported oil consumes foreign currency and economic development depends on affordable energy.

Fuel costs are only part of the true costs of transport. External costs, such as congestion, accidents and environmental pollution, are paid for by society in general in terms of human health, biodiversity, climate change, damage to property and loss of productive time. Evaluating external costs is an important part of realising the total economic and social costs of pollution and congestion from transport and other energy services (Bickel and Friedrich, 2005).

International and national agreements and legislation have created frameworks for stricter environmental management. These include the United Nations Economic Commission for Europe (UNECE) Convention on Long Range Trans-boundary Air Pollution (CLRTAP) 1979, the United Nations Framework Convention on Climate Change (UNFCCC) 1994, the EC Directive on Integrated Pollution Prevention and Control (Directive 96/61/EC) and the United States Clean Air Act of 1970 and its amendment in 1990. The development of national and regional emissions inventories and regular updates are required in terms of these agreements and legislation to guide climate change strategies and air quality management plans.

The above environmental frameworks have required that fuel consumption and emission factors from vehicles are evaluated of as part of several large programmes run by governments, automotive manufactures and energy companies including:

- *The European Modelling and Evaluation Program (EMEP).* One of the major objectives of the EMEP was to produce an atmospheric emissions inventory guidebook - CORINAIR (core European inventory of air emissions) as part of the UNECE CLRTAP (Hill, 2003);
- *The auto oil programmes.* These resulted in research and measurement sub-programmes in the United States, the European Union, Japan and other countries such as the US Air Quality Improvement Research Programme (AQIRP) and European Programme on Emissions, Fuels and Engine Technologies (EPEFE) (ACEA/EUROPIA, 1995). The purpose of these programmes was to guide the formulation of vehicle and fuel regulations and develop robust scientific methods for determining the most cost effective means of reducing emissions from vehicles;
- *The Sustainable Mobility Project (SMP)* (WBCSD, 2004). More recently, the World Business Council for Sustainable Development (WBCSD) forecast fuel consumption and emissions from 2005 to 2030 by projecting vehicle technology developments and their impacts on vehicle fuel consumption and emissions;
- *The European Cooperation in the field of Scientific and Technical Research (COST) directive.* These Research initiatives, combined with funding from the transport research and technological development action plan of the Fourth Framework

programme, has resulted in the MEET (Methods of Estimation Emissions from Transport) project to develop methods of modelling emissions;

- *The Assessment and Reliability of Transport Emission Models and Inventory Systems (ARTEMIS) project*. The purpose of the ARTEMIS project was to develop a unified methodology in the modelling and measurement of fuel consumption and emissions within the competitive and sustainable growth programme of the European environmental action plan of the Fifth Framework programme. ARTEMIS has a strong emphasis on the impacts of real-world driving cycles on emissions from vehicles to overcome the problems of the COST action and the MEET project (Andre, 2004; Joumard, 2006); and
- *The Clean Air for Europe (CAFÉ) programme* (EC, 2005). This is the most recent programme related to air quality in Europe and forms part of the Sixth Framework Environmental Action programme.

In addition to the above programmes, the International Energy Agency has provided several transport, fuel consumption and climate change publications (IEA, 1984; IEA, 1997, 2000a, 2000b, 2000c, 2004).

International measurement, modelling and evaluation of energy use and resultant air pollution are set to continue and become more sophisticated as long as there are negative environmental impacts due to human activity.

1.1.2. The South African context

In South Africa, the transport sector is the fastest growing energy consumer, growing by 27% between 1992 and 2000 (DME, 2003). Imported crude oil meets 17% of the total primary energy demand and most of this is refined into transport fuels (SANEA, 2003). In addition, synthetic fuels produced by liquefaction (the conversion of coal to liquid fuels) meet 30% of final liquid fuel demand. Coal liquefaction releases more CO_2 per litre of fuel product than production from crude oil, increasing the greenhouse gas contribution from transport in South Africa relative to other countries.

Increased demand for transport fuels is primarily due to economic development and the consequent increase in ownership and use of personal motorised vehicles. The majority of motorised vehicles in South Africa are cars, light delivery type vehicles (colloquially known as *bakkies*) and SUVs (sport utility vehicles) used for private passenger transport.

Cars, bakkies and SUVs are the least efficient and most polluting mode of passenger transport per person-kilometre in the context of urban environments (Vasconcellos, 2001:191).

Motorised transport, however, is an essential service in modern society. It facilitates economic development by providing a means to move large quantities of commodities over great distances and enhances the quality of life by providing more choices as to where people live, work and spend their free time. Energy consumed by motorised transport is influenced by urban density (Mindali *et al.,* 2004). The dependence on cars for commuting is particularly evident in South Africa where land use is dispersed and urban sprawl is a dominant feature of urban development, often rendering public transport uneconomical (Green and Mare, 1992; Naude, 1992).

Thirty eight per cent of the South African vehicle fleet is registered in Gauteng Province. A sustained average growth rate of 4% per annum over the last 5 years (NDOT, 2004; NAAMSA, 2006; NAAMSA, 2007) has increased demand for road infrastructure and further aggravated urban congestion and local environmental pollution. Within the largest South African cities liquid fuels represents approximately 50% of the energy demand (SEA, 2006), most of which is used for road transport. Addressing transport demands, associated energy requirements and pollution are major concerns for South African municipalities (COJ, 2007).

A major project to determine South African fuel consumption and emission factors, the Vehicle Emissions Project, was commissioned by the Department of Minerals and Energy in the mid 1990s (Wong, 1999). The purpose of this project was to measure emission factors for vehicles taken from the in-use, specifically South African, vehicle fleet, taking into account differences in vehicle technology and age, fuel composition and altitude of operation. The study considered technical aspects of local fuels due to the proportion of synthetic content; effects of altitude, as a large proportion of the fleet operates on the Highveld; and technical properties of vehicles such as fuel delivery systems (carburetted or fuel injected) and emissions controls (no emissions controls or with a catalytic converter). All these factors differ significantly from European, American or Japanese conditions. The intention of the study was to provide input data for an urban airshed dispersion model, which would then be used to guide regulation and management of vehicle emissions and urban air quality.

In addition to properties and regulations of vehicles and fuels, driving conditions play an important role in determining fuel consumption and emission factors for vehicles. The only study to compare South African driving conditions to those elsewhere was a study by Yates (1985). Yates considered the repeatability the European ECE15 driving cycle test procedure and its suitability to South African driving conditions. Three types of local trips were characterised to perform this comparison: a rush hour commute, a suburban route during midday and a central district trip. The ECE15 driving cycle was shown to be a poor representation of a typical combination of these three South African driving patterns, due to the high proportion of idling time in the ECE15 cycle. Yates concluded that the variability of driving parameters was primarily determined by the prevailing driving conditions. It must be stated, however, that the driving conditions during this period were influenced by South Africa's economic state and vehicle population at the time. A total of 2.1 million cars were registered in 1980 (Sweet, 1991:9.5) and 1986 had the highest inflation rate in the last 25 years (SANEA, 2003). The number of cars doubled by 2005 and inflation has been kept below double digits for the last 10 years. In real terms, the vehicle price inflation was actually negative for the years 2004-2006 (NAAMSA, 2007). This has encouraged rapid vehicle population growth with new vehicle sales doubling from 2002 to 2006, which would certainly result in different driving conditions between now and 22 years ago.

A need for further studies considering environmental externalities due to transport has been expressed by the National Department of Transport (NDOT, 2002: Section 7.3.2). Internalisation of external environmental costs into transport and energy costs is needed so that informed policy decisions can be made which maintain economic development while minimising environmental impacts.

In terms of the South African National Environment Management: Air Quality Act of 2004 (RSA, 2005: Sections 8 and 11), municipalities are required to develop air quality management plans. This has resulted in development of several energy and environmental activities within municipalities, such as the state of energy reports, state of environment reports and climate change strategies. These activities have encouraged academic institutions, municipalities and energy related organisations to collaborate in developing transport, energy and environmental management systems, methods and tools.

One such collaboration initiated to consider energy supply and use within the major metropolitan cities of Gauteng Province is EnerKey. EnerKey is a German - South African partnership initiated as part of the German Federal Ministry of Research and Education programme: *Megacities of Tomorrow: Research for Sustainable Development*. The programme provides a framework for German institutions to collaborate with international partners in developing and implementing practical and original ideas for managing, in a sustainable manner, the rapid growth of cities or regions that are the size, or approaching the size, of a Megacity (> 10 million people). One of the main themes of the EnerKey project is to consider what can be done to minimise fuel consumption and emissions from transport in the Megacity of Gauteng Province, comprising the rapidly merging cities of Johannesburg, Tshwane and Ekurhuleni.

The City of Johannesburg is in the process of implementing an air quality management plan, which includes developing an emissions inventory and an atmospheric pollution dispersion model. An important part of this process is to determine vehicle fuel consumption and emission factors for local driving conditions. The framework of the EnerKey project and the current activities at the City of Johannesburg provide a context for this study.

1.2. Problem statement

The central problem addressed in this thesis is the need for local fuel consumption and emission factors for real-world driving conditions, operating environments and driving styles required to develop accurate mobile emissions inventories.

South Africa does not have the technical and financial resources needed to develop real-world emission factors using conventional methodologies, such as those used in mobile emissions inventories in wealthier counties. Lower cost alternatives have included dynamometer emissions tests using standardised driving cycles (Wong, 1999) and adoption of European and US emission factors embedded in emissions simulation models (Burger *et al.*, 2002). Standardised driving cycles are useful for comparing fuel consumption and emission factors for different vehicles on a normalised basis for emissions certification purposes, but are inadequate in representing real-world driving. Real-world fuel consumption and emission factors developed from detailed emissions measurements are available from emissions simulation models such as EMIT (CERC, 2007), COPERTIII (Ntziachristos and Samaras, 2000) and the HBEFA (de Haan and Keller, 2004a). These models, however, represent emission factors for real-world driving conditions in countries and regions in which they were developed, which do not match the driving conditions in South Africa due to differing driving styles, topology and atmospheric conditions (temperature ranges, pressure altitude).

The City of Johannesburg is in the process of adopting a modelling approach to develop their mobile emissions inventory. This has involved the integration of an emissions simulation software package, EMIT (EMissions Inventory Toolkit), and a transport network model called EMME/2 (COJ, 2003). EMIT is based on emission factors for average vehicle speeds of real-world driving cycles measured in Europe (CERC, 2007). EMME/2 uses the Urban Transport Planning process (Dimitriou, 1992) to determine average vehicle speeds for various road types and times of day, and total vehicle activity. The emissions inventory is built by combining emissions factors from EMIT for average speeds and vehicle kilometres determined by EMME/2 for different road facilities and the structure of the vehicle fleet. The current method does not consider differences in operating environments, auxiliary equipment use and driving style between Europe and South Africa.

In addition to the international models, such as EMIT, being unable to representing local driving conditions, they require detailed information about road gradient, auxiliary equipment use and gear change schemes to accurately simulate emission factors. This information is not readily available for South African cities and would need to be determined to fully benefit from the capability of the available models. Detailed research programmes to collect data for these models represent a considerable investment. In this thesis, I set out to develop a new method to simplify emissions simulation and data collection, which will account for local vehicle usage profiles, operating environments, auxiliary equipment use and driving styles, appropriate for South African cities.

Existing international emission simulation models depended on emission factors for driving cycles (the variation of vehicle speed with time) to estimate emissions for real-world driving. Emissions factors, however, can be simulated with greater accuracy using detailed engine operating parameters, such as engine speed and engine load, because emissions rates have a closer causal relationship to engine-operating parameters than vehicle speed. Use of *vehicle speed* as the sole determinant for emission factors ignores impacts due to road gradient, auxiliary equipment use and driving style (gear change preferences). Driving cycles are related to engine operating parameters, however, via the gearbox of a vehicle, which is why they have been used as a suitable proxy for engine operation in the development of emissions simulation models. Vehicle speed has also been easier and cheaper to measure in the past than engine operating parameters.

Developments in international vehicle emissions legislation and consequent vehicle regulations have resulted in the implementation of on-board diagnostics (OBD) standards. Although the original purpose of OBD capabilities in vehicles was to aid in the inspection and maintenance functions, use of OBD facilitates a practical and affordable means to measure vehicle operating parameters such as engine speed and engine load during normal (real-world) vehicle use. OBDII is the second version of the international OBD standards (ISO 15031 and SAE J1979) for light duty vehicles. OBDII specifies the details of a standardised communications port and data transfer protocol to provide access to the sensors built into modern vehicle engine-management systems. Vehicles sold in the United States were required to have OBDII implemented from the year 1996. In the European Union OBDII was required from the year 2000. OBDII is not required by law in South Africa, but many imported vehicles and vehicles manufactured for export have OBDII implemented.

Small readily available OBDII data loggers can be plugged into the standardised OBD port of a vehicle to record a variety of engine-operating parameters for research purposes (Barlow and Green, 2002). Combined with GPS (Global Positioning System) and an appropriate emissions simulation model, which uses emissions characteristics of engine-operating parameters, accurate fuel consumption and emission factors can be allocated to different road types and times of day without knowing specific details of the operating environment, auxiliary equipment use and driving styles. This forms the basis for an original method to develop emissions inventories for South African cities.

1.3. Hypothesis

Cost-effective and accurate mobile emissions inventories can be produced from (i) an emissions simulation model based on laboratory-determined patterns of engine load and engine speed; and (ii) electronic surveys of real-world vehicle behaviour and engine-operating parameters, using on-board diagnostics and Global Positioning System sensors.

1.4. Objectives

The purpose of this study is to show that vehicle emissions inventories can be accurately and cost effectively produced by measuring engine-operating parameters, vehicle usage profiles and an appropriate fuel consumption and emissions simulation model.

The objectives of the study are thus to:

- Design and validate a new emissions simulation model to estimate fuel consumption and emission factors based on engine-operating parameters using published data;
- Determine vehicle usage profiles, driving conditions and corresponding engine-operating parameters by monitoring (surveying) vehicles used in their day-to-day routines in the City of Johannesburg as a case study; and
- Demonstrate the procedure of producing an emissions inventory for Johannesburg by integrating data from the vehicle survey and the new emissions simulation model.

The aim of this study is build the necessary tools and to demonstrate that the they are appropriate and cost effective in determining proportions of driving conditions and corresponding emission factors for a fleet of vehicles in Johannesburg.

1.5. Scope

This study considers the processes used to develop vehicular emissions inventories. The focus is on how fuel consumption and emission factors are modelled with respect to engine-operating parameters. Data collection procedures are developed for implementation of an emissions simulation model and applied in a limited case study. Impacts of driving conditions on engine-operating parameters, influences of vehicle properties (fuel type, capacity class and emissions regulations), and resulting fuel consumption and emission factors are studied.

Although altitude and temperature play a role in engine performance and emissions formation, these effects were not explicitly considered. However, measured engine loads implicitly include the influence of atmospheric pressure and temperature for the same diving cycles within different atmospheric conditions.

Regulated emissions (NO_x, CO and unburned hydrocarbons: HC), fuel consumption and CO_2 from private passenger vehicles (cars, bakkies and SUVs) that conform to Euro-0 (a mixture of pre-Euro-1 vehicles), Euro-2 and Euro-3 regulations for petrol vehicles and Euro-2 regulations for diesel vehicles are considered.

The survey area for the case study was selected within the municipal boundary of City of Johannesburg. Johannesburg is one of the largest cities in South Africa (in terms of population) and is home to a large proportion of the South African vehicle fleet, making it an appropriate area to consider the energy use and environmental impacts of road transport in urban areas.

1.6. Assumptions

The vehicle survey relied on equipment (OBD data loggers) that is only compliant with Euro-3 and higher emissions regulations. It was assumed that vehicles of the same fuel type and engine capacity class would have similar engine-operating patterns for the same driving conditions irrespective of vehicle age and emissions regulation compliance.

During the survey, it was assumed that volunteers would not change their driving styles due to the knowledge that their driving was being monitored.

The study provides a theoretical approach to estimating fuel consumption and emission factors. It relies on emission factors from emissions measurements done elsewhere. The emissions considered are therefore limited to published measurement programmes. The South African emission factors (Wong, 1999), although adjusted to local conditions, were integral measurements over complete driving cycles, and hence do not provide a suitable set of *base* vector engine-operating parameters for this study.

Vehicle age, mileage, cold starts and evaporative emissions are not considered during this study, although data collected during the study could be used to quantify the number of cold starts.

This study is a proof of concept. It provides a method to collect data, simulate emission factors from the data and uses a case study to demonstrate the overall process. The case study was not intended to be a comprehensive representation of vehicle emissions in the City of Johannesburg, but aimed to demonstrate a new method to produce a local emissions inventory, which accounts for local driving conditions and driving styles.

The proportions of vehicles complying with various emissions regulations were roughly estimated for the purposes of demonstrating the overall emissions inventory development process. An extensive survey of automotive manufacturers would be required to determine the actual shares of emissions regulation compliance, which is beyond the scope of this study.

1.7. Definitions

Common terms used within the development of emissions inventories and fuel consumption and emission factors are provided below.

Emissions inventories

Vehicle emissions inventories quantify the energy consumed and emissions produced by transport and provide source data for atmospheric pollution dispersion models, and transport and energy decision support systems. Emissions inventories are produced by summing the product of vehicle activity (in km) and corresponding emission factors for each vehicle type, vehicle capacity class and driving condition in a study area. Accuracy of vehicle emissions inventories is determined by aggregation of different dimensions, such as the number of unique driving conditions and the number of divisions of vehicle capacity classes within a fleet.

Fuel consumption and emission factors

An emission factor is the rate at which a pollutant is emitted into the atmosphere from an emissions source, such as a factory or a vehicle. Emission factors are expressed as the mass of a pollutant emitted per unit of time or the mass of pollutant emitted per unit of distance travelled ($g\ km^{-1}$), in the case of vehicles. A fuel consumption factor is the rate at which fuel is consumed and is expressed in the same manner as emission factors.

Fuel consumption and emission factors are determined by:

- Vehicles and fuels: The physical properties of a vehicle such as mass, drag coefficient, engine and drive train technologies and the properties of the fuel it uses such as the octane or cetane number, vapour pressure, and any additives it contains;
- Operating environment: The environment in which the vehicles operate including road type, gradient and surface, air density, humidity and temperature and the driving conditions determined by the number of vehicles sharing the same road space (level of congestion); and

- Driving style: The level of acceleration and braking, time spent at different speeds and gear choices are determined by the driver's responses to the operating environment.

Vehicle fuel consumption and emission factors used in emissions inventories are typically defined for various combinations of the above dimensions.

Fuel consumption and emissions maps

Fuel consumption and emissions maps describe the fuel consumption and emissions characteristics of engines. Fuel consumption and emissions rates are represented as constant fuel consumption and constant emission rate lines in a graph of engine speed and engine load. An example of a fuel consumption map is represented in Figure 1.1. The fuel consumption and emissions for a specific engine-operating point are determined by interpolating between contour lines for any engine speed and engine load. The fuel consumption and emissions for a trip are determined by integrating the path of engine operation through the fuel consumption and emissions maps. Generalised fuel consumption maps have been developed by Golverk (1992 and 1994) while Shayler *et al.* (1999) describe a method of predicting fuel consumption maps.

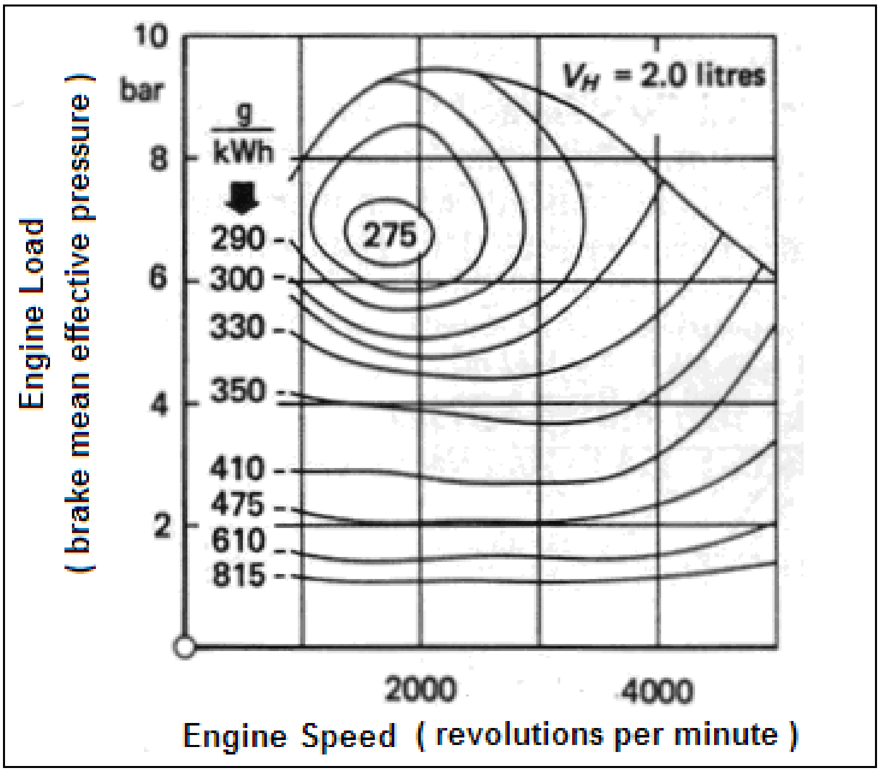

Figure 1.1: An engine fuel consumption map (Hucho, 1987)**.**

Drive train

The drive train of a vehicle determines the relationship between engine-operating parameters and vehicle movement. A drive train consists of all the mechanical components between the engine and the road surface. The gearbox is the most significant component in the drive train in terms of fuel consumption and emissions because it determines the operating regimes within the fuel consumption and emissions maps of an engine. The driver of a vehicle uses the gearbox to match the capabilities of the engine to the desired movement of the vehicle and operating environment; hence, the driving style (choice of when the driver changes gears) can have a significant impact on fuel consumption and emissions.

Congestion

Congestion is typically defined using the increase in travel times during busy periods compared to travel times in quiet periods. A travel time index, which is the ratio of travel time during peak periods to ideal travel time obtained during free-flowing traffic conditions, is often used to quantify congestion (Cambridge Systematics Inc., 2004). Road type and time of day influence congestion due to road design capacities and commuting periods. Congestion is therefore influenced by driving conditions.

Driving conditions

Driving conditions can be defined using a description such as *stop-and-go freeway driving with an average speed of 45 km* h^{-1}. Driving conditions need quantifiable definitions so that they can be reproduced in a controlled environment for the measurement of fuel consumption and emission factors. Vehicle speed and other kinematic parameters are often used to quantify driving conditions.

Vehicle kinematics

Vehicle kinematics such as average vehicle speeds and driving cycles are often used to characterise fuel consumption and emission factors used in emissions inventories. Kinematics are useful proxies for engine-operating parameters because they provide a means to aggregate fuel consumption and emissions from vehicles, can be used to describe driving conditions and are directly linked to engine-operating parameters by the drive train of a vehicle.

Driving cycles

A driving cycle is a detailed kinematic description of the motion of a vehicle in the form of a speed-time series (typically at a 1 Hz frequency) in response to the driving conditions experienced during a trip. Driving cycles do not describe other aspects of the operating environment such as atmospheric conditions and road gradient.

Standardised driving cycles

Standardised driving cycles are used to represent typical trips experienced in a city, country or region. They are used to develop emission factors for the comparison of vehicles on a normalised basis and for vehicle homologation (confirmation that the vehicle emissions conform to regulations). The US FTP75 driving cycle, which was developed from speed measurements made during typical morning commutes in California is illustrated in Figure 1.2. The history of driving cycle development for California and used by the US EPA has been described by Austin *et al.* (1993). The NEDC (New European Driving Cycle) developed using aggregated information from trips made in the European Union is shown in Figure 1.3.

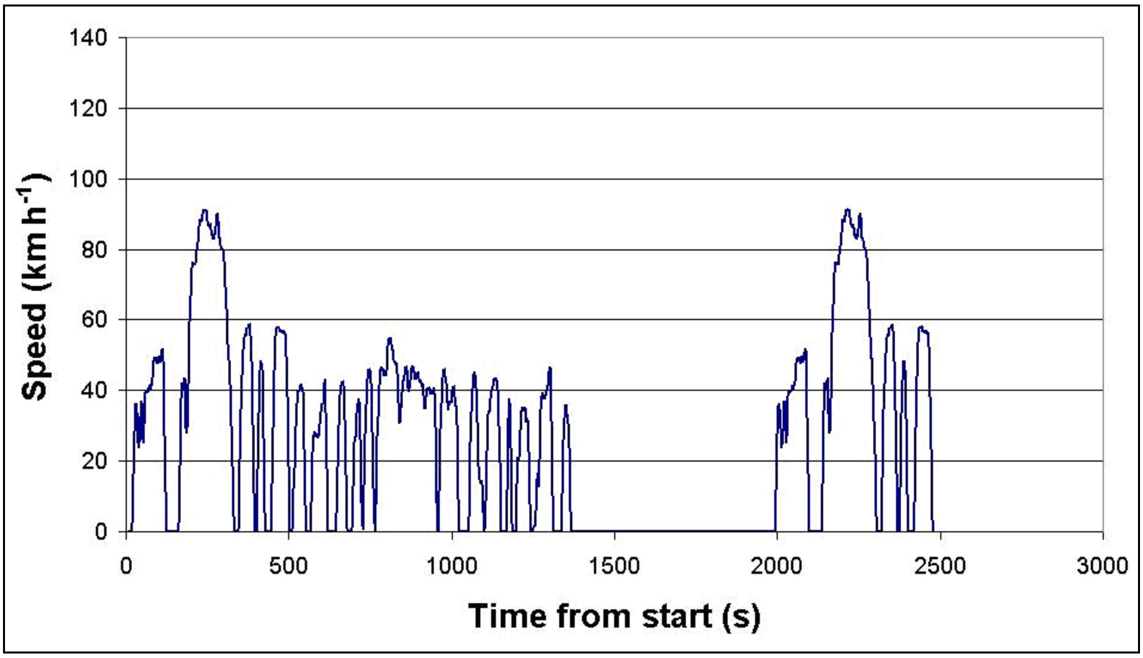

Figure 1.2: The US FTP75 driving cycle.

The NEDC is an artificial cycle in that it is constructed out of repetitions of driving modes of acceleration and constant speeds. The NEDC contains the original ECE15 driving cycle combined with a suburban driving pattern, which was added in 1993 (Robert Bosch GmbH, 2000).

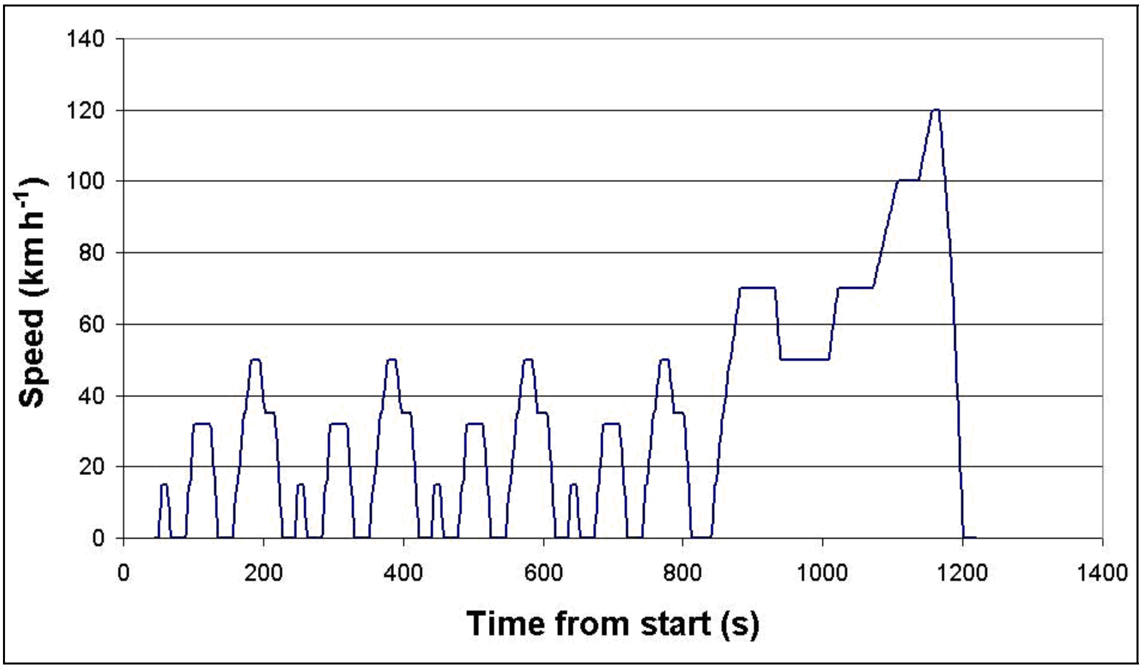

Figure 1.3: The New European Driving Cycle (NEDC)**.**

Standardised driving cycles typically represent commuter trips and do not describe all the conditions that may occur in a city, which vary by both location and time of day. Several driving cycles are needed to describe all the driving conditions used to build emissions inventories

Real-world driving cycles

Real-world driving cycles represent a large range of driving conditions that may occur in reality and are developed using data collected from many hours of driving. Several real-world driving cycles have been developed and tested to produce a large set of real-world fuel consumption and emission factors. The combined ARTEMIS driving cycles (CADC) (de Haan and Keller, 2001; Andre, 2006; Joumard, 2007) and the EMPA Real-world driving cycles (Stahel, 2000; de Haan, 2004b) are examples of real-world driving cycles. Real-world driving cycles are often classified into groups of driving conditions such as freeway driving, urban driving and inner city driving representing sub-cycles. The sub-cycles are divided further into driving patterns that describe the individual driving conditions.

Driving patterns

Driving patterns are parts of driving cycles that have uniform characteristics such as a confined range of speeds or repetitions of acceleration and deceleration. An example of real-world driving conditions (representing freeway driving) divided into three driving patterns is presented in Figure 1.4. The driving pattern represents a relatively uniform combination of road type and driving condition.

Driving cycles and driving patterns can be represented in alternative formats to provide a different view of driving conditions.

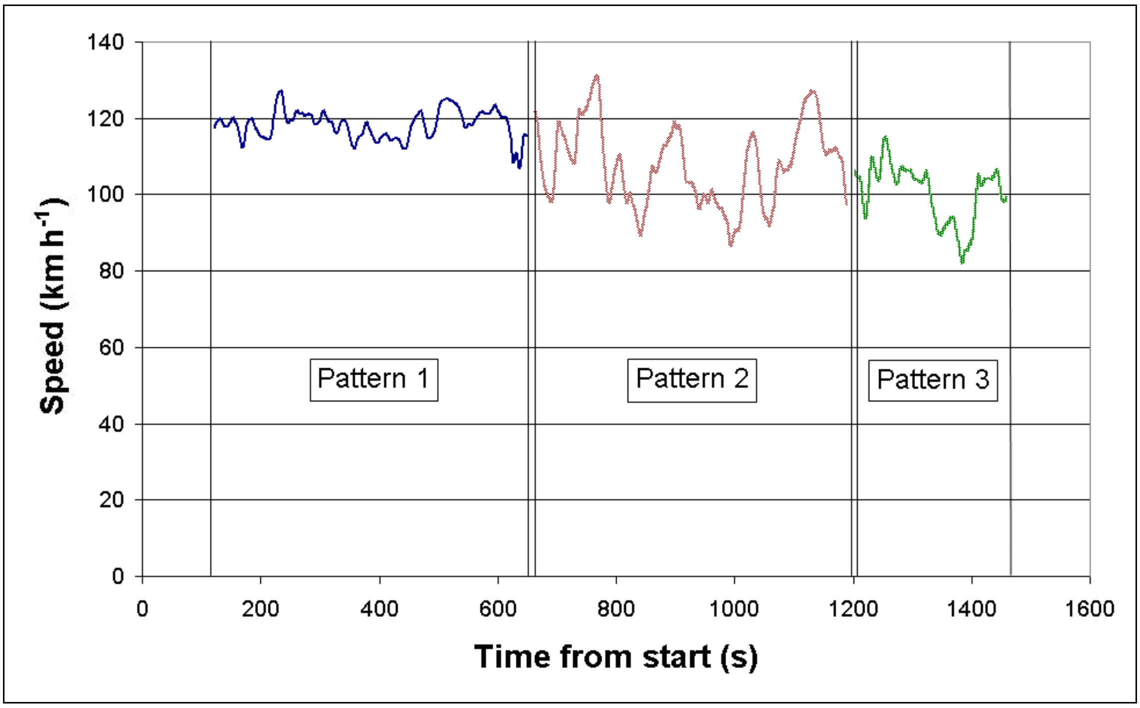

Figure 1.4: Real-world driving conditions for freeways, represented by 3 driving patterns typical of various states of free flowing traffic or congestion.

Scatter plots

A scatter plot is produced by plotting all data points for a driving cycle on a graph of *speed* vs. *acceleration* or of *speed* vs. (*speed* × *acceleration*). The reason for using *speed* vs. (*speed* × *acceleration*) is that the power demand of a vehicle is determined by a function of both *speed* and (*speed* × *acceleration*). Scatter plots show the dominant driving modes experienced during driving cycles. The FTP75 cycle is used as an example in Figure 1.5 to demonstrate the use of a scatter plot. The scatter plot emphasises the dominant operating speeds of 45 km h^{-1} and 85 km h^{-1}.

The New European Driving Cycle, the US FTP75 driving cycle and real-world driving patterns are compared using scatter plots in Figure 1.6, which clearly shows that standardised driving cycles do not represent all driving conditions encountered in real-world driving conditions.

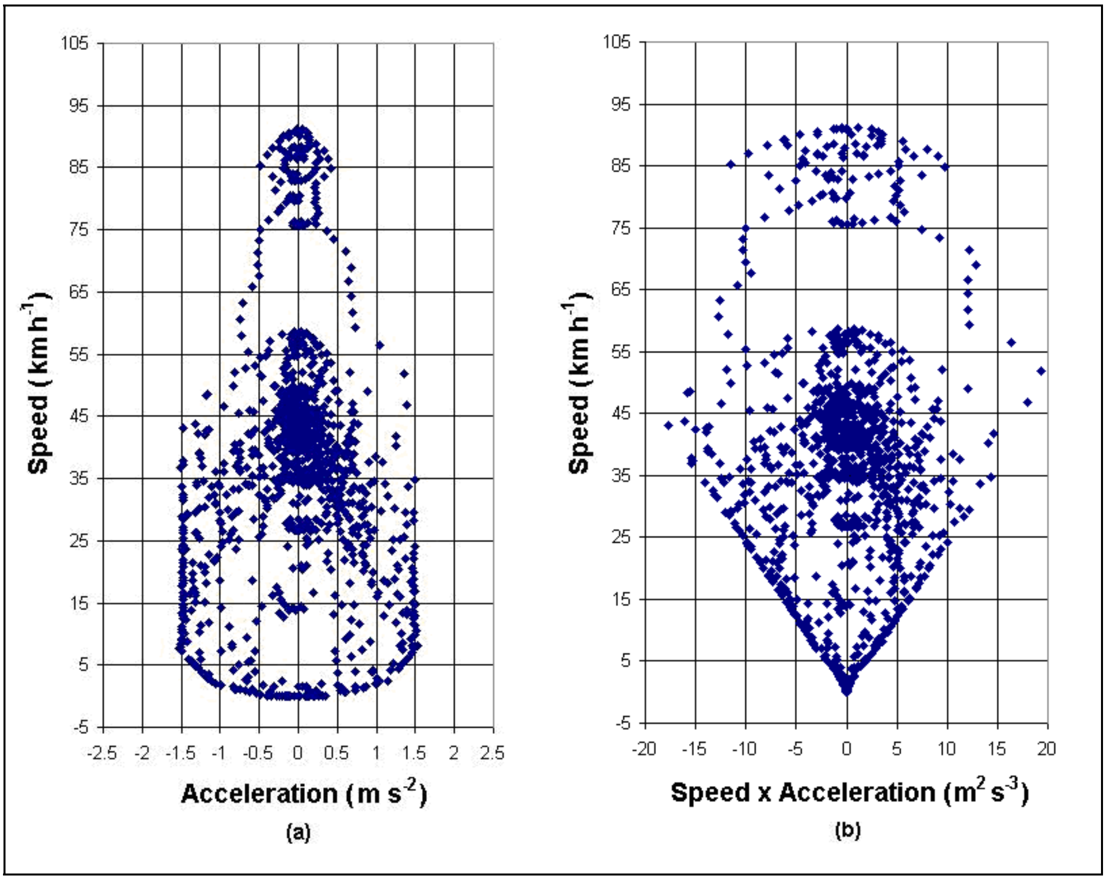

Figure 1.5: Scatter plot of FTP75 cycle (a) using *speed* and *acceleration* and (b) using *speed* and (*speed* × *acceleration*). (Generated by the author from the US FTP75 driving cycle data shown in Figure 1.2.)

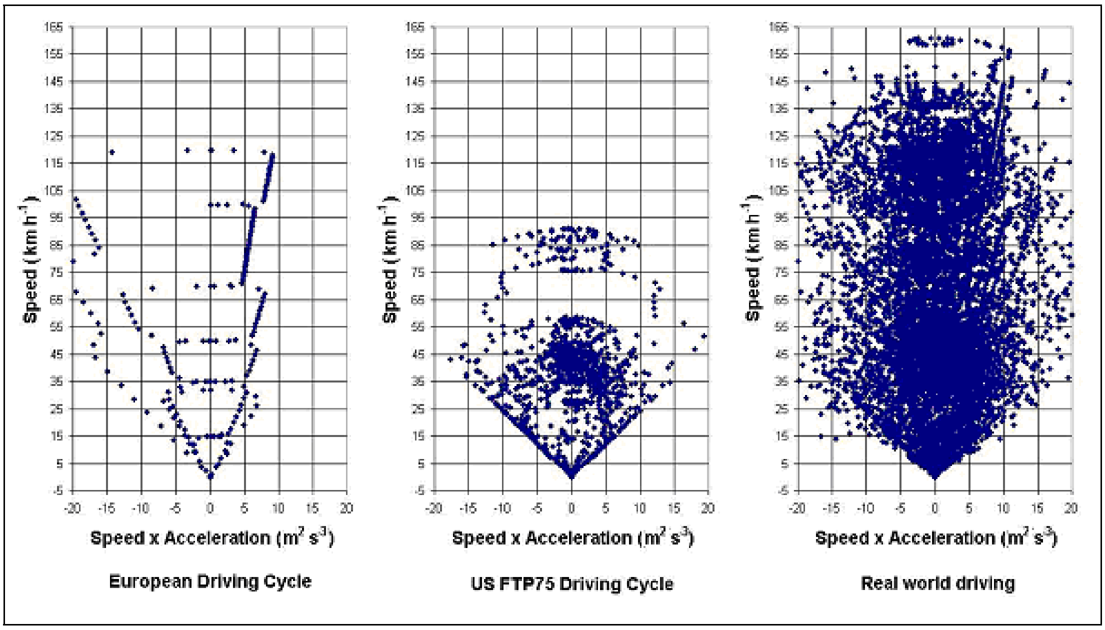

Figure 1.6: Comparison of standardised driving cycles and real-world driving cycles. (Generated by the author from the driving cycle data presented in Figure 1.3 for the NEDC, Figure 1.2 for the US FTP75 and the EMPA Real-world driving cycles (Stahel, 2000; de Haan, 2004b).)

Scatter plots contain many data points, many of which overlap. It is convenient to aggregate the scatter plots using frequency plots.

Frequency plots

Frequency plots not only show dominant driving modes but also quantify the proportion of time spent in each mode. The scatter plot in Figure 1.5a is simplified by aggregating the values into intervals of speed and acceleration as demonstrated in Figure 1.7 using a three dimensional frequency plot of speed and acceleration and the percentage of time in the speed acceleration mode. The frequency plot of speed and acceleration is sometimes referred to as a *Watson plot* (Austin *et al.*, 1993).

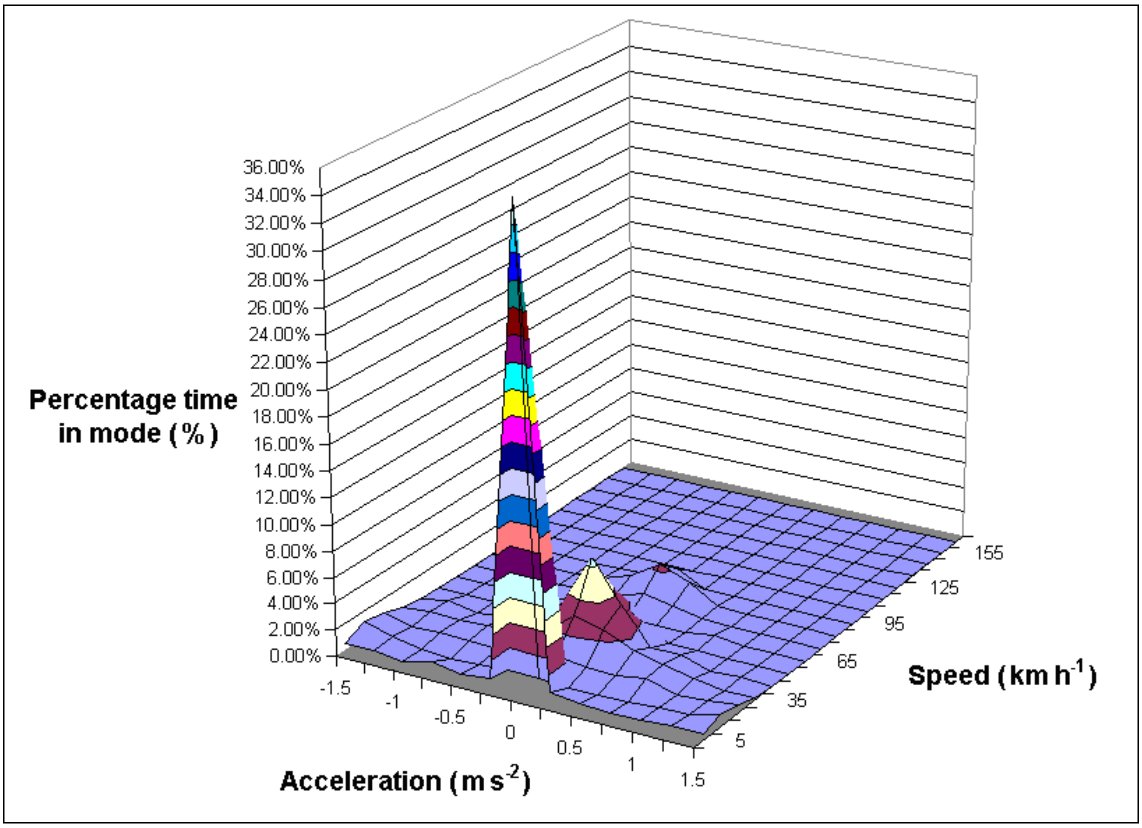

Figure 1.7: Frequency plot of *speed* vs. *acceleration* (or Watson plot) of the FTP75 cycle. (Generated by the author from the US FTP75 driving cycle data shown in Figure 1.2.)

Bubble plots

Frequency plots can also be represented using a bubble plot as in Figure 1.8 which is Figure 1.5b transformed into a bubble plot of *speed* and (*speed* × *acceleration*) and the percentage time in each interval. The bubble plot representation is the preferred method in this study and will be used to compare driving conditions and engine-operating parameters later in this thesis.

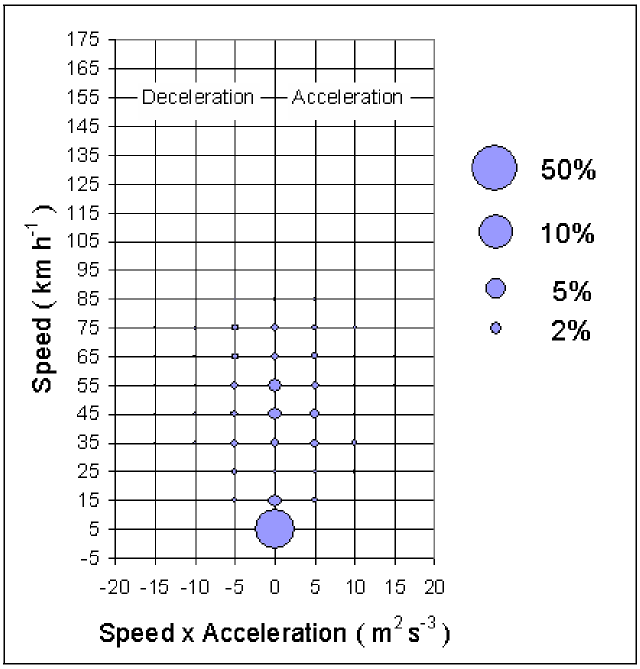

Figure 1.8: Frequency plot of *speed* vs. (*speed* × *acceleration*) for the FTP75 driving cycle. (The circles represent the proportion of time spent in an operating state during a driving cycle.)

Emissions measurements

Once driving conditions have been defined emission factors can be determined for the combinations of driving conditions and types of vehicles. The most common method used to produce emission factors is to simulate driving cycles on a chassis dynamometer while sampling the exhaust gases.

Chassis dynamometer

A chassis dynamometer consists of a set of rollers that support the driving wheels of a vehicle. The energy produced by the vehicle is transmitted by the rollers to a mechanical brake or electrical load where it is dissipated. A driving cycle is simulated on a dynamometer by varying the load applied to the rollers, which is equivalent to the aerodynamic drag, inertia and rolling resistance of the vehicle determined by the kinematics described by the cycle.

A standardised operating environment (atmospheric temperature and pressure, and a level road gradient) is often assumed when simulating driving cycles on a dynamometer so that the impact of driving conditions on fuel consumption and emission factors can be compared on a normalised basis. In addition to the environmental assumptions all auxiliary equipment, such as air conditioners and heaters, are turned off and a fixed gear-changing scheme is assumed, unless these aspects are the specific focus of a test being conducted.

Constant volume sampling (CVS) method

Emission factors for driving cycles are determined by capturing samples of the exhaust gases in bags. This is called the *constant volume* sampling method. The mass of the individual pollutants determined from the contents of the bag are divided by the distance of the cycle to produce an emissions rate in $g\,km^{-1}$. Separate sampling bags are used to capture the emissions for each of the driving patterns within a real-world driving cycle to produce emission factors for different driving conditions.

Instantaneous emissions measurements

Emission factors can also be determined from instantaneous emissions measurements using specialised gas analysis equipment. The emission factors for driving patterns are determined by integrating the instantaneous emissions measurements for the corresponding parts of the simulated driving cycles. Instantaneous emissions measurements can also be used to produce fuel consumption and emissions maps. By sampling at a frequency between 1 and 10 Hz during the simulation of real-world driving cycles, emission factors can be determined for a large combination of engine speeds and engine loads.

Remote emissions measurements and on-board emissions measurements can be used to determine emission factors without using a dynamometer.

Remote emissions measurements

Remote emissions measurements of pollutants and speed can be made from the side of the road using remote sensors. Remote sensing has been used in a number of studies. Singer and Harley (2000) developed a fuel based emissions inventory for Los Angeles using remote sensing. Pokharel *et al.* (2002) developed fuel based emission factors for Denver from on-road emissions measurements. Schifter *et al.* (2005) used a method similar to Pokharel to develop a fuel based emissions inventory for Mexico City. Roadside tests are often location specific but are useful in the calibration or validation of emissions simulation models and provides a method for developing speed dependant emission factors. Remote emissions measurements are viewed as being more accurate than emissions models based on dynamometer tests. This is because remote emissions measurements are made in-situ whereas dynamometer measurements are from limited vehicle tests which assume certain aspects of the operating environment such as atmosphere temperatures and pressures (Pokharel *et al.,* 2002).

On-board emissions measurements

On-board emissions measurements provide another means to develop emission factors. Emissions and vehicle operation, such as vehicle speed and CO, are constantly monitored using portable emissions and vehicle operation monitoring equipment temporarily installed in a vehicle. On-board measurements are valuable in that they can include both environmental conditions and driving styles in the measured emission factors. Frey *et al*. (2000) provide an analysis of driving modes and emissions using on-board emissions measurements to study the effect of traffic light timing in North Carolina while Casanova *et al*. (2007) compared economical and aggressive driving styles in Spain. On-board emissions measurement, however, is expensive and time consuming to use on many vehicles and on different routes required for estimating total emissions for a city.

1.8. Structure of thesis

A review of relevant literature is presented in Chapter 2. Decision support systems are introduced as tools used to formulate transport and energy policies that influence fuel consumption and emissions. Emissions inventories are discussed as they provide the fuel consumption and emission factors used in the decision support systems. Examples of emissions inventories are presented. Finally, fuel consumption and emissions simulation models used to produce fuel consumption and emission factors based on driving conditions and other parameters are discussed in more detail.

Modelling concepts and data collection procedures to develop a fuel consumption and emissions simulation model and an emissions inventory model for local driving conditions are detailed in Chapter 3. The chapter is divided into three main sections. The first deals with a method used to develop *base* engine-operating patterns as a prerequisite for the development of a new fuel consumption and emissions simulation model. The second describes the equipment and procedure used to survey travel behaviour and engine-operating parameters needed to simulate local emission factors using the proposed fuel consumption and emissions simulation model. The third section presents a framework to build a local emissions inventory using the simulation model and vehicle activity measured during the survey.

Implementation of the conceptual methodologies derived in Chapter 3 are presented in Chapter 4 as software components and their simulated results, coded and executed as part of the original contribution of this thesis. The structure and implementation of the fuel consumption and emissions simulation model is discussed and its validity, uncertainties and sensitivity are considered. The proportion of driving conditions and distances travelled by vehicles of various fuel types and capacity classes are provided along with the corresponding engine-operating patterns from the travel and engine-operating parameters survey. Fuel consumption and emission factors, simulated using the model and survey data, are presented as part of an emissions inventory development, which is finally used to evaluate total private passenger vehicle emissions in the City of Johannesburg.

A summary of the study and conclusions, including recommendations for further work, are given in Chapter 5.

2. LITERATURE REVIEW

2.1. Introduction

In this chapter, the role of models in policy formation is introduced. Decision support systems (DDS) used by decision makers to formulate policies are presented. Vehicle emissions inventories, which incorporate fuel consumption and emission factors for various vehicle types and driving conditions, are then discussed. A few of the better known emission factor databases are considered. Finally, methods used to estimate emission factors used to construct emissions inventories are studied in more detail.

2.2. The role of models in policy formulation

Transport, energy and environment policy makers need tools to evaluate economic and environmental impacts of their decisions. Policy options may include congestion charging (Beevers and Carslaw, 2005), fuel pricing (Nakata, 2003), road pricing and quota schemes (Chin, 1996), emissions and fuel economy standards (Decicco, 1995; Gan, 2003), emissions taxes (Sevigny, 1998) and promotion of public transport (Dhakal, 2003).

Mathematical models of transport and energy systems are useful tools in formulating and evaluating such policies. In this study, a model is defined as a calculation procedure, or set of calculation procedures, used to calculate fuel consumption and emissions from transport. The calculations are based on a simplified mathematical representation of physical processes taking place within transport systems, primarily movement of vehicles and production of fuel consumption and emissions from vehicles due to their characteristics and operating conditions.

There is no single model that is able to perform the complete process of calculating fuel consumption and emissions from chemical reactions in the combustion chamber to the total fuel consumption and emissions emitted at street level for a fleet of vehicles. Such a model would be impractical and require large quantities of data and computing power to operate. To simplify complex processes occurring in reality, detailed technical models are often nested within larger economic or decision support model, as in Figure 2.1. Smaller models, which consider physical processes, are used to produce data for higher-level models, which aggregate or sum the effects of the physical processes taking place, by making assumptions about processes and interactions between processes. These assumptions are relevant to the particular question being asked and the objectives of the model. In this way, only data relevant to the case in question are needed.

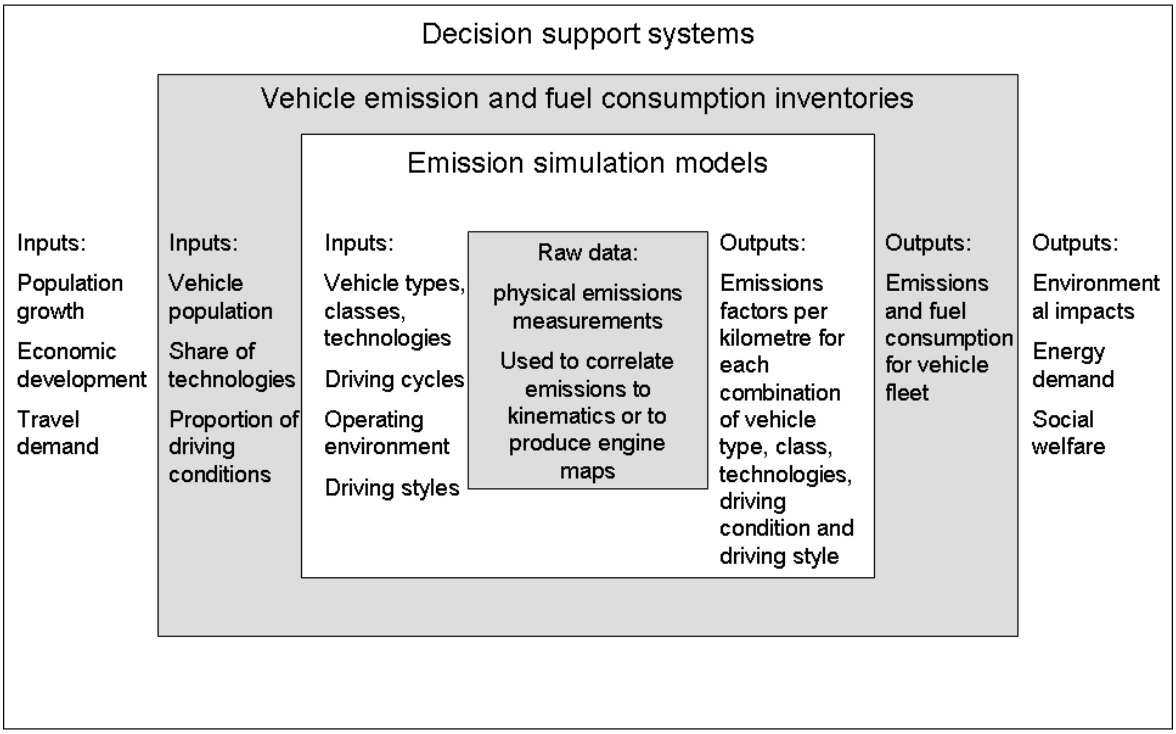

Figure 2.1: Nesting of different levels of models.

There are a large number of models in the literature relating to estimating emissions from transport. Decision support systems are used to evaluate policies using macro economic and population information (Brand *et al.,* 2002; De Ceuste *et al.*, 2006; and DOE/EIA, 2004). Some decision support systems combine emissions models and geographical information systems to simulate the distribution of transport emissions (Arampatzis *et al.*, 2004). Emissions inventories and emissions simulation models consider fleet structure, vehicle activity and driving conditions (de Haan and Keller, 2004a; Ntziachristos and Samaras, 2000). Micro-simulation models estimate the emissions released during chemical reactions, which take place during combustion (Gordon and McBride, 1994; Heywood, 1988).

Many of the existing models have been reviewed and compared by other authors. Jebaraj and Iniyan (2004) review energy models used in India. Wohlgemuth (1998) reviewed the International Energy Agencies transport energy modelling method. In the context of South Africa, Cooper (1988) provided a review of energy models and Mirilees (1993a, 1993b) provided a review of energy models relevant to transport.

2.3. Decision support systems

Decision support systems are tools used by policy makers to quantify environmental, social and economic impacts of transport and energy services. These systems use macro economic and population information such as economic activity (GDP), household incomes and total travel demand to derive total fuel demand and atmospheric pollution. They often take the form of complex computer programmes that forecast, simulate and optimise effects of policy options for different scenarios and include the ability to consider environmental externalities. Many transport decision support systems rely on the urban transport planning (UTP) process. The urban transport planning process, a few relevant decision support systems and their respective data requirements are considered in the following subsections.

2.3.1. The urban transport planning (UTP) process

The urban transport planning process uses a generalised model to estimate travel demand and future transport infrastructure requirements. The UTP process is discussed here because it often forms part of transport and energy decision support systems. Bruton (1978) and Dimitriou (1992) provide descriptions of the UTP process and Kohoutek *et al.* (1999) described a software implementation of the UTP process, including the simulation of emissions. A brief description of the UTP process is given here.

The UTP process involves four consecutive steps: trip generation, trip distribution, modal split and traffic assignment. Trip generation models the motivation for making a trip using demographic information obtained from household surveys such as household income, number of members in the household and ages of the members in the household. Trip distribution estimates the distribution of trips between origin-destination pairs based on sizes of the respective areas and distances between them. Household and roadside surveys are used to calibrate trip distribution estimates. Trips are then divided into different modes of transport depending on levels of income, vehicle ownership and accessibility to public transport. Once the number of trips, their origins and destinations, and their modal share have been estimated, routes that are used to execute trips are determined using traffic assignment or network models. Network models are calibrated using traffic counts at selected points within road networks.

Outputs from the UTP process include *travel demand* (vehicle kilometres) and *traffic flow* (vehicles per hour) for various areas and times day. This information, together with speed-flow relationships (determined from sampled traffic flow and speed measurements during traffic counts), provides average speeds experienced along different routes. Traffic flow, average speed and corresponding emission factors for various vehicle types provide information needed by some decision support systems and emissions inventory models to evaluate total fuel consumption and emissions for a study area (TRB, 2000; Brand *et al.*, 2002). Other decision support systems substitute average speed and their corresponding emission factors for other parameters such as speed and acceleration (de Haan and Keller, 2004a).

2.3.2. TRAN

TRAN is the transport sub-model of the United States of America's National Energy Modelling System (NEMS) (DOE/EIA, 2004). NEMS is a suite of models used by the US Energy Information Agency (EIA) to estimate the demand, supply, conversion and economic impacts of energy use within the different sectors of the US economy. The purpose of TRAN is to forecast energy demand, vehicle fleet structure and emissions from transport.

The structure of TRAN, inputs from the other models in NEMS and outputs are illustrated in Figure 2.2. Inputs into TRAN include fuel prices, new vehicle sales by region, economic data (such as GDP and income distribution), demographic data (such as population and age distribution) and defence spending. Outputs from NEMS are fuel use by region, fuel efficiencies, vehicle miles travelled and emissions.

The NEMS transport model consists of seven sub-models (shaded blocks in Figure 2.2). The modules of most relevance to this study are the LDV (Light Duty Vehicle) Module, the LDV Fleet Module, the LDV Stock Module and the Emissions Module. The LDV module forecasts market share of technologies used in new vehicles based on fuel prices, economic indicators, demographics and fuel efficiency. The module also estimates fuel economies of new vehicles. The LDV Fleet Module calculates travel demand for fleets of vehicles used by companies and utilities. Fuel demand and efficiencies are calculated using the updated vehicle fleet estimated from the market shares of new vehicles. The module also evaluates the number of vehicle sold off to private use. The LDV Stock Module calculates new efficiencies, population structure and fuel consumption of the vehicle population not owned by vehicle fleets.

Although the emissions module is currently inactive, its purpose is to aggregate transport emissions based on vehicle technologies, fuel prices, alternative fuels and efficiencies. Emissions considered are SO_2, NO_x, carbon and VOCs (volatile organic compounds). A likely candidate for the emissions module of the TRAN model is MOBILE6 (TRB, 2000), or a more recent version of the same model called MOVES (TRB, 2000; Boulter, 2007), developed by the US Environmental Protection Agency (EPA). This model is discussed in Section 2.4.

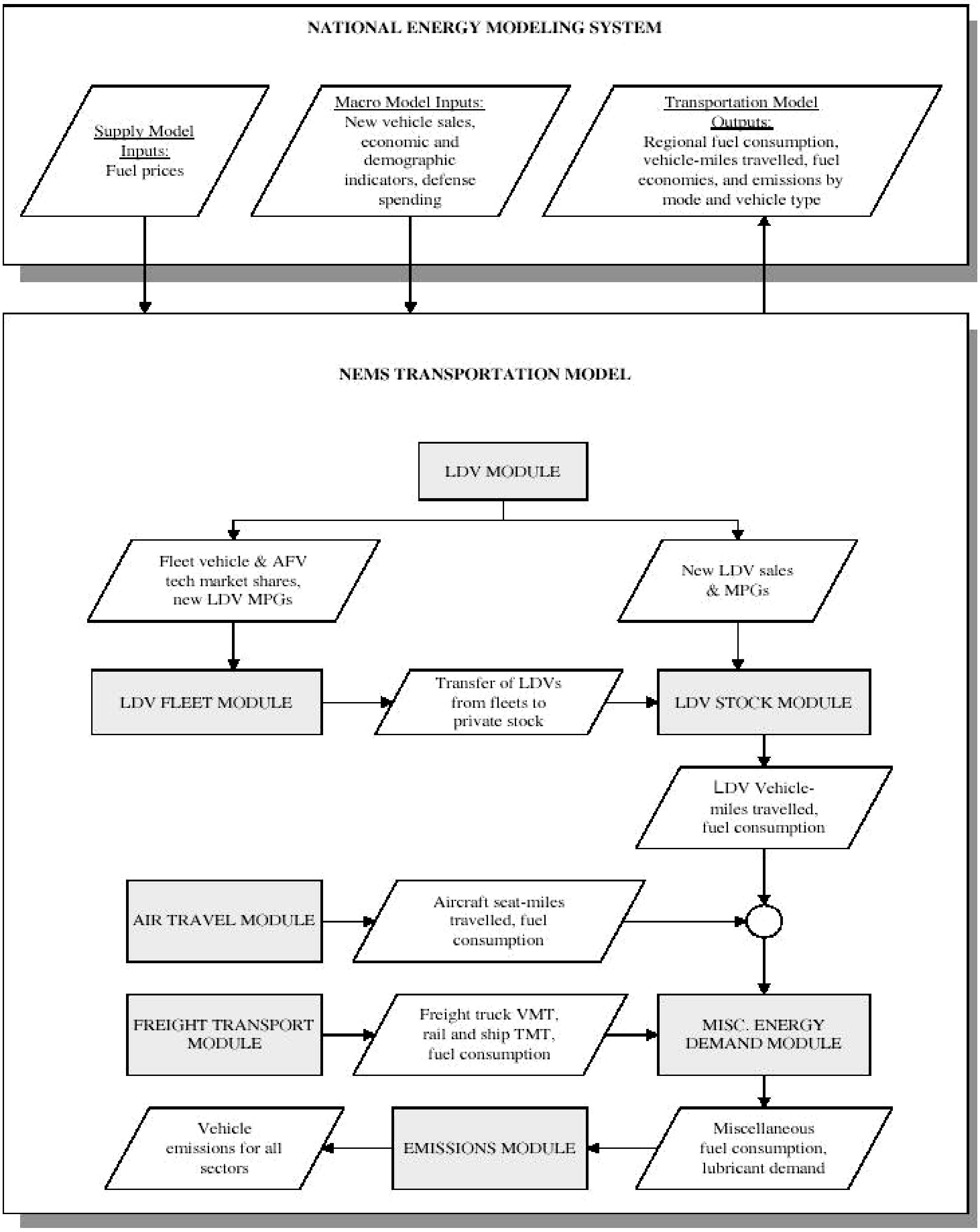

Figure 2.2: NEMS Transport Model (DOE/EIA, 2004).

2.3.3. *STEEDS*

Scenario-based framework to modelling Transport technology deployment: Energy–Environment Decision Support (STEEDS) (Brand *et al.,* 2002) is a software based decision support system. Its purpose is to allow decision makers to evaluate transport energy and environment policy options without needing to integrate a variety of different models. This is accomplished by integrating several models into one system. The structure and components of the STEEDS model are shown in Figure 2.3.

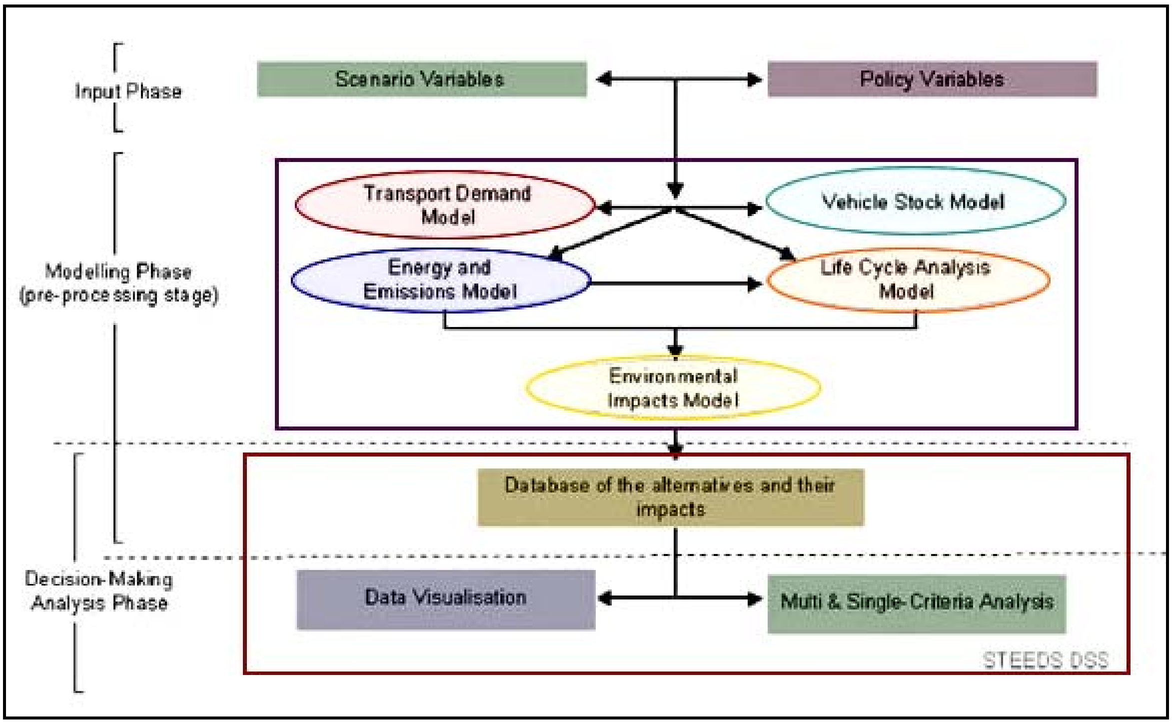

Figure 2.3: The STEEDS model structure (Brand *et al.,* 2002)**.**

The input phase of the modelling process allows users to develop various scenarios based on parameters external to transport systems. This can include population growth, economic development and international fuel prices. Policy options are also developed at the input stage such as investment in public transport, local fuel prices and land use policies.

The modelling phase of the system uses information from scenarios and policy options combined with information about vehicle fleets, transports system and lifecycle analysis to calculate transport demand and related fuel consumption and emissions.

2.3.4. *TREMOVE*

TREMOVE was developed by Transport and Mobility Leuven for the European Commission to simulate transport and environment policies and consider their impacts on transport demand, modal shares, fleet structure, emissions reduction technologies and emissions from transport (De Ceuste *et al.* 2006). The original version of the TREMOVE model was developed as a technical motivation for the European Auto-Oil II programme. TREMOVE is represented in Figure 2.4.

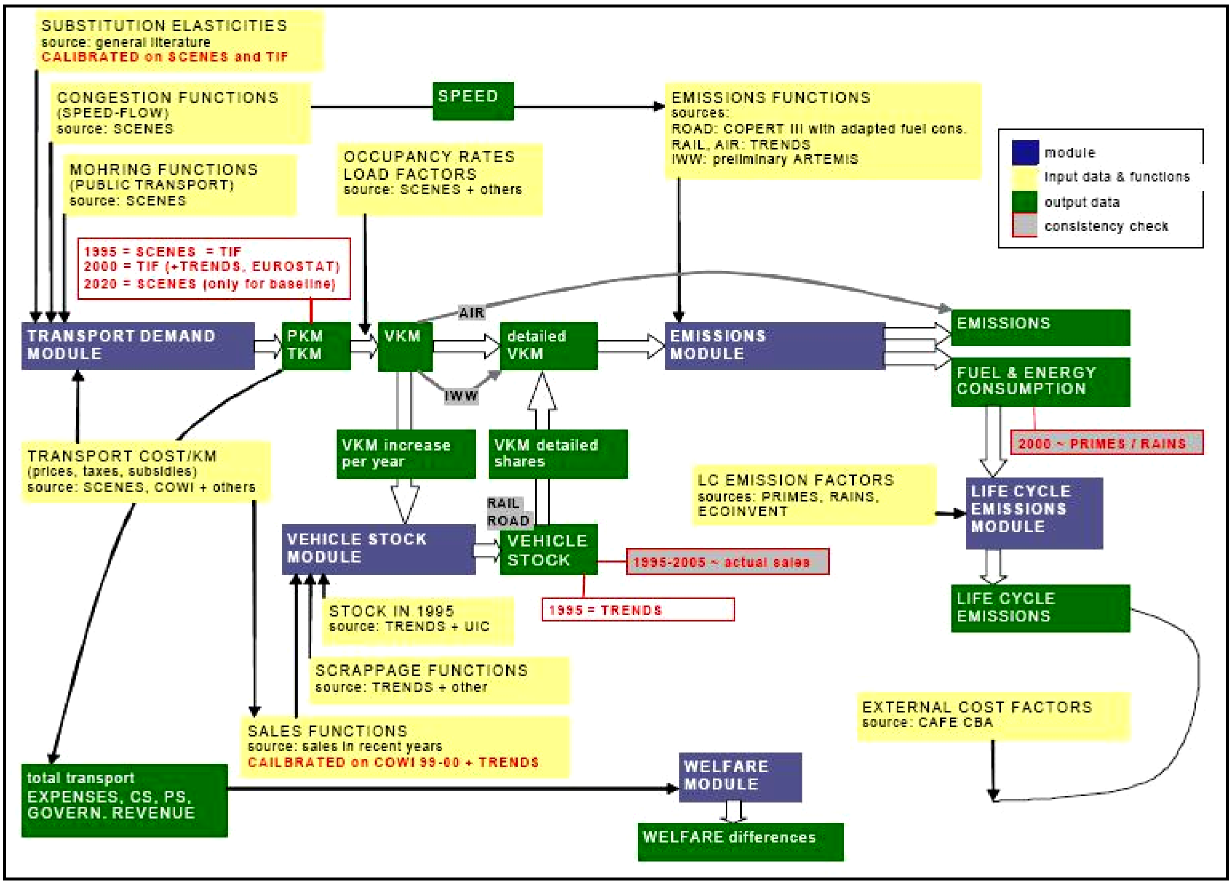

Figure 2.4: Model structure of TREMOVE (De Ceuste *et al.*, 2006)**.**

The model consists of three main modules estimating travel demand, vehicle fleet size and structure and a fuel consumption and emissions. Two additional modules calculate life cycle emissions and changes in welfare due to the policy scenarios. TREMOVE consists of several sub-models, each developed within programmes supported by the European Commission, as illustrated in Figure 2.4. An understanding of the operation of the sub-models can be overwhelming and the advantage of a single integrated system such as STEEDS is emphasised.

The module of interest and relevance to later parts of this study is the emissions model for road transport, which is the COPERT III application discussed in Section 2.4.2.

2.3.5. Summary of decision support systems

The decision support systems mentioned above all have similar structures with three main sub-modules or sets of data: a vehicle stock module, a travel demand module and an emissions module.

The systems discussed have been used to model energy and emissions for national, regional and local levels. The issue in using them in the South African context is whether local data are available and in a suitable format to be used within the models. The decision support systems discussed, however, are dependant on emissions inventories and lower level emissions simulation models. Layering of models in such a way hides details and classification of the emission factors they use.

In order to understand the origin of emission factors used in the higher-level models and hidden by abstraction, emissions inventory models and fuel consumption and emissions simulations models need to be considered in more detail. It is in these models where local driving conditions and vehicle fleet structure are considered. For this reason, decision support systems from elsewhere cannot be used for South African cities without transforming the fundamental emission factors first.

2.4. Emissions inventories

Emissions inventory models allow users to vary the fleet structure, technology proportions, vehicle activity and proportions of driving conditions to estimate total fuel consumption and emissions for a study area. These models consist of fuel consumption and emission factors from emissions measurement programmes and estimates from fuel consumption and emissions simulation models. Simulation models can also be embedded or nested in emissions inventory models. Reynolds and Broderick (2000) reviewed emissions inventory models and provided a real time traffic monitoring emissions inventory developed for the city of Dublin. Boulter *et al.* (2007) review both emissions inventory models and instantaneous emissions models. There are many emissions inventory models available. Some of the better-known national and international ones are discussed in the following sections.

2.4.1. MOBILE

MOBILE is the United States of America's national mobile emissions model developed by the Environmental Protection Agency. The purpose of the model is to determine regional mobile emissions inventories and for air quality management and planning (TRB, 2000).

MOBILE conforms to the general structure of emissions inventories (as defined in Section 1.7) consisting of a database of emission factors based on a range of vehicle types, capacity classes, technologies, driving modes (cold start or hot and stable), age and average speeds. Average speed is used as an indicator of driving conditions and is determined from transport models such as the Urban Transport Planning process, run by transport planning departments.

The basic calculation in estimating fuel consumption and emissions from transport using MOBILE is illustrated in Figure 2.5.

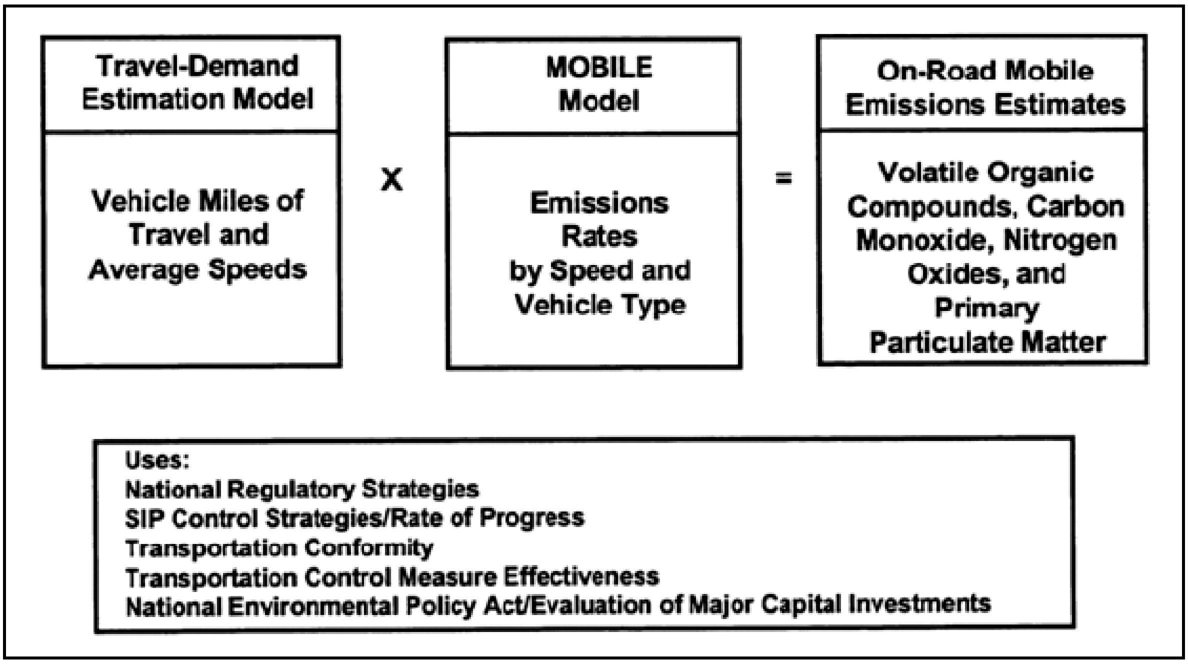

Figure 2.5: Use of MOBILE to estimate total emissions (TRB, 2000).

Emission factors used in MOBILE are calculated using the FTP (Federal Testing Procedure, see Figure 1.2) (Austin *et al.*, 1993), standardised driving cycle and correction factors based on average speed.

MOBILE has been criticised for its inability to account for road gradient, it uses average vehicle speeds as one of the main input parameters (which on its own is not a good indicator of emissions as levels of acceleration can vary greatly for the same average speed) and its lack of validation (TRB, 2000).

MOVES (Nam and Giannelli, 2005) was scheduled to replace the 6th version of the MOBILE model in 2006 as the preferred EPA regulatory emissions inventory model. This model incorporates new technology vehicles such as hybrid and hydrogen (both fuel cell and internal combustion engine) vehicles.

2.4.2. COPERT

Computer program to calculate emissions from transport (COPERT) is a computer program that calculates emissions from vehicle type, emissions regulation, vehicle activity (vehicle kilometres) and average vehicle speed and road type (rural, urban and inner city) (Ntziachristos and Samaras, 2000). It is now in its third version (COPERT III). The basic methodology used in COPERT is outlined in Figure 2.6.

COPERT was developed within COST319 action and the MEET (Methods for Estimating Emissions from Transport) project funded by the European Environment Agency as part of the Fourth Framework Programme under the topic of transport (Ntziachristos and Samaras, 2000). It is the most commonly model used for national emissions inventories in Europe (Ekström *et al.* 2004).

The model uses average speeds of whole driving cycles for three land use forms: rural, urban and inner city. The model was developed using a range of typical driving cycles experienced in Europe, a linear regression of their average speeds and the measured emission factors. The form of the linear regression use in COPERT is presented in Figure 2.7.

The COPERT equations are embedded in the Emissions Inventory Toolkit (EMIT) used by the City of Johannesburg as their emissions inventory database. EMIT is used as the data repository for the Johannesburg's Atmospheric Dispersion Modelling System (ADMS) (CERC, 2007). COPERT has a similar limitation as MOBILE in that it uses average speeds, but it is able to compensate for road gradient using correction factors (developed from additional emissions tests), and for congestion by altering the fractions of urban and inner city travel.

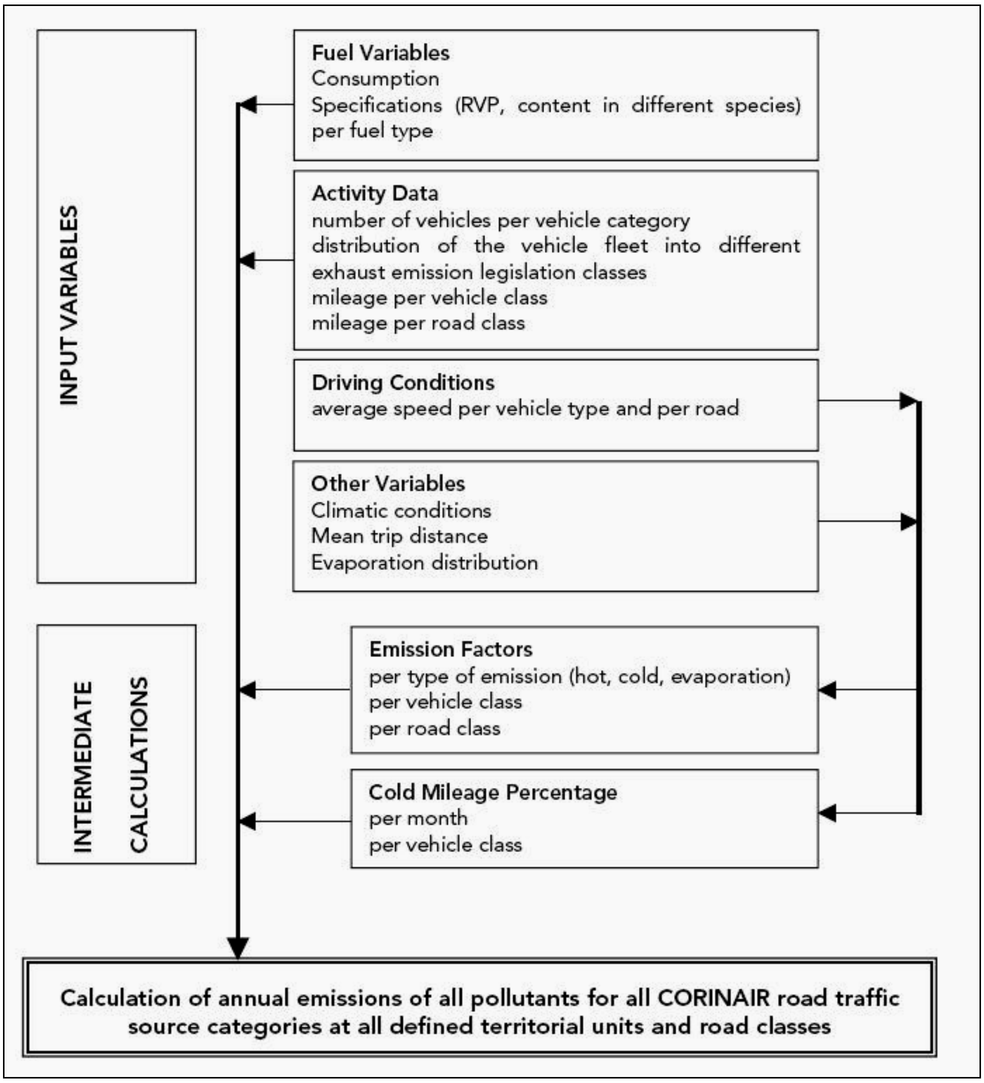

Figure 2.6: Basic application of the COPERT methodology (Ntziachristos and Samaras, 2000).

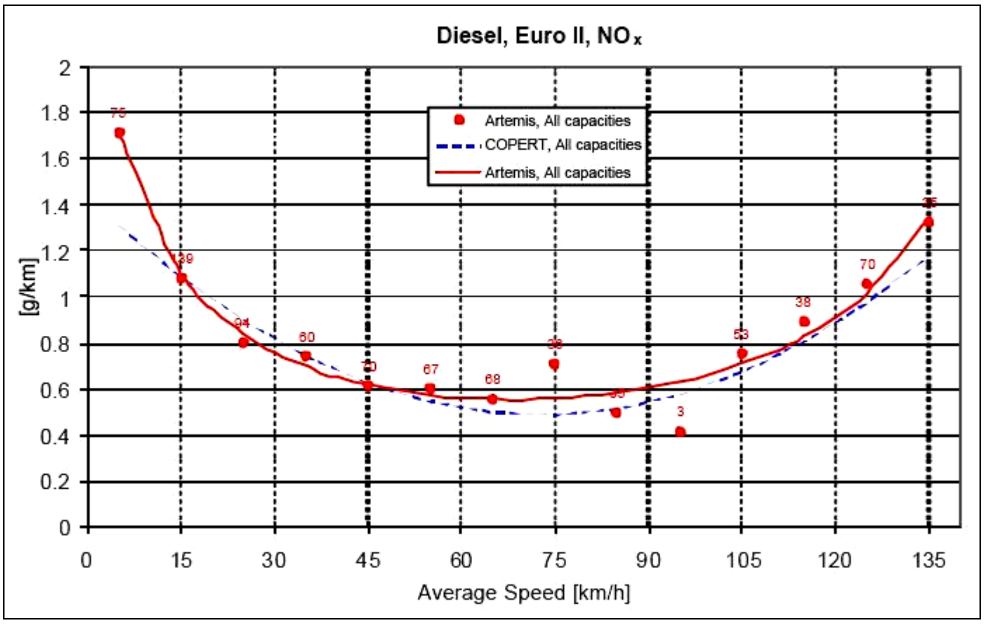

Figure 2.7: Functional form of the COPERT regression (Ntziachristos *et al.*, 2006).

2.4.3. HBEFA

The Handbook of Emission factors (HBEFA) (Hassel *et al.*, 1994; SAEFL, 1999; de Haan and Keller, 2004a) was commissioned by German Federal Ministry for the Environment and the Swiss Ministry for Landscape and Forestry for the development of emission factors for the two countries. In its current version (Version 2.1), it provides emission factors for a variety of different vehicle types, traffic situations, road gradients, cold start situations and air conditioner use. Traffic situations are defined by road type, level of congestion and average speed such as *congested freeway with an average speed of* $40\ km\ h^{-1}$ or *free flowing arterial road with an average speed of* $60\ km\ h^{-1}$ calibrated to conditions experienced in Germany and Switzerland. The traffic situations are linked to specific driving patterns defined within the methodology used to evaluate their emission factors from dynamometer tests (de Haan and Keller, 2004b).

The HBEFA is a database of emission factors and set of predefined fleet structures for Germany and Switzerland. The model does not allow one to vary travel demand, fleet structure, mix of vehicle emissions regulations, or the proportion of travel but does provide a mechanism to extract fuel consumption and emission factors for specific vehicle types and set of situations. The user is left to build their own scenarios of fleet structure, travel demand and technologies external to the model. For this reason, data from the HBEFA are often extracted and used in other models, which provide facilities to consider possible scenarios and policy options (see the IKARUS transport model and TREMOD - Traffic Emissions Estimation Model, described below).

The methodology used to develop emission factors used in HBEFA is considered in Section 2.5.

2.4.4. IKARUS Transport Model

IKARUS was a project initiated by the former German Federal Ministry for Education, Science, Research and Technology (BMFT) and is the abbreviation for *Instruments for climate (change) gas reduction strategies*. The IKARUS transport model (ITM) was developed by TÜV Emissions Control and Energy Systems GmbH and the Jülich Research Centre as part of the IKARUS project. The purpose of this model was to consider transport activity, vehicle technologies and fuels to project changes in transport efficiency and emissions in Germany. The IKARUS transport model uses emission factors from the HBEFA.

The model allows one to vary the proportion of different vehicle capacity classes and fuel types, driving conditions, distance driven and technologies in the form of scenarios to consider their impact on climate change mitigation and to optimise costs, energy consumption and emissions from transport.

The ITM focuses on technologies and driving conditions and estimating fuel consumption and emissions from summing the activity of the individual vehicles using a *bottom-up* approach. The structure of the IKARUS transport model is shown in Figure 2.8.

The ITM has been used to simulate CO_2 and pollutant emissions for Germany up to the year 2030 (Linßen *et al.*, 2005). To do this it uses an emissions database of the German vehicle fleet and then considers how this fleet will change under assumed scenarios.

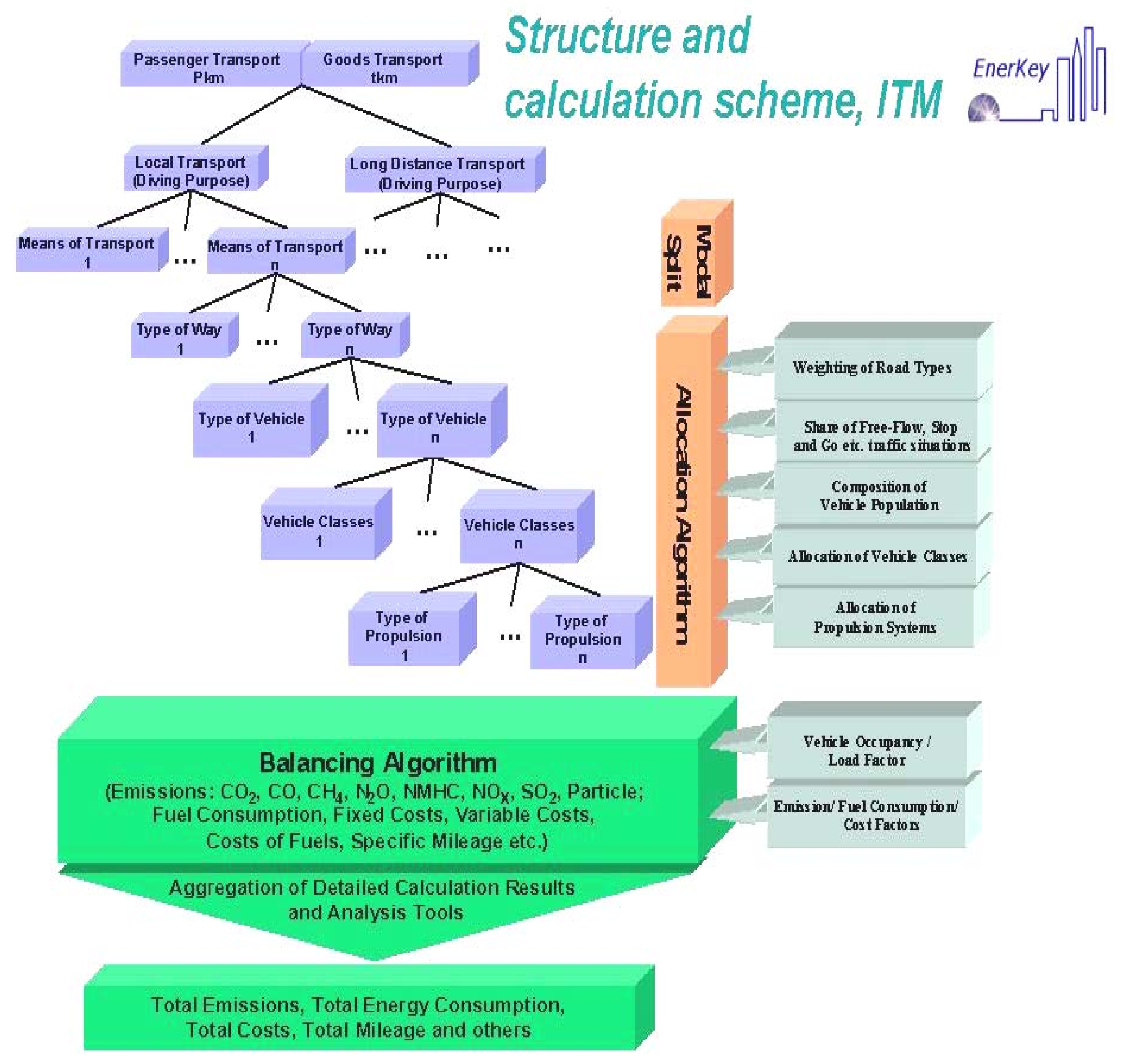

Figure 2.8: IKARUS Transport Model (Brosthaus *et al.*, 2003)**.**

It has been suggested that the ITM be used to estimate emissions in Johannesburg for the EnerKey project. The model is able to consider transport policy options at the municipal level by varying driving conditions and shares of different vehicle types and technologies.

A concern about using the model for Johannesburg was that the driving conditions in the ITM are calibrated for Germany. (The other decision support systems already discussed are also calibrated for specific countries). In order to use the ITM for Johannesburg an appropriate transformation is required to match South African driving conditions and driving patterns to those in Germany and Switzerland. This would be enabled by creating an equivalent set of HBEFA emission factors, based on South African vehicle fleet and driving conditions.

2.4.5. Fuel based emissions inventories

Fuel based emissions inventories (Schifter *et al*., 2005; Singer and Harley, 2000) have been used as a first order means to estimate total emissions where vehicle activity has not been readily available or measured accurately enough to estimate average vehicle speeds and detailed emission factors. These emissions inventories use fuel consumption as a proxy to estimate vehicle emissions. They are calibrated for typical emission factors per unit fuel consumed and overall driving conditions using remote roadside emissions measurements which measure the ratio of different gases in exhaust fumes.

2.4.6. Summary of emissions models

The emissions inventory models mentioned above provide aggregated emission factors for discrete combinations of driving conditions and vehicle types, capacity classes and regulations (or technologies). In most cases, descriptions of the driving conditions are qualitative, such as *high speed freeway driving* or *stop and go inner city driving*; or overly simplified, such as *freeway driving at an average speed of 120 km* h^{-1}. These descriptions are generalised for countries in which they were developed and have no demonstrated correlation to local conditions. Quantitative descriptions of South African driving conditions are needed as a necessary input in assessing the applicability of these models to local circumstances.

To provide a mechanism to derive fuel consumption and emission factors for South African conditions from the above models one needs to consider how fuel consumption and emission factors used in models were derived. With this understanding the emissions factors can be transformed for South African conditions. Structures of emission simulations models are discussed in the following section, as a foundation on which to build an emission factor database applicable for South Africa, which will be one of the major tasks of this research investigation.

2.5. Emissions simulation models

In this section, models used to determine fuel consumption and emission factors for different vehicle types, driving conditions, vehicle operation and driving styles are discussed. Models are broadly classified and selected examples are studied in detail.

2.5.1. Classification of emissions simulation models

Two types of emissions simulation models are considered by building on definitions in Section 1.7. The first model is based on correlating vehicle kinematics to fuel consumption and emission factors. The second model is based on engine-operating parameters and emissions maps. The two types of models differ in complexity, how they characterise emission factors and their purpose. Depending on their purpose, they can be divided further into aggregate and instantaneous models.

Models based on kinematics use driving cycles, driving patterns, average vehicle speed, or combinations of speed and acceleration to characterise emission factors. Kinematics models provide aggregated emission factors for emissions inventories based on descriptions of driving conditions. These models do not directly account for engine loads due to road gradient, auxiliary equipment use and driving styles (e.g. drivers gear changing habits); these factors are typically compensated for by using correction factors produced from engine operation models or calibrated using supplementary dynamometer tests. Kinematic models generally use emission factors determined using the constant volume sampling method of measuring emissions, but in some cases are also determined from instantaneous emissions measurements. In cases where emissions are characterised by vehicle speed, it is also possible to use emission factors derived from infrared remote sensing of vehicle exhaust fumes.

Models based on fuel consumption and emissions maps rely on derived engine-operating parameters to estimate fuel consumption and emissions for any instant. These models provide fuel consumption and emission factors for a comprehensive range of engine loads. Road gradients, auxiliary equipment use and driving styles can be accounted for by conversion into additional engine loads. Emissions maps are often used to simulate fuel consumption and emissions in network models. Network models, such as NEMO (Network Emissions Model) (Rexeis and Hausberger, 2005), simulate the path and speeds of a vehicle travelling though a road network and typically estimate fuel consumption and emissions on a second-by-second time basis. They are useful in studying impacts of traffic management techniques such as traffic light synchronisation (Tate *et al.*, 2005). Emissions and fuel maps are determined from instantaneous measurements making these models data intensive.

Engine maps are sometimes criticised for not compensating for transient effects (for example, effects of engine acceleration) on fuel consumption and emissions (Barth *et al.,* 2000). The ability for emissions maps to account for transient effects depends on circumstances under which measurements are made. Measurements taken while an engine is following a standard simulated cycle take into account transient effects of a generalised typical driving cycle. Such cycles are, however, unlikely to take into account real-world driving behaviours of stop-start traffic congestion, or aggressive acceleration behaviours quite common in South African driving conditions. These driving habits result in higher fuel consumption and emissions. They can be taken into account in models only by monitoring real-world driving patterns.

Both kinematic and engine-operating parameter models can be either aggregate or instantaneous. Aggregate models provide fuel consumption and emissions for broadly described conditions such as the morning commute, whereas instantaneous models provide fuel consumption and emissions continuously at short intervals throughout a journey. Aggregate models are useful for calculating total emissions for a city, country or region. Instantaneous models are useful to study emissions for an intersection or a specific section of road, or in comparing various scenarios of traffic interventions.

Three models are discussed below. An aggregate kinematic model, an instantaneous kinematic model and a model based on fuel consumption and emissions maps. Other models with similar structure and operating principles to the three examples given are briefly mentioned.

2.5.2. TÜV method

The TÜV method was developed for the first version of the HBEFA (Handbook of Emission factors) (Hassel *et al.,* 1994). The method uses instantaneous emissions measurements taken during simulation of real-world driving cycles grouped into matrices of vehicle *speed* and (*speed* × *acceleration*). Table 2.1 provides an example of a speed and (*speed* × *acceleration*) matrix used in the TÜV method.

Fuel consumption and emission factors for any vehicle capacity class and emissions regulation and driving cycle can be estimated using a frequency matrix of the cycle (such as Figure 2.9) multiplied by appropriate fuel consumption and emissions matrices developed from dynamometer tests (Table 2.1).

Table 2.1: An example of a *speed* and (*speed* × *acceleration*) matrix used in the TÜV method.

Vehicle: open loop catalytic converter, capacity class: 1.4 – 2.0 ℓ **Parameter: CO (g h^{-1})**							
Speed (km h^{-1})	**Speed x Acceleration (m^2 s^{-3}) range and (mid-point)**						
	< -12.5 (-15)	≥ -12.5 & < -7.5 (-10)	≥ -7.5 & < -2.5 (-5)	≥ -2.5 & < 2.5 (0)	≥ 2.5 & < 7.5 (5)	≥ 7.5 & < 12.5 (10)	≥ 12.5 (15)
0				149			
5			102	223	592		
15		103	103	266	633	998	
25	96	106	142	344	532	608	1 005
35	116	111	167	261	439	667	1 223
45	95	136	179	227	437	699	1 090
55	77	129	180	221	417	486	1 260
65	73	102	151	194	406	523	1 199
75	89	163	219	236	322	608	1 366
85	110	157	256	254	274	358	812
95	205	325	251	230	351	600	970
105	222	348	439	317	423	463	938
115	431	705	641	575	651	931	1 346
125	695	1 040	943	935	1 268	1 798	2 278
135	1 273	1 489	1 365	1 374	2 062	2 916	2 928
145	1 822	1 766	2 219	3 000	3 598	3 522	
155			3 479	4 028	4 301	4 838	
165				4 129			

Source: Hassel *et al.*, 1994

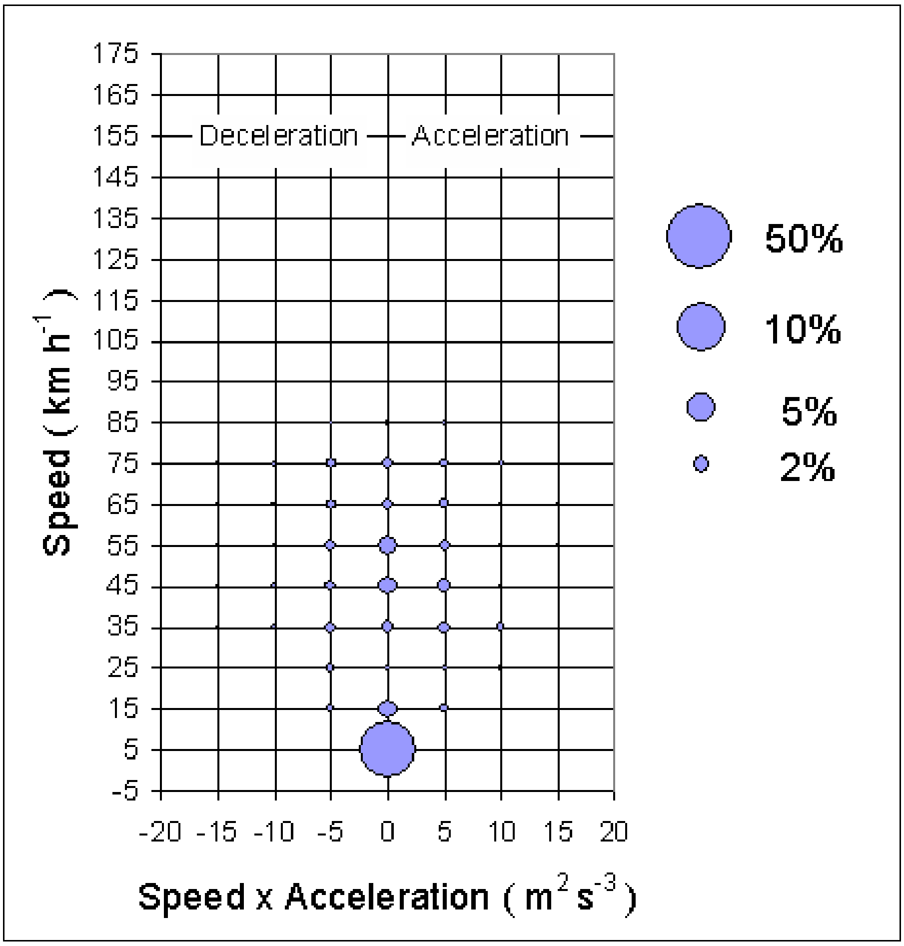

Figure 2.9: An example of a frequency plot used with emissions matrices to estimate fuel consumption and emissions for a driving cycle.

The fuel consumption and emissions are calculated by summing the product of values in the emissions matrix with corresponding values in the frequency matrix. This is represented in Equation 1:

$$EF_{cycle} = \sum_{\substack{i=1 \\ j=1}}^{\substack{j=m \\ i=n}} (EF_{i,j} \times P_{i,j}) \tag{1}$$

where EF_{cycle} is the emission factor for the cycle in $g\,h^{-1}$; $EF_{i,j}$ is the emissions or fuel consumption factor for the *speed* interval (*i*) and the (*speed* × *acceleration*) interval (*j*) in the emissions matrices; $P_{i,j}$ is the proportion (%) of time spent in the *speed* interval (*i*) and the (*speed* × *acceleration*) interval (*j*) for the cycle; and *n* and *m* are the number of *speed* and (*speed* × *acceleration*) intervals respectively.

The TÜV method is a descriptive model because it does not consider physical parameters such as vehicle size and mass, and road gradient that cause emissions, but describes the correlation between kinematics and emissions. The method does not account for engine loads due to road gradient, auxiliary equipment and gear change strategies. These are compensated for by using supplementary dynamometer tests and by applying correction factors to base emissions results.

An advantage of this model is that only speed profiles are needed to estimate emissions for a model run, while data intensive inventories of vehicle fleet characteristics are not needed.

2.5.3. HBEFA method

Instantaneous emission factors from the TÜV method used in version 1.1 and 1.2 of the HBEFA were found to be unsuitable for vehicles of Euro-2 and higher emissions regulations due to large variances in resulting instantaneous emissions (de Haan and Keller, 2004b). This is because of the wide variety of different emissions control mechanisms used in newer vehicles.

An alternative method, which characterises fuel consumption and emissions according to driving patterns, and which represents driving situations and their corresponding frequency plots, defined in Section 1.7, was developed by de Haan and Keller (2004b). Fuel consumption and emission factors for a newly measured driving pattern are determined by finding the linear combination, which produces the closest match to the new pattern, using up to three existing patterns of known fuel consumption and emission factors out of an available set of 12 patterns defined by the EMPA real-world driving cycles.

The matching procedure involves finding the combination of predefined patterns with the same average *speed* and (*speed* × *acceleration*) values of the new pattern and which results in the smallest sum of differences squared value between the frequency plot of the combination of predefined patterns and the new pattern. The formula for calculating the sum of the difference squared is represented in Equation 2:

$$SDS_{l,m} = \sum_{\substack{k=1 \\ j=1}}^{\substack{k=n \\ j=p}} (T_{j,k}^{l} - T_{j,k}^{m})^2 \tag{2}$$

where $SDS_{l,m}$ is the sum of the differences squared for patterns l (the new pattern) and m (the combination of predefined patterns); T is the proportion of time spent in the interval (j,k); and n and p are the number of *speed* and (*speed* × *acceleration*) intervals in the frequency plots respectively.

Emission factors (EF) of the new pattern are estimated by adding the corresponding emission factors of the matching combination of driving patterns as in Equation 3:

$$EF_{new\ pattern} = X \times EF_{pattern\ 1} + Y \times EF_{pattern\ 2} + Z \times EF_{pattern\ 3} \tag{3}$$

where $EF_{new\ pattern}$ is the emission factors for the new pattern; $EF_{pattern\ 1}$, $EF_{pattern\ 2}$, $EF_{pattern\ 3}$ are emission factors for individual patterns in the combination of predefined patterns; and X, Y *and* Z are proportions of predefined patterns in the combination.

The advantages of this model are the same as for the TÜV method in that besides the fuel type and emissions regulations, properties of vehicles do not need to be known. A disadvantage of the method is that it is not able to account for road gradient, auxiliary equipment and driving style.

2.5.4. CMEM

The Comprehensive Modal Emissions Model (CMEM) (Barth *et al.*, 2000) was developed at the College of Engineering-Centre for Environmental Research and Technology (CECERT) at the University of California-Riverside in collaboration with the Lawrence Berkeley National Laboratory at the University of Michigan under the National Cooperative Highway Research Program. CMEM is an instantaneous emissions model. It is deterministic in that it uses physical properties of vehicles and operating environments to estimate fuel consumption and emission factors. CMEM has been used in microscopic (at the scale of single streets) simulation of fuel consumption and emission factors from traffic (Tate *et al.*, 2005).

The structure of the model is shown in Figure 2.10. The model depends on a power factor or fuel rate. Emission factors for any fuel rate, engine speed and air fuel ratio are determined during a calibration procedure using multiple dynamometer simulations for different combinations of vehicle type, engine technologies, exhaust controls and driving modes.

For a given set of operating variables (speed, acceleration, road gradient and driving mode) and vehicle properties, the model calculates the power demand and engine speed (from vehicle speed and a gearshift schedule) and relates this to a fuel rate. The emissions can then be determined by finding the fuel rate that corresponds to the vehicle type, engine technologies, exhaust controls and driving modes.

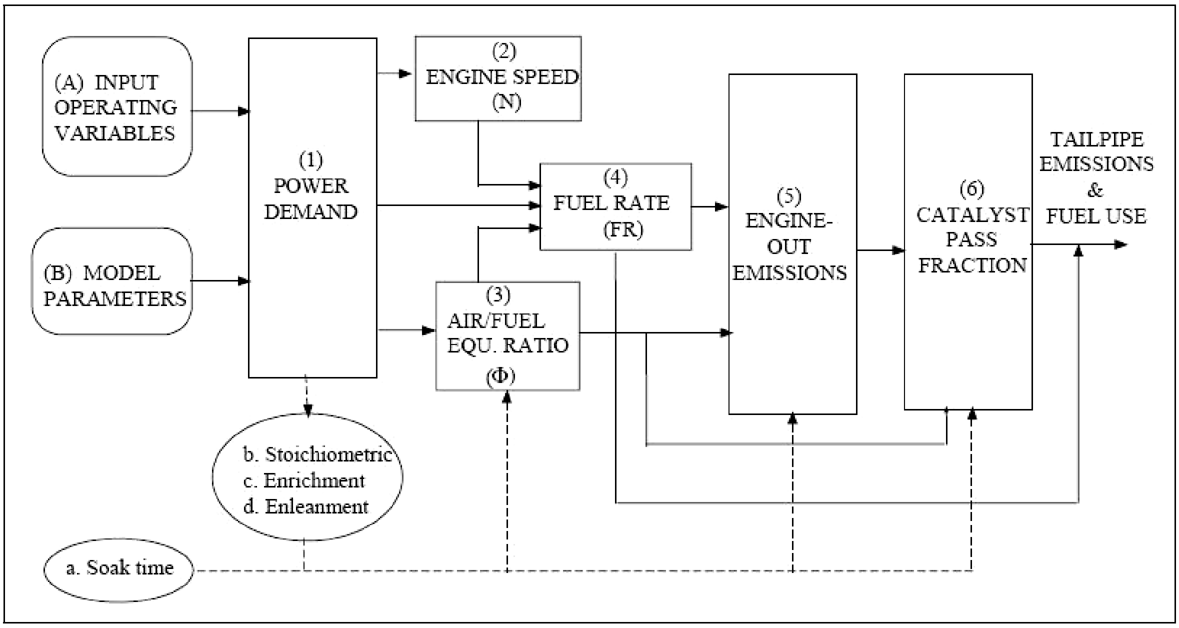

Figure 2.10: Structure of the Comprehensive Modal Emissions Model (CMEM) (Barth *et al.* 2000).

Advantages of the model are that it can take account of loads other than kinematic loads. In addition, the model differentiates between emissions out of the engine and emissions out of the exhaust. This allows the model to account for different combinations of engine technologies and exhaust after-treatment controls. Disadvantages of the model are that it requires detailed information about vehicles (including emissions control equipment) comprising the overall fleet, operating environments and driving cycles that are being simulated, which makes the model data intensive.

2.5.5. Other models

VESIM was developed by General Motors during the 1970s for estimating fuel consumption. The model was modified by request of California Air Resources Board (CARB) to include emission factors. The modified model was called VSIME and more a recent version of the model developed is referred to as VEHSIME (TRB, 2000). VESIM (Vehicle Emissions Simulation Model) uses emissions maps and vehicle characteristics to estimate emissions from any given driving cycle.

PHEM (Passenger car and Heavy duty vehicle Emissions Model) (Zallinger *et al.*, 2005) is an instantaneous emissions model developed as part of the ARTEMIS project (Andre *et al.*, 2006; Joumard *et al.,* 2007) and uses engine speed and engine power emissions maps. The emissions maps were developed from dynamometer simulations of the CADC (Common ARTEMIS Driving Cycles) driving cycles simulated on a dynamometer. The model is similar to the CMEM model but used a different set of driving cycles to calibrate the model.

The EMPA instantaneous emissions model is based on engine-operating state using engine speed and load (Ajtay *et al.,* 2005). This model is similar to the PHEM model.

The US Department of Energy has developed a fuel consumption and emissions model called ADVISOR (Johnson *et al.* 2000) which simulates fuel consumption and emissions based on the path of engine operation through engine fuel consumption and emissions maps due to any given driving cycle. This model was specifically designed to consider hybrid vehicle performance.

Other instantaneous emissions models simulate fuel consumption and emissions based on temperature, pressure and chemical reactions occurring in the combustion chamber during any one cycle of engine revolution. These models typically simulate emissions in a time scales of the order of one ms. The NASA equilibrium program is a good example of such a model (Heywood, 1988; Gordon and McBride, 1994).

2.5.6. Summary of emissions simulation models

Emission simulation models that use only kinematics are not able to account directly for road gradient, auxiliary equipment use and gear change schemes. They use empirical correction factors to account for such loads. Models that use fuel consumption and emissions maps to estimate fuel consumption and emissions, are able to account for non-kinematic loads but require data for individual vehicles and for operating environments, and are thus data intensive.

From considering the above models, it is proposed here that the ideal model for developing emission factors for emissions inventories should be able to:

- account accurately for all loads on an engine due to real-world driving i.e. account for road gradient, auxiliary equipment use and driving styles;
- represent all driving conditions experienced during real-world driving;
- account for transient engine operation effects;
- balance data requirements with flexibility and accuracy; and
- consider availability of data and simplify data collection processes.

2.6. Chapter summary

In this chapter, the importance of evaluating transport and energy policies to ensure that the best possible choices are made in protecting the environment and conserving energy, while facilitating mobility and economic development, was emphasised.

Decision support systems were introduced as tools to help policy makers make decisions by quantifying the outcome of different scenarios and policy options. Emissions inventories were discussed as data repositories of emission factors used by decision support systems to build scenarios of different shares of vehicle types, technologies and driving conditions. Both decision support systems and emissions inventory models hide details about driving conditions used to determine source emission factors. Emissions simulation models were discussed as mechanisms used to estimate fuel consumption and emission factors used in emissions inventories for different vehicle types, capacity classes and technologies based on kinematics and engine operation. The need for an emissions simulation model was presented as a means to determine local emission factors based on local driving conditions.

Advantages and disadvantages of various kinds of emissions simulation models were discussed in detail. Kinematic emissions simulation models are descriptive and correlate fuel consumption and emissions to driving conditions expressed using driving cycles or driving patterns. Kinematic models cannot directly account for engine loads such as road gradient, auxiliary equipment use and driving styles. Correction factors determined from additional tested are needed. Models, which use fuel consumption and emissions maps, account for all loads placed on an engine but require detailed information about vehicles and environments being modelled. This makes them more suitable to micro-simulation of networks, intersections and sections of road, rather than whole city simulations.

For the development of emissions inventories an ideal emissions simulation model should take advantage of aggregation methods used in the kinematics models but should rather use engine-operating parameters to determine fuel consumption and emissions characteristics.

In the next chapter, the concept for a new fuel consumption and emissions simulation model is developed. The procedure to collect data from local driving conditions for the model is described. A method of integrating simulated emissions factors from the simulation model and vehicle activity to produce an emission inventory is then outlined.

3. METHOD

3.1. Introduction

In this chapter, original methodologies that form the foundation for new tools to develop emissions inventories for South African cities are described, as set out in the objectives: Section 1.4. The overall research design is presented, followed by methodologies for three component sub-projects: (i) development of *base* engine-operating patterns and corresponding fuel consumption and emission factors to be used as the fundamental data layer in the development of a new emissions simulation model; (ii) an electronic survey of vehicle activity and engine operation in the City of Johannesburg; and (iii) integration of the emissions simulation model and survey data to produce emissions factors for a new emissions inventory model for Johannesburg.

3.2. Overall research design

Limitations of existing emissions simulation models have been discussed in Chapters 1 and 2. The objectives of this research design are to develop a novel emissions simulation model and emissions inventory, by adapting existing and creating new methods. A critical design criterion is to circumvent the need for either expensive dynamometer determinations of emissions based on real world driving cycles, or for extensive monitoring of gas emissions using on-board emissions monitoring.

The novel approach developed in this thesis, in the design of a fuel consumption and emissions simulation model, is to categorise fuel consumption and emission factors based on engine-operating patterns. A set of *base* engine-operating patterns and their emission factors are developed by transforming emission factors for a published set of vehicles and driving cycles. The benefit of using engine-operating parameters to characterise emissions is that fuel consumption and emission factors can be determined without applying correction factors for road slope, auxiliary equipment use and driving styles as required when using kinematic models.

The data collection procedure took the form of an electronic vehicle and engine operation survey using on-board diagnostics (OBD) and the Global Positioning System (GPS). The survey served to collect engine-operating parameters and vehicle location so that engine-operating patterns could be correlated to road types and periods of the day. Trip information and kinematic data provided a means to determine travel behaviour (vehicle usage profiles) and various driving conditions experienced in the City of Johannesburg. A benefit of this data collection process is that it directly measured engine load and engine speed. This simplified the modelling process because engine operation did not need to be derived from other parameters such as road gradient, auxiliary equipment use and driving styles. The collection of data using automated electronics reduced the possibility of human error, but was data intensive and required considerable processing. Data intensity, however, was lower than for kinematic models because kinematic models require a sampling frequency greater than 1 Hz to calculate acceleration. The engine-operating parameters could be sampled at a lower rate because no derivatives with respect to time needed to be calculated.

The emissions inventory was designed to integrate vehicle activity, emission factors (calculated by applying the emissions model to measured engine-operating patterns), structure of the vehicle fleet, and fuel sales in a new software application. A benefit of using a vehicle survey for developing emissions inventories was that it provided vehicle activity information from the perspective of the vehicle. This provided a new, more accurate assessment of mechanisms that influence fuel consumption and emissions than the Urban Transport Planning (UTP) process discussed in Section 2.3.1. The UTP process considers vehicle activity from the perspective of infrastructure and provides average speeds so effects of acceleration and other parameters on fuel consumption and emission factors cannot be studied. An important part of the proposed emissions inventory was that it relied on fuel sales to estimate total vehicle activity for the case study.

3.3. Development of base engine-operating patterns and emissions factors for a fuel consumption and emissions simulation model

3.3.1. Purpose

The purpose of the fuel consumption and emissions simulation model is to estimate fuel consumption and emissions for measured engine-operating patterns (visually represented as frequency plots of engine speed and engine load). In this section, a set of *base* engine-operating patterns and their fuel consumption and emission factors are developed from published data. The *base* engine-operating patterns are used subsequently in Section 4.2.1, within the software implementation of the emissions simulation model, to estimate emission factors for measured engine-operating patterns based on discrete combinations of the *base* engine-operating patterns developed here. The final structure, implementation and validation of the model are presented in the Section 4.2.

3.3.2. Approach

In the literature review, kinematic models (TÜV and HBEFA methods) were presented as a means to evaluate emission factors for measured driving patterns using frequency matrices of vehicle *speed* and (*speed* × *acceleration*). Emission factors for driving patterns, however, only reflect fuel consumption and emissions due to forward motion of a vehicle. In reality, there are other demands imposed on engines including varying atmospheric conditions, changing road gradients, use of auxiliary equipment such as air conditioners and heaters, engine idling and driving styles not described by driving patterns.

It is possible to account for non-kinematic power demands by directly measuring the demand placed on an engine (through on-board diagnostics) and deriving fuel consumption and emission factors from fuel consumption and emissions maps. The high level of detail and accuracy provided by emissions maps and instantaneous models, however, is not needed for developing emissions inventories because of the geographical scale considered by emissions inventories and the degree of aggregation they require. Aggregation of fuel consumption and emission factors from several vehicles to produce single factors for classes or groups of vehicles increases the variance of emission factors used in emissions inventories. This is significant in terms of overall uncertainties associated with total emissions estimates from emissions inventory models, which can be several times higher than uncertainties for dynamometer emissions measurements from a single vehicle. Engine operation still needs to be taken into account but additional detail provided by emissions maps is superfluous.

The novel approach used here is to characterise fuel consumption and emission factors for discrete engine-operating patterns. This simplifies the data collection procedure, has lower data intensity and requires less processing power than models based on detailed emissions maps. Results of the Swiss Institute of Materials Science and Technology (EMPA) emissions measurement programme were selected for use in this work to produce engine-operating patterns using kinematics of driving cycles and properties of vehicles (Soltic, 2001; Stettler *et al.*, 2004; and Weilenmann, 2005). Vehicle properties and speed-time series are part of the EMPA source data. Engine-operating patterns were calculated in this study as part of the original contribution of this thesis and are a new way to process and interpret the data from the EMPA emissions testing programme. The method is illustrated in Figure 3.1 and described in the following text.

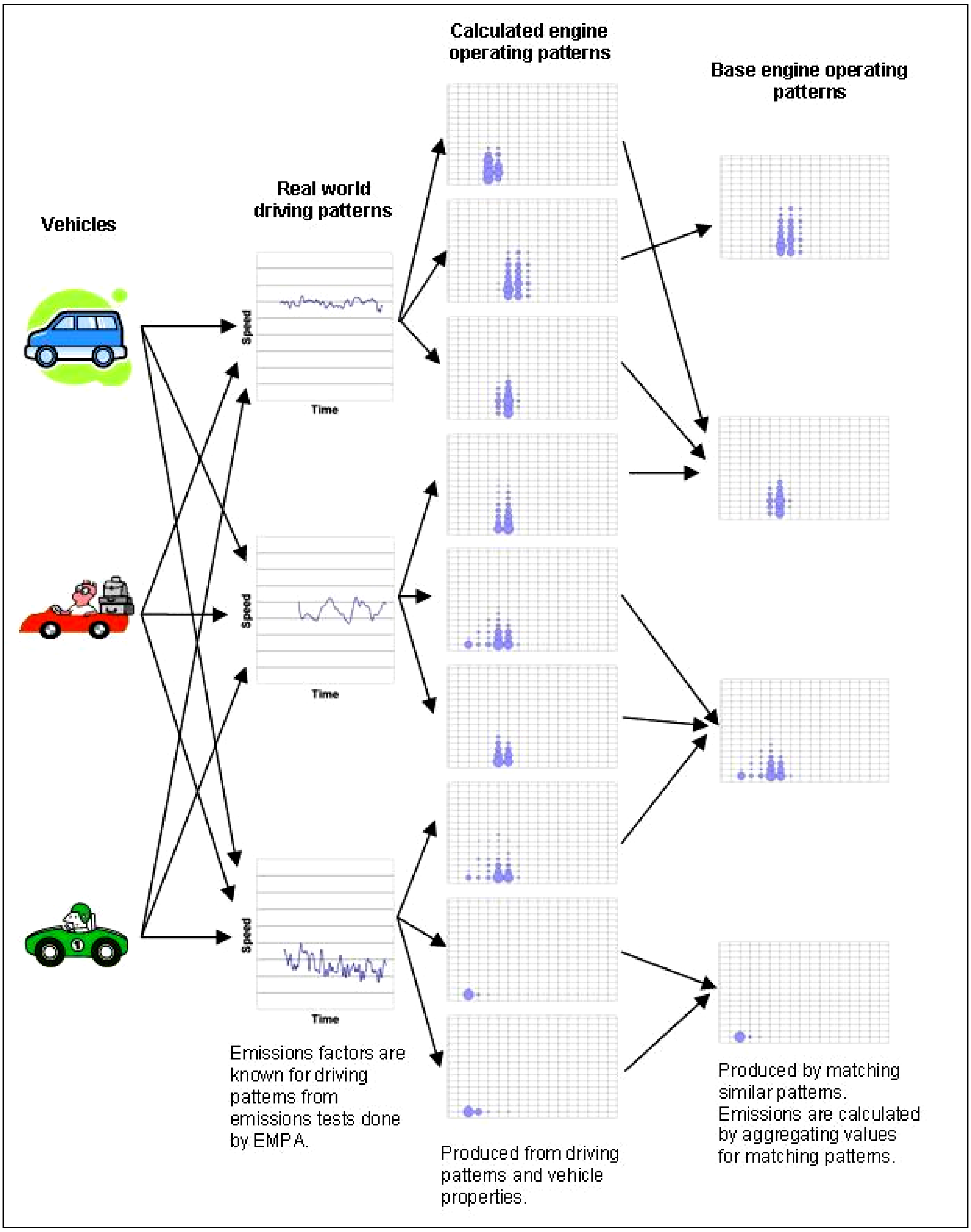

Figure 3.1: Approach used to develop *base* engine-operating patterns and their fuel consumption and emission factors.

Engine-operating patterns were calculated for each combination of vehicle and driving pattern and then grouped into sets of similar patterns. All patterns and their fuel consumption and emission factors for each set were aggregated to produce a single pattern for the set, called a *base* engine-operating pattern, with corresponding average fuel consumption and emission factors.

The proposed simulation method determines fuel consumption and emission factors for a new pattern by finding the linear combination of any three *base* patterns with the closest match to the new pattern, for a fuel type and emissions regulation. This is described in more detail in the implementation of the model in Chapter 4.

3.3.3. Data sources

Source fuel consumption and emission factors

The EMPA emissions testing programme (Soltic, 2001; Stettler *et al.*, 2004; and Weilenmann, 2005) provides a large set of driving patterns from high-speed freeway driving to urban stop-and-go driving, along with their fuel consumption and emission factors for a number of vehicles. Vehicle makes and models tested in the programme cover many of the vehicle models prevalent in the South African vehicle fleet.

Data from the EMPA emissions testing programme were used to develop the Swiss-German-Austrian Handbook of Emission Factors (SAEFL, 2004) and the PHEM instantaneous emissions model. The HBEFA has been used to develop emissions inventories in Germany, Switzerland and Austria, and PHEM has been used in road network emissions models (Linßen *et al.,* 2005; Zallinger *et al.*, 2005).

Driving cycles

Driving cycles used in this study include the NEDC (New European driving cycle), the German autobahn cycle and four EMPA real-world driving cycles called R1, R2, R3 and R4. (The speed-time series were obtained from the EMPA in electronic format.) Each cycle is represented in a speed-time relationship and is split into three phases. Each phase in a cycle can be referred to as a driving pattern and has a fuel consumption and emission factors for HC, NO_x, CO and CO_2 associated with it for each vehicle model considered. The speed-time series for the driving cycles are included in APPENDIX A: *Driving Cycles from the EMPA Testing Programme*.

EMPA test vehicles

The individual makes and models of vehicles from the EMPA emissions testing programme used to develop the emissions model are listed in APPENDIX B: *Vehicles from the EMPA Emissions Testing Programme*. The list of vehicles is summarised in Table 3.1 terms of emissions regulations and fuel types.

Table 3.1: Number of vehicles tested in the EMPA emissions testing programme and used to develop the fuel consumption and emissions model.

Regulation	Fuel	
	Diesel	**Petrol**
Euro-0	0	4
Euro-2	8	12
Euro-3	0	21
Total	**8**	**37**

Vehicle technical data

Technical details of vehicles were obtained from motoring journals (*Car*, various years), vehicle specification databases (*Carfolio.com*, *Carinfo.autold.com*, *Globalcar.com* and *Vehix.com*), *Mead and McGrouther 2003 Vehicle Digest* (2003), and the *Bosch Automotive Handbook* (Robert Bosch GmbH, 2000). These details include vehicle properties and performance characteristics (maximum power, maximum torque and corresponding engine speeds, engine capacity, fuel type, bore and stroke), aerodynamic properties (frontal area and drag coefficient), gear ratios and wheel sizes.

Data pre-processing

Data used during the analysis was manually copied from the EMPA reports (originals are in Adobe Acrobat PDF format), motoring journals and other sources and inserted into a Microsoft Access® database for further analysis.

3.3.4. Analysis

Calculation of engine-operating patterns

Engine speed and engine load were calculated for every second of each combination of driving pattern and vehicle model from the EMPA emissions measurement programme. Conventional units used to compare engine performance maps are mean piston speed in $m\ s^{-1}$ (which is directly proportional to engine speed in rpm and engine stroke) and *bmep* (brake mean effective pressure) in *kPa,* were used to indicate engine speed and engine load respectively.

Mean piston speed was calculated from the product of vehicle speed, gear ratios, final drive, wheel sizes, wheel slip, engine stroke and the NEDC gear changing scheme (used as the gear changing schemes in all EMPA emissions test), using Equation 4 derived from Heywood (1988:44) and Wong (2001:240):

$$S_p = \frac{SLR_{fd}R_i\lambda}{1.8\pi(D_r + 2W_tP_t)} \tag{4}$$

where S_p is mean piston speed in $m\ s^{-1}$; S is vehicle speed in $km\ h^{-1}$; L is engine stroke in m; R_{fd} is the ratio of the final drive; R_i is gear ratio of the i^{th} gear determined by the vehicle speed and the NEDC gear changing schema: if $0 \le S < 15$, then $i=1$; $15 \le S < 35$ $i=2$; $35 \le S < 50$ $i=3$; $50 \le S \le 70$ $i=4$; and $S \ge 70$ $i=5$; λ is percentage slip assumed to be 3.5% (Wong, 2001:240); D_r is the wheel rim diameter in m; W_t is the tire width in m; and P_t is the tire profile in percentage.

Engine load was calculated using equations modified from Heywood (1988:49), Robert Bosch GmbH (2000:337) and Gillespie (1992:119):

$$bmep_{inst} = \frac{S\eta}{3{,}6V_dN}\left(ma + R_rmg + mg\sin(\alpha) + \frac{1}{2}\rho\frac{C_dA_fS^2}{3{,}6^2}\right) \tag{5}$$

where $bmep_{inst}$ is instantaneous load at the fly wheel in kPa; S is speed of the vehicle in $km\ h^{-1}$; η is the combined efficiency of gearbox and final drive taken from Wong (2001:238) as a first approximation: 94% 1st gear, 95% 2nd gear, 96% 3rd gear, 97% 4th gear, 98% 5th gear and 95% final drive; m is mass of the vehicle in kg; a is acceleration of the vehicle in $m\ s^{-2}$; R_r is the rolling resistance coefficient of the vehicle (taken as 0.015); g is gravitational acceleration 9.81 $m\ s^{-2}$; α is inclination of the road in degrees (assumed 0 for all the cycles used by the EMPA for emissions measurements); ρ is air density taken as 1.2 $kg\ m^{-3}$; C_d is drag coefficient of the vehicle; A_f is frontal area of the vehicle in m^2; N is engine speed in $rev\ s^{-1}$; and V_d is engine displaced volume in *litres.*

Engine-operating patterns were produced by grouping calculated data points for each combination of vehicle and driving pattern into intervals of engine speed and engine load. The intervals used for engine speed and engine load are defined in Equations 6 and 7 respectively. The number of data points in each engine speed and engine load interval was then divided by the total number of data points for the driving pattern to normalise the engine-operating patterns i.e. the sum of all the values in each interval in the patterns is equal to 1.

$$(j - 0.5) \text{ and } (j + 0.5) \text{ in } m\ s^{-1} \text{ where } j \text{ is an integer and } (1 \le j \le 17) \tag{6}$$

$$(100(k - 1)) \text{ and } (100k) \text{ in } kPa \text{ where } k \text{ is an integer and } (1 \le k \le 17) \tag{7}$$

Processing of the EMPA source data was performed using a set of macros and SQL (Structured Query Language) queries, which implemented the calculations described in Equations 4 to 7 within the Microsoft Access® environment. The graphical outputs were produced using Microsoft Excel® linked to the Access® database. All processing was done on X86 processor based computers running the Windows XP® operating system.

Six hundred and seventy five engine-operating patterns were produced from the combination of driving cycles and vehicles from the EMPA emissions measurement program (15 driving patterns × 45 vehicle models). These patterns are referred to here as the *original* engine-operating patterns and are uniquely numbered using a randomly assigned number between 0 and 676. An example of an engine-operating pattern is presented in Figure 3.2.

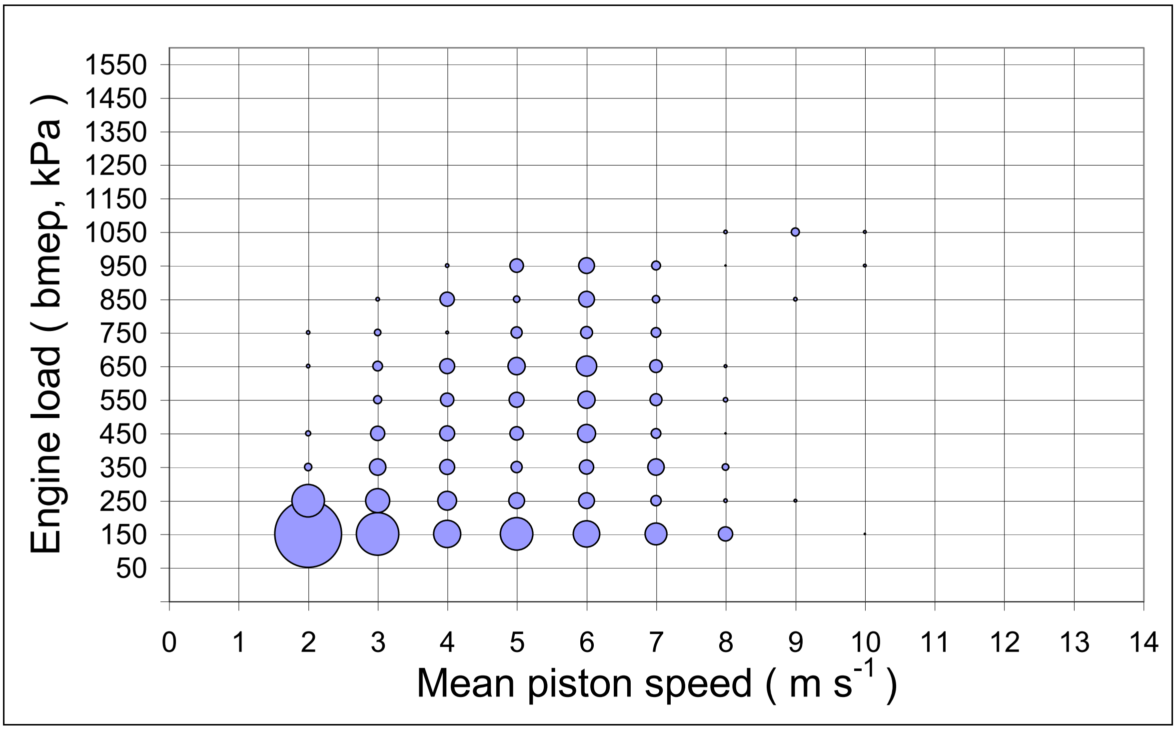

Figure 3.2: An example engine-operating pattern (the sizes of all the circles add up to unity and indicate the fraction of time spent in each engine speed and engine load interval).

Reducing the number of engine-operating patterns

The *original* engine-operating patterns calculated using the procedure above represent the demand placed on the engines of individual vehicles. Emissions inventories, however, need average fuel consumption and emission factors for groups of vehicles to be able to estimate fuel consumption and emissions for vehicle fleets.

The *original* engine-operating patterns were grouped into sets of similar patterns by comparing the patterns, in each fuel type and regulation category, to each other using a matching index (*MI)*. The matching index was designed as part of this study to quantify the intersection between two engine-operating patterns. The *MI* provides an alternative to the *SDS* (sum of differences squared, Equation 2 in Section 2.5.3) method used by de Haan and Keller (2004b) to compare driving (*speed* and *speed* × *acceleration*) patterns. The *MI* gives an absolute indication of the intersection between two patterns whereas the *SDS* is sensitive to the number of engine speed and engine load intervals that contain data in the patterns being compared. A more detailed motivation for using the *MI* as an alternative to the *SDS* is given in APPENDIX C: *Comparison of MI to SDS.*

The formula for calculating the *MI* is presented in Equation 8:

$$MI_{l,m} = 1 - \frac{1}{2} \sum_{\substack{k=1 \\ j=1}}^{\substack{k=17 \\ j=17}} \left(\left| T^{l}_{j,k} - T^{m}_{j,k} \right| \right) \tag{8}$$

where $MI_{l,m}$ is the matching index for the patterns l and m; and T is the proportion of time spent in the interval (j,k) of the engine-operating pattern matrices (frequency plots).

The *MI* has a maximum value of one when the two patterns being compared match perfectly. The *MI* is zero indicating when there is no intersection between the patterns being compared.

To find all possible matches of *original* engine-operating patterns for a fuel type and emissions regulation, pattern (P_l) is compared with pattern (P_m) where l and m are varied between (1 and N-3) and (l+1 and N) respectively. N is the total number of patterns for each fuel type and regulation pair. Once a pattern has been included in a valid set, it is excluded from any further examination to prevent duplication and unnecessary calculations.

Each set of *original* patterns is represented using a single *base* engine-operating pattern calculated by aggregating all the *original* patterns in the set. Fuel consumption and emission factors for the *base* patterns were produced by calculating the average values from the constituent *original* patterns. The fuel consumption and emission factors are calculated per volume engine capacity so that vehicles of different capacities can be grouped into the same sets. The *base* patterns are identified using the number belonging to the first *original* pattern that occurs in each set. For a set of patterns to be valid, it was required to contain at least three *original* engine-operating patterns and the *MI* between all the patterns in the set was required to be >0.5 for Euro-0 petrol vehicles, >0.67 for Euro-2 petrol vehicles, >0.72 for Euro-3 petrol vehicles and >0.55 for Euro-2 diesel vehicles.

The *MI* was chosen to produce a range of *base* engine-operating patterns that was large enough to represent a broad coverage of engine operation, but small enough to allow for a rapid iteration procedure for the matching of new patterns in the implementation of the model. Twelve patterns was selected as the appropriate number of *base* patterns to represent most engine-operating patterns. The number of *base* patterns is significant because if there were too many, then the number of *original* patterns per *base* pattern would decrease and the fuel consumption and emission factors would represent fewer vehicles and be susceptible to the properties of individual vehicle models as mentioned by de Haan and Keller (2004b) for the development of driving patterns for the HBEFA. If the number of *base* patterns is too small, increasing the number of *original* patterns per *base* pattern, the variance of the fuel consumption and emission factors for each *base* pattern increases.

A different *MI* was used for the different fuel types (petrol and diesel) and emissions regulations (designated Euro-0, Euro-2 and Euro-3 – refer to Table 3.1) to match the corresponding number of vehicles in the EMPA data. There are fewer Euro-0 petrol and Euro-2 diesel vehicles in these data so a smaller *MI* was used to produce the same number of *base* patterns as the other fuel types and regulations.

Using the method defined above to match and group engine-operating patterns, the 675 *original* patterns were reduced to four sets of 12 patterns each, for a total of 48 *base* patterns. A set of 12 patterns was derived for each of the following fuel type and emissions regulation pairs Euro-0 petrol, Euro-2 petrol, Euro-3 petrol and Euro-2 diesel. The complete set of derived *base* engine-operating patterns, their emissions factors and uncertainties developed in this study are presented in APPENDIX D: *Base Engine-operating Patterns*. As an example of these patterns, Figure 3.3 provides the *base* patterns calculated for Euro-3 petrol vehicles, while Table 3.2 presents the corresponding average fuel consumption and emission factors. The authors interpretation of these results follow.

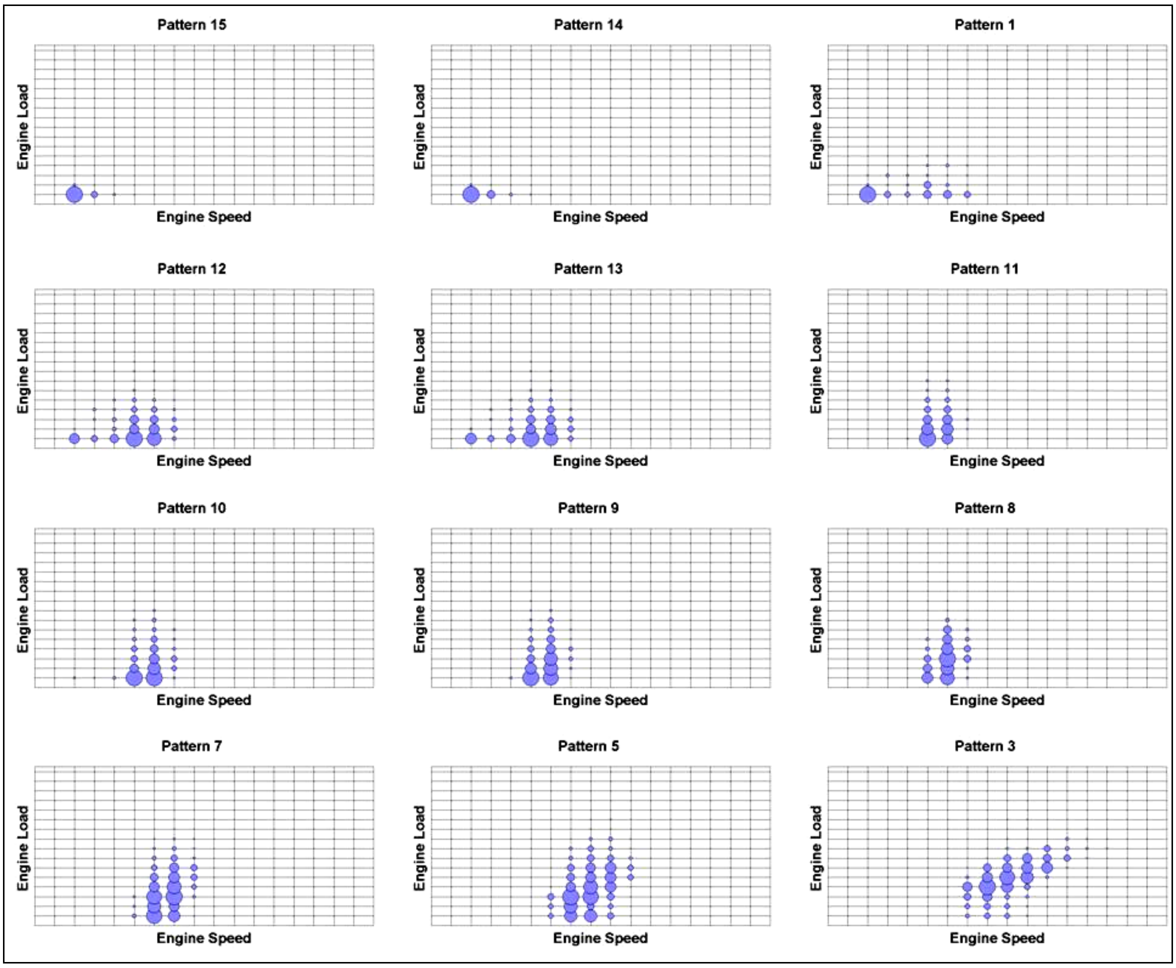

Figure 3.3: ***Base* engine-operating patterns for Euro-3 petrol vehicles.** (Patterns are ordered by increasing average power.)

Table 3.2: Average fuel consumption and emission factors per ℓ engine capacity for Euro-3 petrol vehicles. (Patterns are ordered by increasing average power.)

Parameter	Unit	Pattern ID											
		15	14	1	12	13	11	10	9	8	7	5	3
Fuel cons.	$g\ s^{-1}\ \ell^{-1}$	0.12	0.13	0.25	0.29	0.29	0.34	0.34	0.37	0.45	0.53	0.70	0.98
CO_2	$g\ s^{-1}\ \ell^{-1}$	0.38	0.39	0.76	0.88	0.88	1.04	1.05	1.16	1.38	1.64	2.18	3.03
CO	$mg\ s^{-1}\ \ell^{-1}$	0.89	0.84	4.70	1.53	1.43	0.69	1.40	0.92	1.92	3.14	8.45	6.93
HC	$mg\ s^{-1}\ \ell^{-1}$	0.05	0.05	0.66	0.03	0.03	0.05	0.05	0.06	0.08	0.08	0.19	0.17
NO_x	$mg\ s^{-1}\ \ell^{-1}$	0.04	0.03	0.32	0.21	0.20	0.23	0.32	0.24	0.10	0.20	0.47	0.32

The effect of engine-operating patterns on fuel consumption and emission factors can be significant. The factors generally increase with increasing power demand, except for CO, which also increases with the range of engine operation within the engine-operating patterns. The fuel consumption and emission factors typically vary by a factor of 10 between a close to idling condition (patterns 14 and 15) and aggressive driving patterns with high engine speeds and high engine loads (patterns 5 and 3). In some cases the difference in emissions rates between extreme engine-operating patterns, such as idle (pattern 15) and high engine speed and engine load (pattern 3), can be up to two orders of magnitudes higher depending on the pollutant and emissions regulation of the vehicle (see tables in APPENDIX D: *Base Engine-operating Patterns*).

Patterns 14 and 15 look very similar and their emissions factors are similar too. This is a result of the matching criteria for the engine-operating patterns. If the *MI* was chosen to be smaller (a larger tolerance for matching patterns) then patterns 14 and 15 would have been combined and their emissions factors would have been aggregated.

Uncertainty analysis of base engine-operating patterns

The *base* engine-operating patterns form the fundamental data layer of the fuel consumption and emissions simulation model. Uncertainties due to the *base* patterns propagate through the model and affect uncertainties of any simulated results. The uncertainties of the *base* patterns are related to the number of *original* patterns that are used to calculate the *base* patterns and the variance of their values. The fuel consumption and emission factors, their standard deviations and standard errors for the *base* engine-operating patterns are included in APPENDIX D: *Base Engine-operating Patterns*. These are summarised in Table 3.3 in terms of the average relative standard error.

Table 3.3: Summary of uncertainties for fuel consumption and emission factors for the *base* engine-operating patterns.

	Average relative standard error (%)			
Parameter	**Petrol**			**Diesel**
	Euro-0	**Euro-2**	**Euro-3**	**Euro-2**
FC	10	3	3	4
CO_2	9	3	3	4
CO	28	27	28	13
HC	21	25	24	15
NO_x	14	27	26	9

The analysis shows a higher certainty for CO_2 and fuel consumption than for pollutant emissions. There is a greater variability in the pollutant emissions because they are more sensitive to engine operation and the different vehicle technologies within the same fuel type and emissions regulation than CO_2 and fuel consumption.

The sensitivity of the implemented fuel consumption and emissions model with respect to the input parameters is considered in Chapter 4 along with the description of the model.

3.3.5. Limitations

The proposed fuel consumption and emissions simulation method depends on a range of engine-operating patterns, which resulted from a set of predetermined driving cycles. This approach is limited to the range of engine-operating patterns resulting from the driving cycles used in the EMPA emissions testing programme.

Emissions rates deteriorate with vehicle age and mileage. These factors were not considered during this study. The other modes of road transport (mini-buses, buses and freight) were also not considered, but if existing driving cycles and emissions factors exist for other modes which use petrol or diesel internal combustion engine the same methodology could be applied.

3.4. Design of an engine-operation and travel survey

3.4.1. Purpose

The purpose of the travel behaviour and engine operation survey was to measure engine-operating patterns for different types of vehicles and driving conditions using the City of Johannesburg as a case study. The survey provided raw data for the simulation of local fuel consumption and emission factors and to determine the level of vehicle activity in the city. The survey also served as a means to estimate annual vehicle kilometres travelled by the various vehicle fuel types and capacity classes, and a profile of private passenger vehicle usage. These sets of data are needed for the development of emissions inventories.

3.4.2. Approach

In the survey methodology two types of tools are combined in an original research application to provide data for estimating emission factors for various road types and periods of the day. OBD on-board electronic diagnostic analysers, essentially developed as a diagnostics tool, and GPS, designed for navigation systems, allow for a cost effective means to simultaneously measure and record vehicle engine-operating patterns and location. Together with an emissions simulation model based on emission factors transformed from European real-world driving cycles these tools provide a mechanism to develop local emissions inventories.

The emissions simulation model needs appropriate data to estimate fuel consumption and emission factors for different vehicles, operating environments and driving conditions in the study area. The methodology used to develop the *base* engine-operating patterns for the simulation model, in the previous section, and the data collection process discussed here were developed together to minimise the complexity of the model and to take advantage of the technologies available to monitor vehicle operation. The data collection process was also designed to collect information not currently available regarding South African vehicle activity characteristics such as the proportions of different road types used by vehicles of different fuel types and classes.

Engine load and engine speed were measured directly so that additional measurement programmes to determine auxiliary equipment use, average road gradient and driving style (gear change choice) would not be required. Measured engine operations implicitly include these effects. Vehicle speed was measured to provide an indication of the level of congestion being experienced for different road types and time of day, and to consider the effects of vehicle fuel type and engine capacity on average vehicle speed.

The survey also collected data regarding travel behaviour, such as when people use their vehicles and vehicle kilometres driven per type of vehicle, which are needed in the development of emissions inventories and policy formulation.

3.4.3. Data acquisition

Vehicle sample

A random sample of thirty vehicles belonging to volunteers who work within the boundaries of the City of Johannesburg was used for the survey. A list of all vehicles in the sample is included in APPENDIX E: *Vehicles Sampled During Survey*. This list is summarised in Table 3.4.

Table 3.4: Number, share and average capacity of vehicles sampled during the survey by fuel type and capacity class.

	Diesel				Petrol			
	Capacity class (ℓ)			Total	Capacity class (ℓ)			Total
	< 1.4	1.4 - 2.0	> 2.0		< 1.4	1.4 - 2.0	> 2.0	
Vehicles in sample	1	2	2	5	5	13	7	25
Share of sample (%)	3	7	7	17	17	43	23	83
Average capacity (ℓ)	1.4	1.9	2.7		1.2	1.7	2.7	

The proportions of vehicle types in the sample are compared to the profile of the vehicle population for Johannesburg (for the end of 2004) in Figure 3.4. Although the sample is small, the profile is adequately representative of the overall fleet.

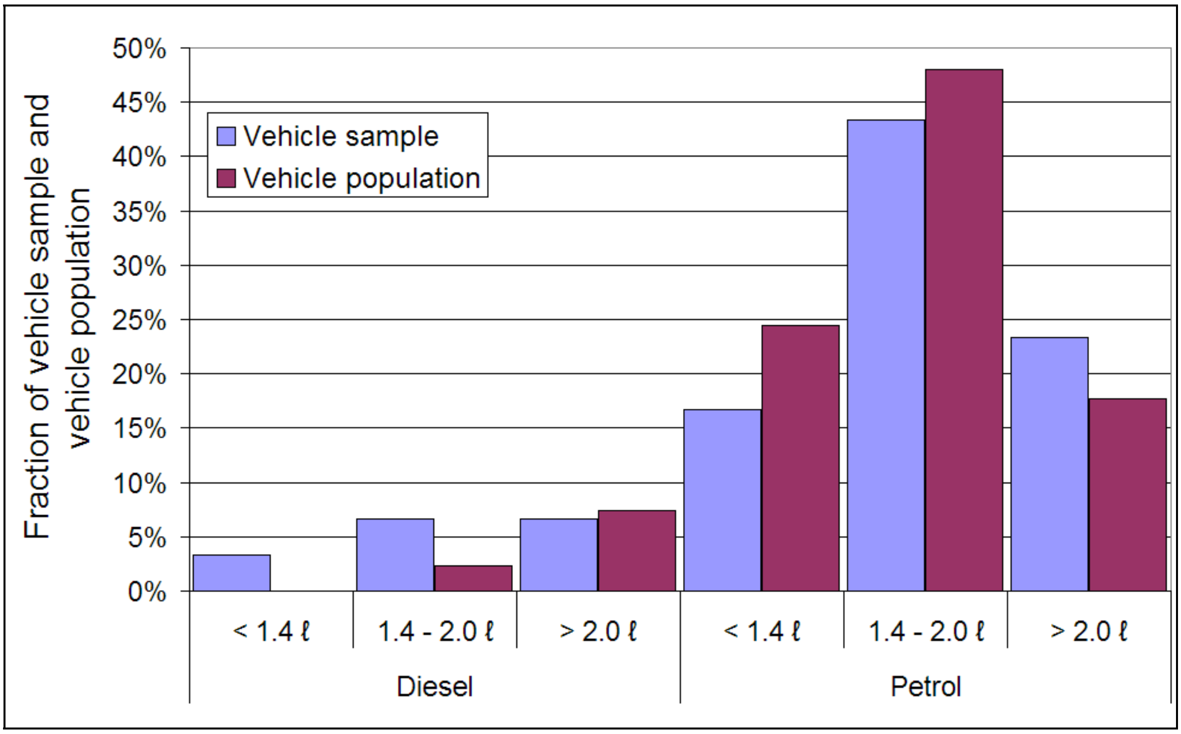

Figure 3.4: The vehicle sample compared to the vehicle population in terms of the fraction of fuel types and capacity classes.

There was a rapid introduction into the market of < 1.4 ℓ and 1.4 – 2.0 ℓ capacity class diesel vehicles between the end of 2004 and 2006, which explains the differences in the diesel vehicle categories between the sample and the vehicle population. The objective of the survey was to determine the typical engine-operating patterns for the different types of vehicles so it was not necessary for the sample to match the population exactly.

As a justification of the sample size, other projects can provide some perspective. The Vehicle Emissions Project (Wong, 1999) used 67 vehicles for a national assessment of the South African vehicle population and the Modem/Hyzdem driving cycles, developed within the ARTEMIS (Assessment and reliability of transport emission models and inventory systems) project, used 77 vehicles and 2 200 hours of driving in 4 European cities (de Haan and Keller, 2001; Andre, 2004).

Road database

The road database was obtained from the City of Johannesburg in the form of GIS (geographical information systems) files. Roads in the GIS database were grouped into three road types for this study: freeways, main roads (arterials) and streets (Figure 3.5).

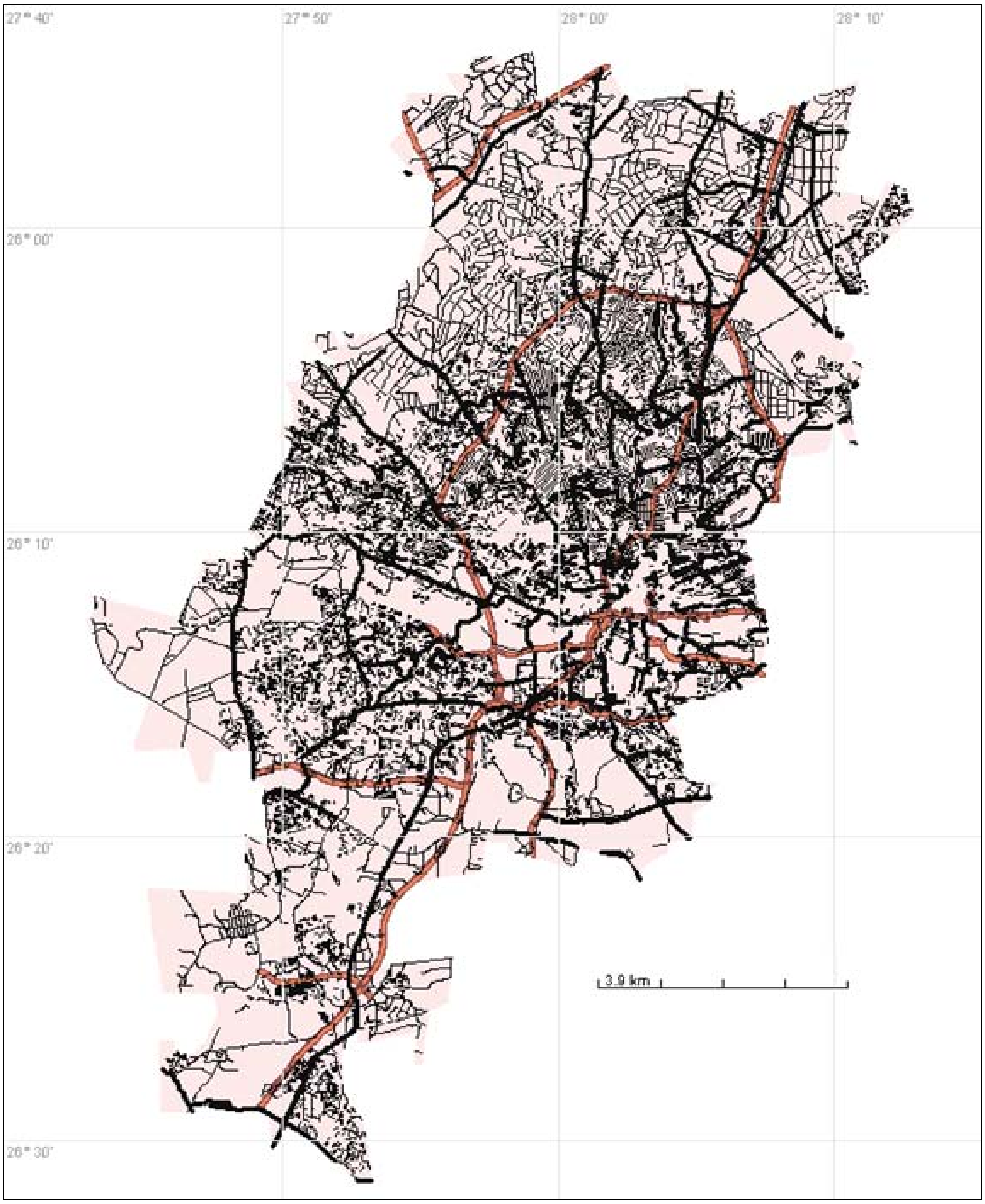

Figure 3.5: Johannesburg's road network showing freeways (orange lines), main roads (thick black lines) and streets (thin black lines).

3.4.4. Equipment

OBD data logger

Engine-operating parameters (engine speed and engine load) and vehicle speed were logged during the survey using a DriveRight$^{®}$ CarChip$^{®}$E/X OBDII (on-board diagnostics) data logger manufactured by Davis Instruments. The specifications for the OBDII data logger are included in APPENDIX F: *CarChip OBDII Data Logger Specifications*. The specifications of most importance in this work are the accuracy of engine speed, which is accurate to ±1 rpm, and the engine load, which is accurate to ±0.1%. The standardised OBDII port, its usual location within a vehicle and the insertion of the CarChip data logger are illustrated in Figure 3.6.

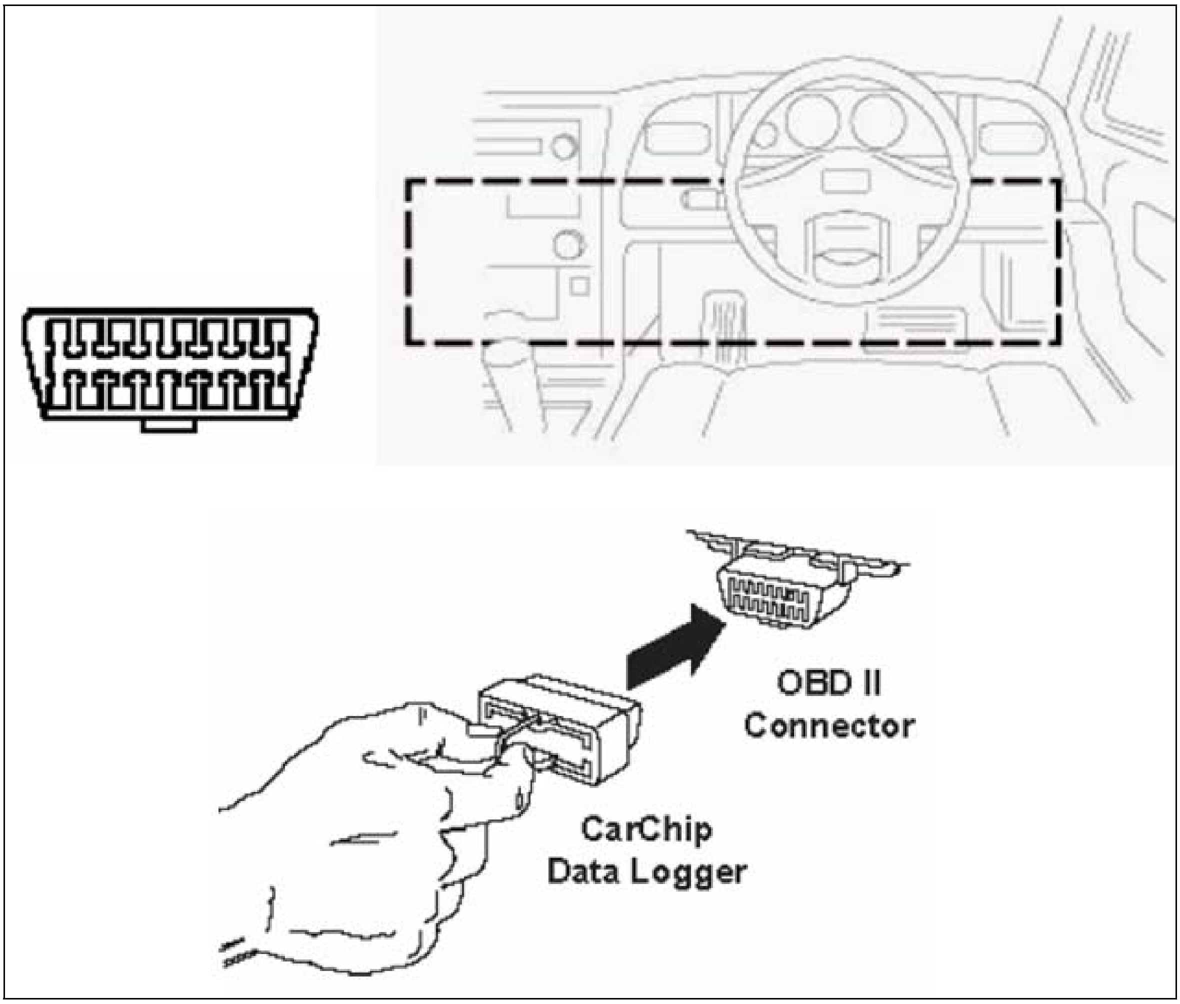

Figure 3.6: OBDII standardised port, its location within vehicles and the CarChip data logger (Davis Instruments, 2004)**.**

GPS module and data logger

Vehicle speed and location were logged during the survey using a FastTrax GPS® (Global Positioning System) module and DGPS-XM4-ALT data logger produced by Robert Keskull (http://www.gps-datalogger.com/). Positions determined by the FastTrax GPS modules have an uncertainty of ±3 m. Four sets of OBD and GPS equipment were used on a rotational basis during this study. A photograph of the GPS data logger, the adapter for vehicle cigarette lighter sockets and the GPS sensor (encased in a custom made casing) are shown in Figure 3.7.

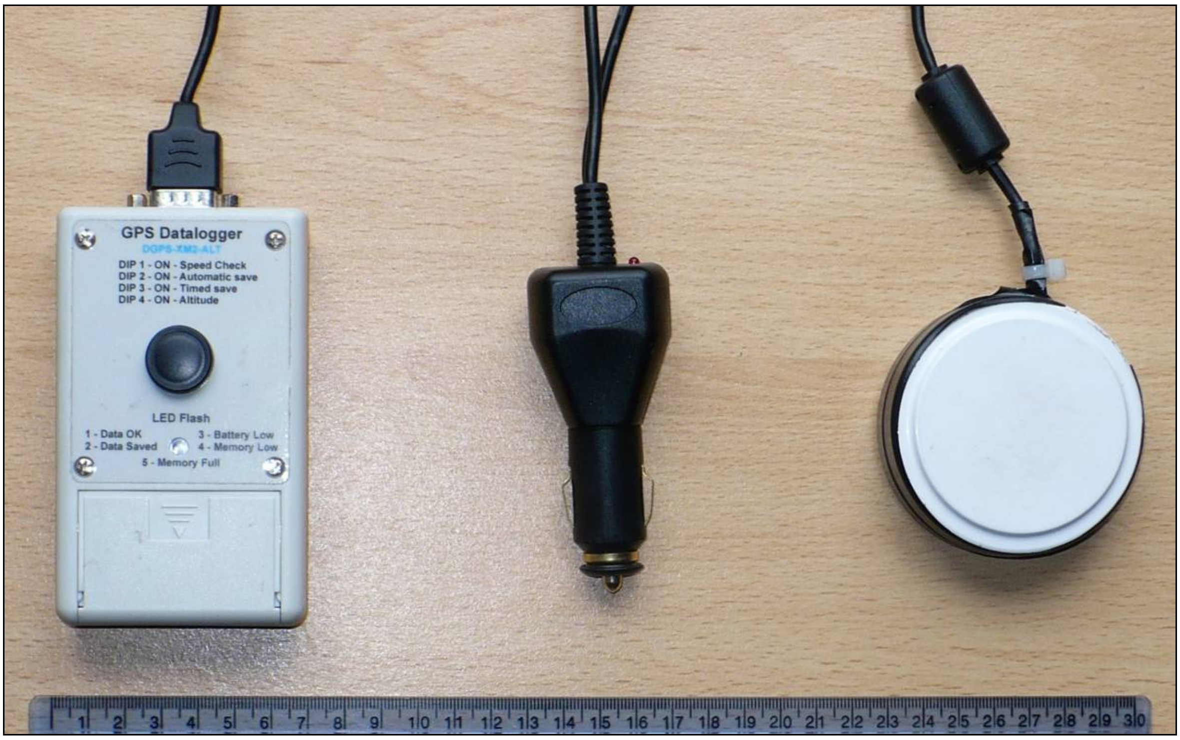

Figure 3.7: GPS datalogger (left), adapter for cigaette lighter sockets (middle) and GPS sensor (right).

3.4.5. Procedure

Data collection

Each sample vehicle was fitted with a set of OBD and GPS loggers for a period of approximately two weeks. Vehicles were driven by their owners, as they normally would be during this period. The only requirement was that the OBD sockets in the vehicles were operational. This was tested by briefly inserting the data logger into the OBDII port of the sample vehicle, starting the vehicle and letting it idle for a few minutes and then downloading the reports from the data logger onto a computer. The report indicated whether the data logger was compatible with the specific vehicle.

No special instructions were given to the drivers in order to avoid changes in driving behaviour. In some cases, however, it was necessary to ask the drivers to plug the GPS unit into and out of the cigarette lighter power socket at the beginning and end of trips as the power socket of some vehicles remained on when the ignition was off. If the power socket remained on while the vehicle was parked, the battery in the GPS data logger would discharge. The equipment required no other human interaction from the volunteers.

The GPS units recorded position and time at one-second intervals. The OBD units recorded time and speed at one-second intervals and engine-operating parameters at five-second intervals. The OBD data loggers also logged information about each trip including start time, duration and distance. For the purposes of this study a trip was defined as the period between when an engine was started and when it was turned off.

Data processing

Engine-operating data from the OBD data logger and location data from the GPS logger were downloaded after each sampling period using the manufacturers' software. The data were then manually copied into Microsoft Excel files where they were formatted and screened for missing values and outliers (caused for example by the GPS losing contact with the satellite when passing under a bridge or entering an underground parking). After the entire set of vehicles had been sampled, individual Excel files were combined into a single Microsoft Access® database. The data flow from the survey to the database is shown in Figure 3.8.

GPS data points were allocated to road types by matching their coordinates to the closest road element in the Johannesburg GIS (Geographical Information System) road database. The OBD and GPS data were correlated to each other based on the date, time and unique vehicle identifier within the Access® database. The data compilation is represented in Figure 3.9.

During the survey, engine speed was logged in revolutions per minute and the engine load was logged as a percentage of maximum engine load for any given engine speed. The maximum engine load is defined in the OBDII standard (ISO 15031/SAE J1979) as the percentage of maximum volumetric efficiency for petrol vehicles and the percentage of maximum fuel flow rate for diesel vehicles. This is equivalent to the percentage of the maximum torque curve of an engine. The measured rpm and engine load values were converted to mean effective pressure and mean piston speed using the torque curves and engine strokes for the vehicles in the sample (obtained from Car Magazine). This was done so that the data were in the correct units and dimensions to be used in the fuel consumption and emissions simulation model.

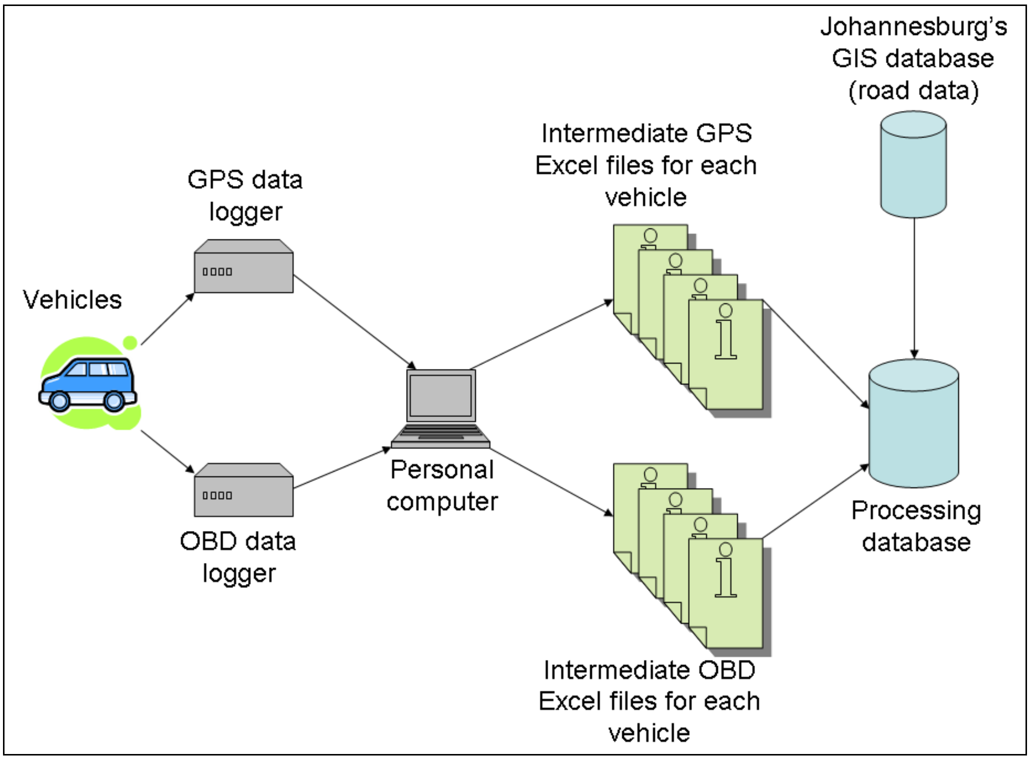

Figure 3.8: Data flow of vehicle performance survey data.

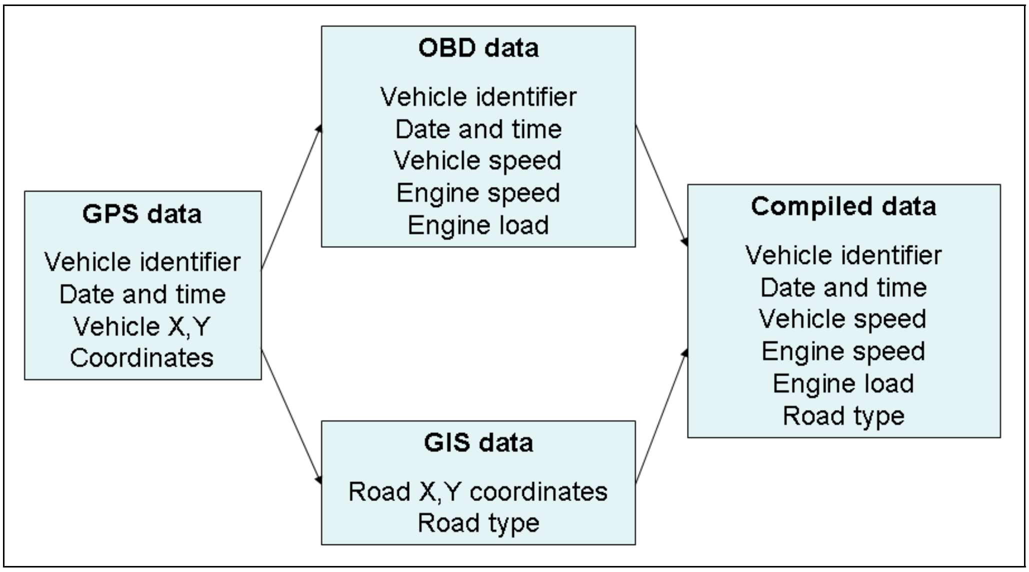

Figure 3.9: Merging of the GPS, GIS and OBD datasets within the Access® database.

Two problems arose during the survey. The OBD data loggers had time drift that resulted in time loss (or gain depending on the specific data logger) in the order of three seconds per day and the GPS sensors were not accurate enough to differentiate between roads that are close to and running parallel to each other. The time drift was compensated for by correlating the speed from the OBD data logger to the speed measured by the GPS. This was visually done by comparing the OBD and GPS speed profiles, one trip at a time, and adding a correction factor to the time from the OBD data. The second problem was rare and only occurred when there were service roads next to a freeway or at intersections. This problem was addressed by considering the data points before and after the unresolved condition occurred.

3.4.6. Analysis

Data from the survey were analysed to determine (i) how driving conditions influence engine operation and (ii) vehicle usage profiles. This was done by aggregating the data using five dimensions: day of the week (either week or weekend), period of the day, road type, vehicle fuel type and engine capacity class.

Driving conditions and travel behaviour

Driving conditions are determined by travel behaviour and number of vehicles using the road network at the same time. Travel behaviour was determined by considering the distribution of distance travelled and time spent travelling by the sample of vehicles by time of day, day of the week and road type. Driving conditions were determined by calculating average vehicle speeds, acceleration and number of stops by time of day, day of the week and road type. Hourly intervals were used for analysis of driving conditions and travel behaviour. For development of local engine-operating patterns, driving conditions and travel behaviour were aggregated into longer time intervals of several hours e.g. morning or evening rush hours.

Relationships between the parameters were explored using Microsoft Excel pivot tables linked to the Access® database of compiled data (summarised in Figure 3.9).

Survey data were used also to determine vehicle kilometres travelled per year for vehicles of different fuel types and capacity classes. Travel behaviour was determined by calculating average distances travelled per year for each fuel type and capacity class using trip data collected during the survey. Once again, a combination of Microsoft Excel pivot tables linked to the Access® database was used.

Developing local engine-operating patterns

Measured engine speeds and engine loads from the survey were binned into speed and load intervals to produce engine-operating patterns for each vehicle, day of week, period of day and road type. The binning process was the same as described in Section 3.3.4 for the development of the *base* engine-operating patterns for the fuel consumption and emissions simulation model. The resulting patterns were then aggregated further by fuel types and capacity classes. This ensured an equal weighting of each vehicle in the sample irrespective of the number of hours each vehicle was monitored.

Aggregate engine-operating patterns were produced for six intervals of the day: 06:30 – 09:00 (morning commute), 09:00 – 12:00 (mid morning), 12:00 – 14:00 (lunch time), 14:00 – 16:00 (mid afternoon), 16:00 – 18:30 (evening commute period) and other (all other periods i.e. 18:30 – 06:30) instead of using one hour intervals used to determine the driving conditions. This was necessary because the lower sampling frequency of the engine-operating parameters (every 5 seconds) compared to vehicle speed used to determine overall driving conditions (every second), and the separation of the engine operation data into vehicle fuel types and capacity classes reduced the quantity of data available for each grouping of dimensions.

The dimensions and intervals used to aggregate the engine-operating patterns are summarised in Table 3.5. There are 216 possible combinations of engine-operating patterns from the table i.e. 3 road types × 6 periods of the day × 2 days of the week × 2 fuel × 3 capacity classes.

Table 3.5: Dimensions and intervals used to aggregate the engine-operating patterns.

Operating environment dimensions				**Vehicle dimensions**	
Road types	Periods of day	Period description	Day of week	Fuel	Capacity class (ℓ)
Freeway Main road Street	06:30 – 09:00 09:00 – 12:00 12:00 – 14:00 14:00 – 16:00 16:00 – 18:30 18:30 – 06:30	Morning commute Midmorning Lunch time Mid-afternoon Evening commute other	Weekday Weekend	Petrol Diesel	< 1.4 1.4 – 2.0 > 2.0

3.4.7. Limitations

The number of vehicles sampled limits the certainty of the conclusions drawn from the survey. In the case of diesel vehicles only one < 1.4 ℓ capacity class vehicle was sampled and two of each 1.4 – 2.0 ℓ and > 2.0 ℓ capacity class were sampled, which is too few to make any reliable conclusions about these vehicles. As the main objective of this study is to demonstrate a process rather than produce a complete vehicle emissions inventory, the sample is viewed as sufficient to demonstrate typical engine operation for diesel vehicles, and to indicate their differences from petrol engines. The small sample does not reduce the accuracy of the emissions simulation model but influences how representative the sampled data are with respect to actual driving behaviour.

The equipment was convenient to use due to its size and ease of installing and removing it from a vehicle. Extracting and processing the data, however, was more complicated. For each trip, the data from the OBD logger was manually copied and formatted in Microsoft Excel before it could be imported into a database and coupled to the GPS data. This was a limitation in the manufacturer's software.

The memory capacity of the OBD and GPS data loggers limited the survey period to approximately 25 hours of driving. This allows for about two and a half weeks of normal vehicle use before the equipment needed to be removed to have the data extracted. Unfortunately, due to the design of the equipment, if this period is exceeded, there is data loss. The OBD overwrites the oldest data, whereas the GPS logger protects existing data and rejects new data. This was avoided by sampling each vehicle for only two weeks.

3.5. Outline of an emissions inventory model

3.5.1. Purpose

The purpose of this section is to outline a method of producing a vehicle emissions inventory using an implementation of the simulation model described in Section 3.3, data collected using the surveying method described in Section 3.4, and information about the vehicle population and fuel sales in the City of Johannesburg.

3.5.2. Approach

The design concept for an emissions inventory model (Figure 3.10) was developed by the author to provide a framework for calculating total fuel consumption and emissions in the City of Johannesburg.

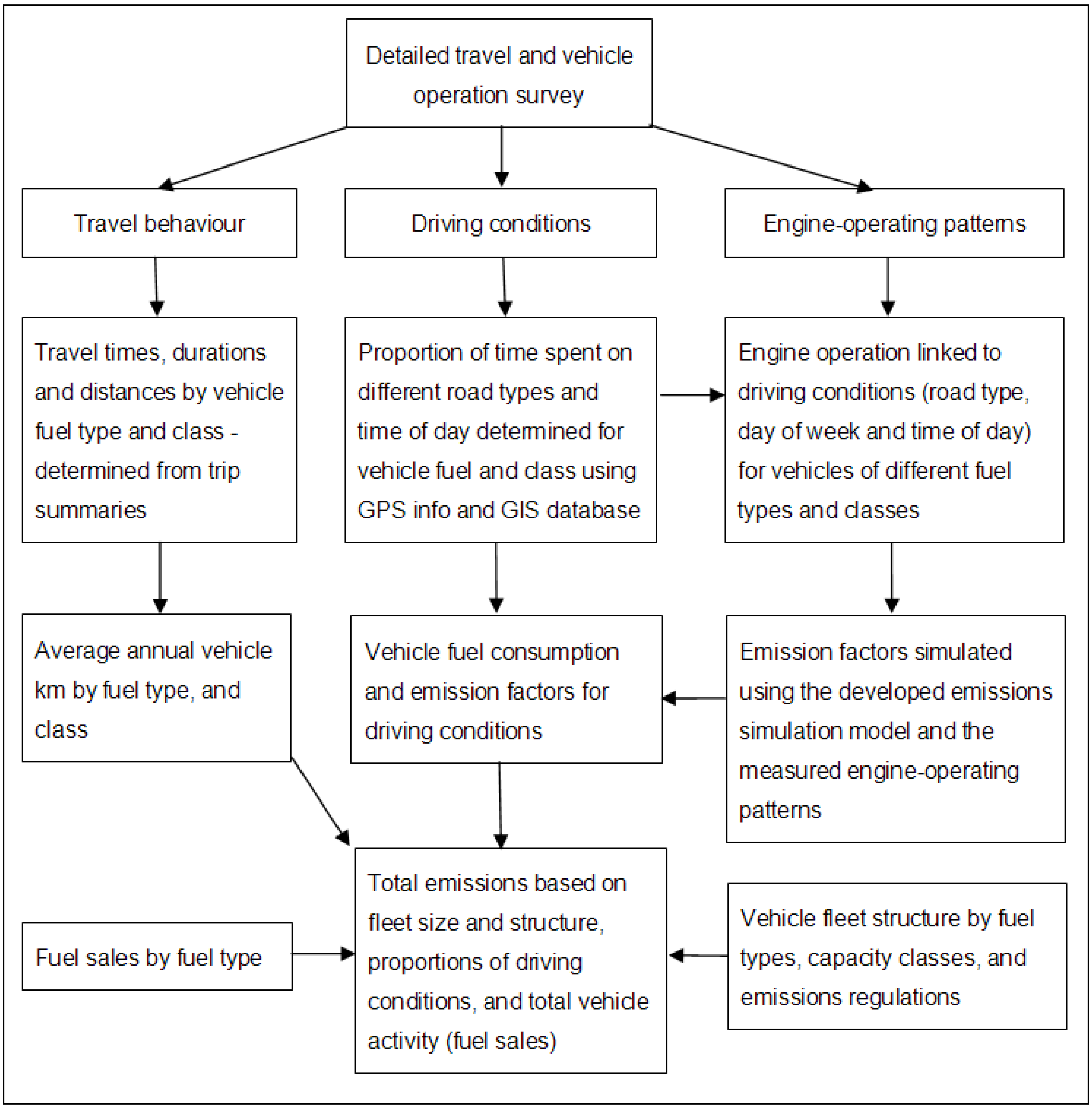

Figure 3.10: Structure of an emissions inventory model based on the proposed emissions simulation model and surveying method.

The emissions inventory model uses three types of information from the travel survey and the fuel consumption and emissions simulation model:

- Travel behaviour - the trip lengths and time of day when vehicles of various fuels types and engine capacities are used;
- Driving conditions - resulting from the number of vehicles that simultaneously use the different road types at different times of the day; and
- Emission factors - simulated using the emissions simulation model and the engine-operating patterns from the survey data.

The inventory model uses pre-calculated fuel consumption and emission factors from the emissions simulation model and the surveyed engine-operating patterns. Total vehicle activity was estimated for travel behaviour from the survey, vehicle fleet structure and fuel sales as an alternative to the conventional means discussed in Section 2.3.1. Fuel sales were used to estimate total vehicle kilometres from the fleet average fuel consumption using a similar method as used by Zachariadis and Samaras (2001) to validate vehicle kilometre statistics in Europe.

The final implementation of the emissions inventory model uses a set of software modules and a supporting database. Simulated emission factors, vehicle activity by fuel type and class and fuel sales for Johannesburg were stored in the database. The novel approach combines emission factors simulated for local conditions with vehicle activity to produce a database-driven urban emissions inventory. The vehicle fleet structure and fuel sales data are discussed here along with the a conceptual outline of the procedure to develop the emissions inventory. The software architecture is presented in Chapter 4.

3.5.3. Data sources

In addition to the data collected in the survey and the emission factors from the simulation model, the Gauteng vehicle registration database and fuel sales were used.

Vehicle registration database

The vehicle registration database for Gauteng was obtained from the City of Johannesburg for the years 2000 to 2004. The database represents the state of the fleet at the end of each year. Proportions of vehicles registered in the three largest cities in the province are given in Table 3.6; these were assumed to stay constant for 2006.

Table 3.6: Shares of the private passenger vehicle population in Gauteng province by city at the end of 2004.

Share of vehicle population by city (%)		
City	**Fuel**	
	Petrol	**Diesel**
Ekurhuleni	28	29
Johannesburg	36	32
Tshwane	25	28
Other	11	12
Total	**100**	**100**

Johannesburg has the largest share of the vehicle population with the highest ratio of petrol to diesel vehicles compared to the other cities.

The total private passenger vehicle population of the Gauteng was obtained from data published in the National Association of Automobile Manufacturers of South Africa annual report for 2007 (NAAMSA, 2007). This is summarised in Table 3.7.

Table 3.7: Estimated size of the private passenger vehicle population in Gauteng Province at the end of 2006.

Gauteng Province vehicle population ('000s)	
Light delivery vehicles (bakkies, SUVs, vans)	536
Motor cars and station wagons	2 042
Total end 2006	**2 578**

The proportions of different fuel types and engine capacity classes, calculated from the vehicle registration database for Johannesburg (NDOT, 2004) for the years 2000 to 2004, are shown in Figure 3.11.

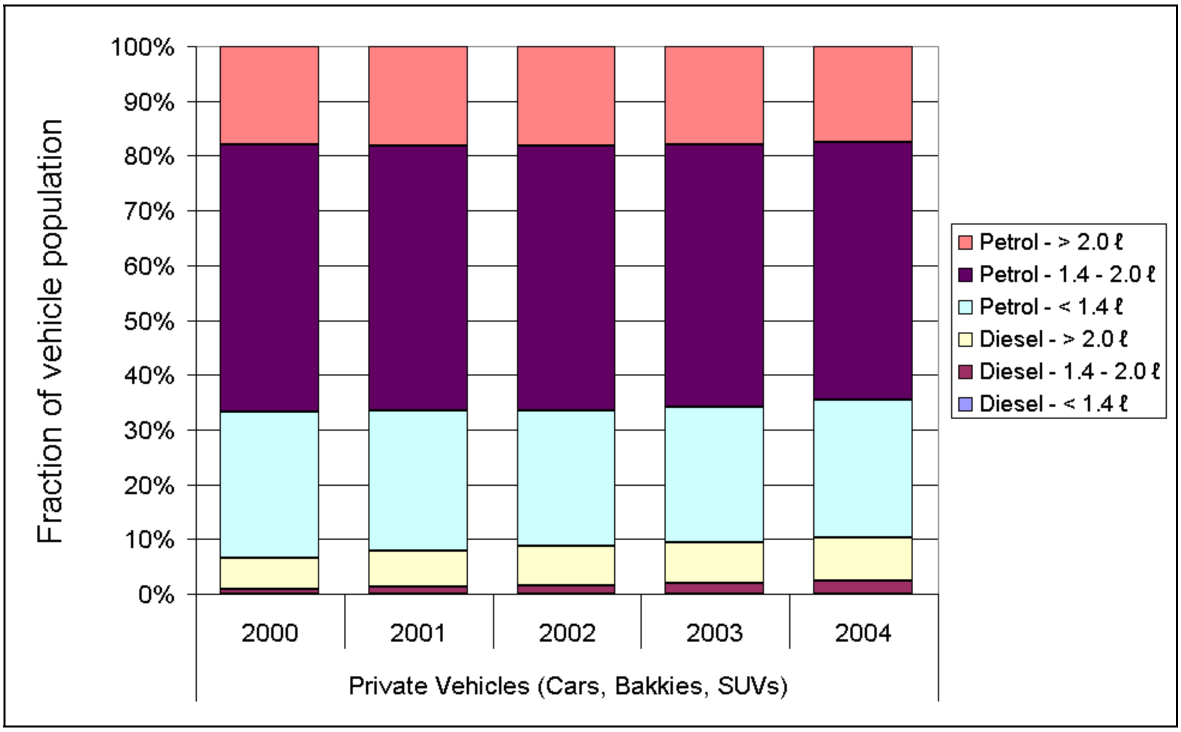

Figure 3.11: Structure of the Johannesburg vehicle fleet 2000 to 2004 (NDOT, 2004).

A straight-line curve fit was used to extrapolate the proportions of each vehicle fuel type and capacity class over the five-year period to estimate the fleet structure at the end of 2006.

An estimate of the total number of private passenger vehicles registered in Johannesburg at the end of 2006 was estimated to be 979 thousand (852 thousand petrol vehicles and 127 thousand diesel vehicles) using the data in Table 3.7 and extrapolation of the fleet structure from Figure 3.11. The fleet structure thus estimated for developing the emissions inventory is given in Table 3.8.

Table 3.8: Vehicle fleet structure for Johannesburg at the end of 2006.

Fuel	Share of fuel type (%)	Capacity class (ℓ)	Share of fuel type and capacity class (%)
Petrol	87	> 2.0	18
		1.4 - 2.0	45
		< 1.4	24
Diesel	13	> 2.0	9
		1.4 - 2.0	3
		< 1.4	1
Total	100		100

The vehicle fleet structure was disaggregated further into categories equivalent to different European emissions regulations. All diesel vehicles were assumed to comply with the Euro-2 diesel regulations because this was the only data available from the EMPA testing program for diesel vehicles. For petrol vehicles, estimates were made based on vehicle age, the joint implementation strategy for the control of exhaust emissions from road-going vehicles (RSA, 2003) and the Euro regulations. With these assumptions, all vehicles sold before 2006 would be pre Euro-2 specifications (or fall into the Euro-0 category of the developed emissions model). Although Euro-2 was the minimum requirement for vehicle models sold in South Africa from the beginning of 2006, Euro-3 and Euro-4 regulation models are also available due to imports and models manufactured in South Africa for export but also sold on the local markets.

The proportions of emissions regulations for petrol vehicles were thus assumed 45% Euro-0, 35% Euro-2 and 20% Euro-3 for the emissions inventory calculations. These assumptions are estimates based on the age distribution of the vehicle population and the share of imported vehicles over the last 10 years obtained from the NAAMSA 2006 annual report. The exact structure of the vehicle population in terms of emissions regulations would need to be determined from an extensive survey of automotive manufacturers. This is beyond the scope of this study.

Fuel sales

Fuel sales were obtained from Chevron, secretary for the petroleum industry, by magisterial districts in Gauteng Province from the year 2002 to the first quarter of 2007. Total fuel sales for the City of Johannesburg per annum for the study period were calculated to be 334 million litres of diesel and 1 620 million litres of petrol.

Total fuel sales to private passenger vehicles were adjusted to compensate for retail fuel sold to taxis. Taxis were defined as vehicles capable of carrying 12 or more passengers and with an engine capacity smaller than 3 ℓ. Estimates of average annual distance travelled by taxis and their fuel consumption were obtained from Tomecki and Taylor (1994) and Schermers and Tomecki (1992). An average distance of 35 thousand kilometres per year with an average fuel consumption of 15 ℓ/100 km (6.67 km ℓ^{-1}) for diesel taxis and 18 ℓ/100 km (5.56 km ℓ^{-1}) for petrol taxis was used in the calculations. The number of taxis was obtained from the vehicle registration database. The 1 700 diesel taxis and 26 000 petrol taxis registered in Johannesburg were estimated to use 9 million litres (2.7%) of the diesel and 164 million litres (10%) of the petrol sold in Johannesburg during the study period. Other consumers of retail fuel were not considered.

As with the vehicle population, the fuel sales were also split into the different cities in Gauteng province, shown in Table 3.9. Johannesburg has lower diesel fuel sales compared to petrol sales when compared to the other cities, but overall the fuel sales in the city are greater than the other cities in relation to the vehicle population size. This suggests that either vehicles in Johannesburg are used more than vehicles registered in the other cities or motorists from other cities are filling up in Johannesburg, which implies there needs to be a net commute into Johannesburg from surrounding cities.

Table 3.9: Share of fuel sales in Gauteng province by city for 2006.

City	Fuel	
	Petrol	**Diesel**
Ekurhuleni	25	28
Johannesburg	40	35
Tshwane	19	19
Other	16	17
Total	**100**	**100**

Share of fuel sales in Gauteng by city (%)

3.5.4. Procedure

Total annual fuel consumption and emissions in Johannesburg for the study period were estimated from the survey data using the procedure presented in Figure 3.12.

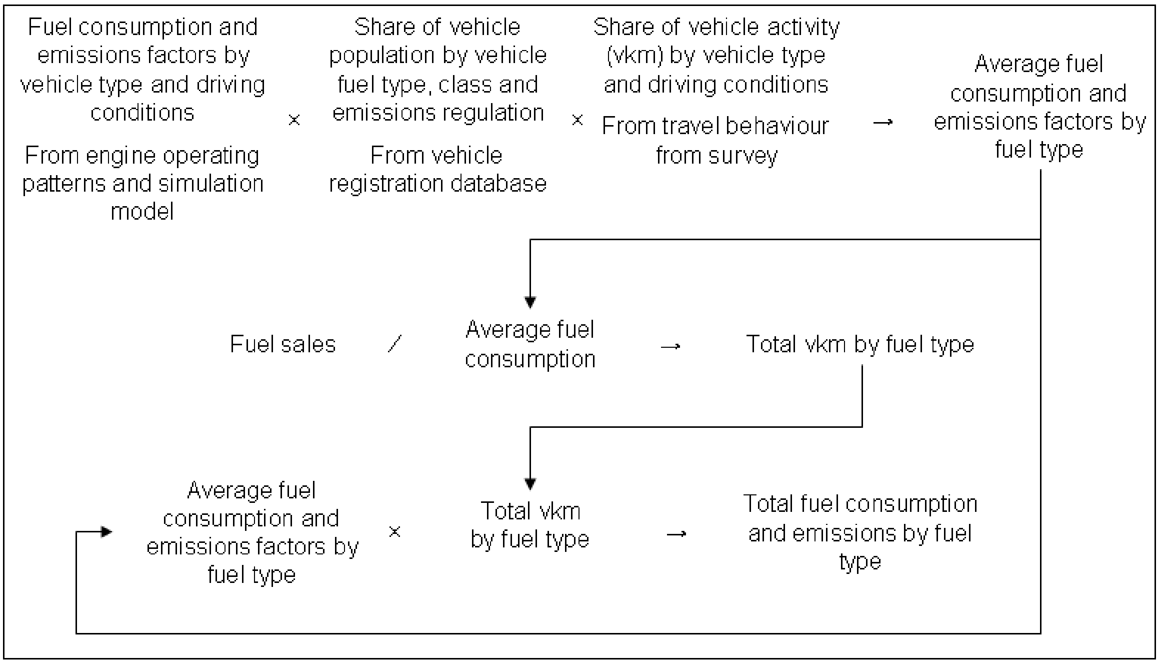

Figure 3.12: Total fuel consumption and emissions calculation procedure.

Local fuel consumption and emission factors were produced using the fuel consumption and emissions simulation model and the engine-operating patterns for all combinations of driving conditions and vehicle types measured during the survey. A custom computer program was written (in transact SQL) which was used to loop though all the engine-operating patterns stored in an Access® database and called the emissions simulation program to calculate the fuel consumption and emission factors for each pattern.

Average fuel consumption and emission factors were determined for petrol and diesel vehicles using the emission factors calculated from the engine-operating patterns weighted according to the structure of the vehicle population and the proportion of driving conditions for the different capacity classes and emissions regulations of the two fuel types.

Total vehicle kilometres for petrol and diesel vehicles were determined by dividing retail fuel sales (minus fuel consumed by taxis) by average fuel consumption for the two types of vehicles. Total emissions were calculated from the product of average emission factors for the two fuel types and their total vehicle kilometres. The procedure was implemented as an original software tool, which will be discussed in Section 4.4.

3.5.5. Limitations

The method described does not consider the geographical distribution of vehicle activity within the City of Johannesburg but determines total fuel consumption and emissions for average driving conditions, total private passenger vehicle activity and the mix of various vehicle types and road facilities within the study area. Retail fuel sales to commercial vehicles was not differentiated from sales to private passenger vehicles. This implies that the commercial vehicles were assumed to travel the same amount and have the same fuel consumption as the equivalent engine capacity class and fuel type. A more detailed study of commercial vehicle use and fuel consumption is needed to disaggregate private and commercial fuel sales at retail fuel stations.

The accuracy of vehicle registration database posed some questions, as a large proportion (about 40%) of the vehicles in the database had either no fuel type or capacity class. To overcome this, vehicles with missing data were assigned values in proportion to the parts of the database that had valid data. It is recommended that for future studies of this type higher quality and up-to-date information from the eNatis (National Department of Transport Information System) would enable a more precise representation of the vehicle population.

The emissions inventory model is dependant on the quantity and quality of data from the vehicle population and from the travel survey. The size of the survey is a limitation to the accuracy of the model.

3.6. Chapter summary

In this chapter, the method used to develop a fuel consumption and emissions simulation model was described, a travel behaviour and engine operation surveying procedure to collect data for the simulation model was presented, and a method to construct an emissions inventory from the simulation model and survey was detailed.

The proposed fuel consumption and emissions simulation model takes advantage of a similar statistical aggregation method used in the HBEFA model (de Haan and Keller, 2004a). A novel feature is the substitution of a method to account for non-kinematic engine loads by using engine-operating patterns, instead of the prior method of using driving patterns. This provides emission factors that are more realistic by accounting for topography, driving style and auxiliary equipment, but at the expense of spatial resolution. In addition to the benefits of being able to account for non-kinematic engine loads, there are benefits due to the lower variability in the fuel consumption and emissions when matching engine-operating patterns than when matching driving patterns.

The electronic survey provided a convenient and unobtrusive way to collect travel behaviour and engine operation data. The engine-operating data can be used in the fuel consumption and emissions simulation model to determine emission factors for Johannesburg and the trip information can be used to determine vehicle usage profiles of various types of vehicles. Combining these two sets of data and information about the vehicle fleet and fuel sales provides information needed to produce an emissions inventory.

The method of combining the data to produce an emissions inventory (or emission factors for different vehicle types and driving conditions) was then described. The method is limited by the size of the survey sample and the accuracy of the vehicle registration database.

Innovative technological methods to use OBD and GPS demonstrate a practical and feasible means to develop South African emissions inventories in a coast effective manner.

In the next chapter, the implementation of the emissions simulation model, results of the survey, and the outcome of the emissions inventory model are presented and discussed.

4. RESULTS AND DISCUSSION

4.1. Introduction

In this chapter, the structure and implementation of a new fuel consumption and emissions simulation model, developed as part of this study, are presented and validated. Results of the engine operation and travel survey in Johannesburg are presented and discussed. Finally, the architecture of the emissions inventory model is discussed and total fuel consumption and emissions for Johannesburg are estimated for the study period using the proposed emissions inventory model.

4.2. Description of the emissions simulation model

The function of the fuel consumption and emissions simulation model was to estimate the fuel consumption and emission factors for measured engine-operating patterns. This was done by matching measured engine-operating patterns to a discrete linear combination of the *base* patterns developed in Section 3.3. The fuel consumption and emission factors for the *base* engine operating patterns are presented in APPENDIX D: *Base Engine-operating Patterns and Emission Factors*. In this section the software implementation and structure of the model is discussed and validated, including a sensitivity analysis of the model to the various input parameters.

4.2.1. Structure and implementation

Numerical methods have been preferred for the development of this model, as they are more appropriate to the nature of the engine-operating patterns, rather than differential calculus and other curve fitting techniques. The engine-operating patterns, as defined in Section 3.3.4, are made up of discrete values for engine speed and engine load intervals. This makes them suitable for advanced database techniques, which are ideal for filtering and matching large sets of numerical data.

The basic principle behind the model is that similar engine-operating patterns for the same fuel type and emissions regulation compliance have similar fuel consumption and emission factors. From this, fuel consumption and emission factors for a newly measured engine-operating pattern can be derived by matching it to engine-operating patterns of known fuel consumption and emission factors. This is mathematically executed by finding the maximum matching index (defined in Equation 8, Section 3.3.4) of the new engine-operating pattern and a combination of engine-operating patterns of known fuel consumption and emission factors. The *base* engine-operating patterns, developed in Section 3.3, provide a set of reference engine-operating patterns and corresponding fuel consumption and emission factors. Individual *base* engine-operating patterns represent specific driving conditions that on their own may not closely match measured engine-operating patterns. However, by adding several *base* patterns together in various combinations to produce an *aggregated* pattern, it is possible to build an artificial pattern which closely matches any measured pattern.

Practical implications of this method require that the number of *base* patterns and interval step sizes for the proportion of each *base* pattern contributing towards an *aggregate* pattern be limited. For the purposes of this study the maximum number of *base* patterns involved in any linear combination is limited to three and the proportion that each *base* pattern that may contribute towards the *aggregate* pattern is in intervals of 1%. The procedure involves numerically maximising Equation 9 :

$$MI_{\overline{P_i},\ X\overline{P_A}+Y\overline{P_B}+Z\overline{P_C}} \tag{9}$$

where P_i is the pattern being evaluated; P_A, P_B, and P_C are *base* patterns with the unique identifiers *A, B* and *C* respectively and are of the same fuel type and emissions regulation as pattern *i;* $A \neq B \neq C$; P_i, P_A, P_B and P_C are two dimensional vectors; *X*, *Y* and *Z* are the scalar proportions of patterns P_A, P_B, and P_C respectively in 1% intervals; and $X+Y+Z = 1$.

The structure and operation of the model is shown in Figure 4.1. Inputs into the model are fuel type, emissions regulation, an engine-operating pattern to be evaluated, average engine speed and average engine load of the pattern. Outputs from the model include the linear combination of *base* engine-operating patterns that best match the new pattern, the resulting matching index (*MI*), the emissions rates per litre engine capacity (in $g\ s^{-1}\ \ell^{-1}$) of CO, HC, NO_x, CO_2 and fuel consumption.

Within the software implementation of the simulation model an optimisation strategy was used to maximise the speed of the calculation process. The procedure in Figure 4.1 illustrates the optimisation strategy for the calculation of fuel consumption and emission factors for a measured engine-operating pattern.

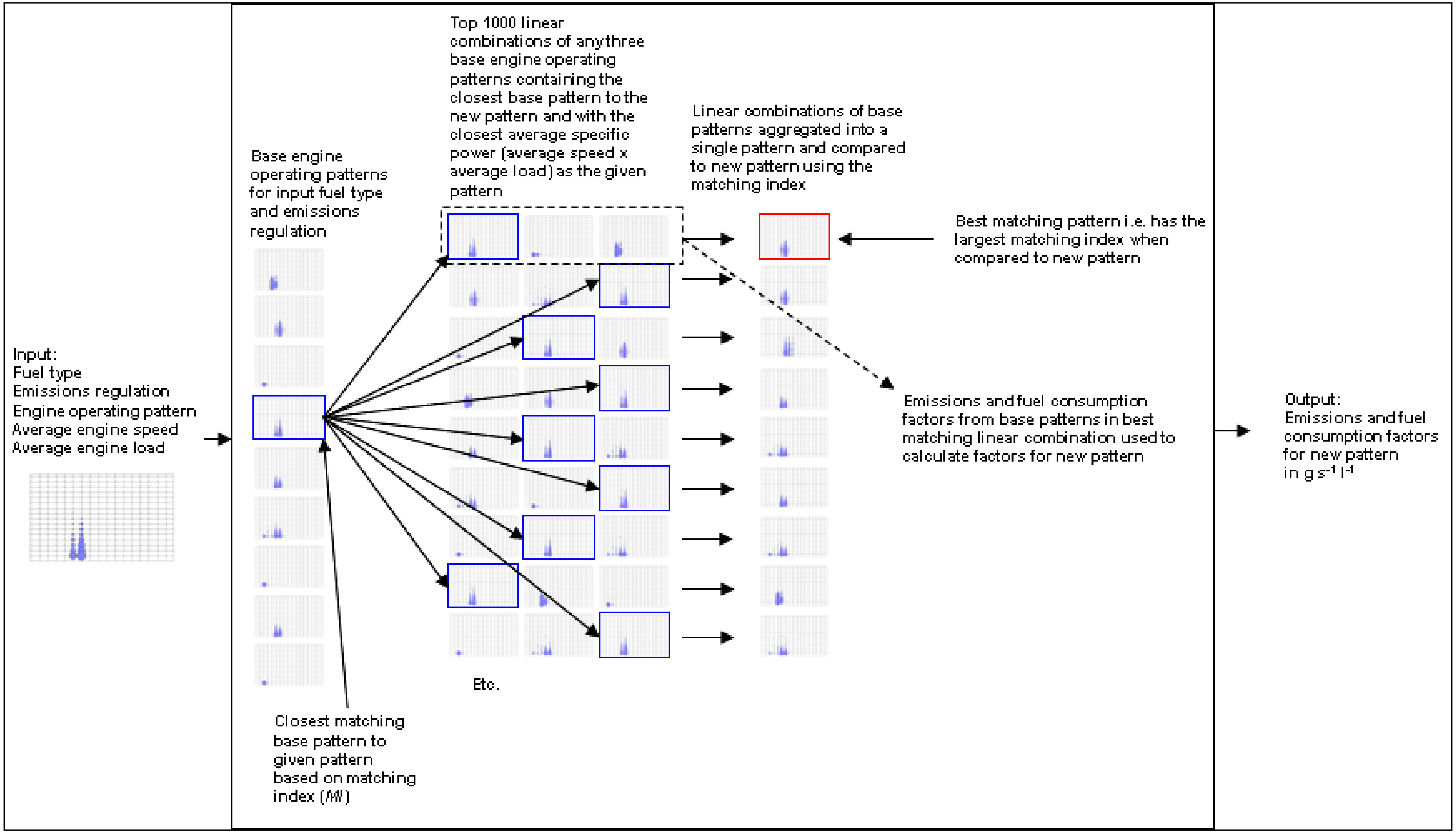

Figure 4.1: Structure and optimisation process within the fuel consumption and emissions simulation model.

An initial part of the optimisation involved pre-calculating *average engine speed*, *average engine load* and *specific power* (*average engine speed* × *average engine load*) for all combinations of any three *base* engine-operating patterns of the same fuel type and emissions regulation pair (Euro-0 petrol, Euro-2 petrol, Euro-3 petrol and Euro-2 diesel). A total of 4.5 million combinations are possible. These were inserted into a database table which was then indexed for rapid searches. Three steps were used to optimise the process of evaluating the fuel consumption and emission factors for a *new* engine-operating pattern:

(i) The closest matching *base* engine-operating pattern for the specified fuel type, emissions regulation and pattern being evaluated is found i.e. the *base* pattern that has the highest *MI* when compared to the new pattern;

(ii) All linear combinations of *base* patterns that include this closest matching *base* pattern and two other patterns are compared to the new pattern using the average specific power calculated for the new pattern and extracted from the pre-calculated table of values for the *base* patterns; and

(iii) A single engine-operating pattern is calculated for each of the 1 000 closest matching combinations (by specific power) of *base* patterns and compared to the new pattern by calculating the matching index. The linear combination of *base* patterns which results in the maximum matching index is then used to calculate the fuel consumption and emission factors for the new pattern.

Evaluating all possible combinations of base patterns would not add any accuracy to the model and would increase processing time considerably. The closest single matching *base* pattern from point (i) ensures that the individual *base* patterns, which deviate considerably from the average power of the new pattern, are excluded from the analysis, to avoid unnecessary calculations. The average specific power calculation point (ii) ensures that only the most relevant (1 000 closest) combinations of *base* patterns are compared to the new pattern using the matching index (MI) calculation.

The *MI* calculation is processor intensive so reducing the number of times this calculation is executed improves the speed of the overall process. The optimisation strategy reduced the time to evaluate a single pattern from an average of 1 minute to 10 seconds, effectively reducing the time it took to calculate the emissions factors for all the measured engine operating patterns from the survey from six hours to just over one hour.

The software implementation of the model relies on six tables in a database: (i) definitions of the *new* engine-operating patterns to be evaluated; (ii) definitions of *base* engine-operating patterns; (iii) fuel consumption and emission factors for the *base* patterns; (iv) average engine speeds and average engine loads for all possible combinations of any three *base* patterns; (v) best matching combination of base patterns for the new pattern as a result of the simulations; and (vi) emissions factors resulting from the simulations.

The fuel consumption and emissions simulation model was implemented as a set of stored procedures and user defined functions (both are software components to be called by other processes within the context of a relational database management system) within Microsoft SQL Server®. The components were written in Transact SQL, which is a mixture of procedural and set based progamming languages used in SQL Server®.

The definitions of the relevant tables in the database are provided in APPENDIX G: *Emissions simulation model table definitions* and the computer code for the stored procedures and user defined functions are provided in APPENDIX H: *Transact SQL code for emissions simulation*.

4.2.2. Model validation

The simulation model was validated by comparing known fuel consumption and emission factors to simulated fuel consumption and emission factors for a set of reference engine-operating patterns. The *base* engine-operating patterns developed in Section 3.3.4 provided such a set of reference patterns. Fuel consumption and emission factors for each *base* pattern were simulated using the other *base* operating patterns of the same fuel type and emissions regulation. This was done by setting pattern i in Equation 9 to each of the *base* patterns with the additional condition that $i \neq A \neq B \neq C$.

The best linear combination of patterns resulting from validation of the *base* patterns are presented in Table 4.1, where *A, B, C, X, Y and Z* are the parameters in Equation 9. More detailed results of the validation for the fuel consumption and emissions of *base* engine-operating patterns are presented in APPENDIX I: *Emissions Model Validation*.

The figures in Appendix I and Table 4.1 show that the model is less effective in predicting engine-operating patterns that excede the engine-operating envelopes resulting from the transformation of the EMPA driving cycles to engine operating patterns in this study as a result of aggressive acceleration and high speed driving.

Table 4.1: Cross validation of *base* engine-operating patterns.

Fuel and regulation	Base pattern being validated	Best matching linear combination of base patterns						Matching index
		Pattern A		Pattern B		Pattern C		
		Pattern #	X	Pattern #	Y	Pattern #	Z	
Petrol Euro-0	90					89	100%	94%
	89	76	15%			90	85%	97%
	76	87	16%	88	24%	89	60%	89%
	88	76	8%	86	1%	87	91%	98%
	87	85	18%	86	13%	88	69%	96%
	86	85	43%	87	56%	88	1%	94%
	85	84	58%	86	35%	87	7%	98%
	84	83	13%	85	68%	86	19%	98%
	83	81	5%	82	56%	84	39%	76%
	82	76	12%	81	40%	83	48%	71%
	81			80	76%	82	24%	79%
	80	81	100%					74%
Petrol Euro-2	510					509	100%	94%
	509	496	4%			510	96%	94%
	496			507	48%	509	52%	82%
	507	496	7%			508	93%	95%
	508	496	1%	504	7%	507	92%	97%
	506	504	33%	505	37%	508	30%	81%
	505	496	14%	504	51%	506	35%	89%
	504	503	54%	505	35%	506	11%	96%
	497	496	28%	500	21%	503	51%	56%
	503	502	26%	504	74%			84%
	502			500	49%	503	51%	63%
	500	502	100%					47%
Petrol Euro-3	15					14	100%	93%
	14	1	4%			15	96%	94%
	1	13	51%	14	49%			82%
	13	1	3%	8	2%	12	95%	99%
	12			13	100%			98%
	11	9	63%	12	37%			83%
	10	9	55%	11	26%	12	19%	90%
	9	8	44%	10	15%	11	41%	95%
	8	3	1%	7	32%	9	67%	83%
	7	5	44%	8	55%	10	1%	67%
	5	3	48%	7	46%	14	6%	60%
	3	5	100%					55%
Diesel Euro-2	390					389	100%	99%
	389			387	1%	390	99%	99%
	376	387	39%	389	9%	390	52%	79%
	388	386	17%	387	80%	390	3%	98%
	387	385	22%			388	78%	97%
	386	384	24%			388	76%	96%
	385	382	10%	384	16%	386	74%	96%
	384	383	23%	385	4%	386	73%	95%
	383	382	60%	384	38%	386	2%	89%
	382	380	19%	381	12%	383	69%	87%
	381	380	93%	382	4%	384	3%	89%
	380	381	100%					89%

Shaded rows indicate Patterns with the lowest prediction accuracy

This is evident from Table 4.1, where the engine-operating patterns at the boundry of the engine-operating patterns are resolved to 100% of the next engine-operating patterns at close to an idle operating conditions and 100% of the previous engine-operating pattern for maximum power patterns. From the matching indexes in Table 4.1 the boundary conditions for idling can still be closely matched to other *base* patterns but the matching index at the high power end of the scale are not matched as closely.

A prediction error was calculated from the emission factors for the *base* engine-operating patterns and the simulated factors from the model using Equation 10:

$$PE = \frac{\left| EF_{BP} - EF_{simulated} \right|}{EF_{BP}} \tag{10}$$

where PE is the absolute prediction error in percentage; EF_{BP} is the aggregate emissions factor for the *base* pattern calculated in Section 3.3.4; and $EF_{simulated}$ is the simulated emissions factor calculated from the optimised linear combination of up to three other *base* patterns for the same fuel type and emissions regulation.

The overall results of the validation are shown in Table 4.2 and Table 4.3 in terms of the average absolute prediction error and the bias (average signed relative error).

Table 4.2: Average absolute prediction error (PE) of emissions simulation model.

Absolute prediction error (%)		Parameter				
Fuel	**Regulation**	**FC**	**CO_2**	**CO**	**HC**	**NO_x**
Diesel	Euro-2	4	4	14	13	3
Diesel Average		4	4	14	13	3
Petrol	Euro-0	7	6	18	17	10
	Euro-2	6	5	28	19	37
	Euro-3	6	6	33	32	35
Petrol Average		6	6	27	23	27
Grand Average		5	5	23	20	21

Table 4.3: Average bias of the prediction error of model.

Bias of prediction error (%)		Parameter				
Fuel	Regulation	FC	CO_2	CO	HC	NO_x
Diesel	Euro-2	-1	-1	-4	-1	1
Diesel Average		-1	-1	-4	-1	1
Petrol	Euro-0	2	2	5	4	7
	Euro-2	-2	-2	-3	-1	13
	Euro-3	-2	-2	4	4	7
Petrol Average		-1	-1	2	2	9
Grand Average		-1	-1	1	1	7

These results are favourable when compared to those published by de Haan and Keller (2004b), who reported average absolute relative errors for combined Euro-2 petrol, Euro-3 petrol and Euro-2 diesel vehicles of 42% for CO, 8% CO_2 and fuel consumption, 41% for HC and 20% for NO_x. The bias was reported as 17% for CO, -3% for CO_2 and fuel consumption, 21% for HC and 4% for NO_x.

The modelling method developed in this study has thus improved the predictability of the CO_2, CO and HC emissions and the fuel consumption. The prediction of NO_x is marginally worse. An advantage of the model is that it has very little overall bias (tendency to over or under predict values), except for the NO_x emissions, which are over predicted by an average of 7%.

4.2.3. Sensitivity analysis

A sensitivity analysis was performed to study how simulated fuel consumption and emission factors change in response to changes in the input parameters (average engine speed, average engine load, fuel type and emissions regulation). A two-step process was used. The first step finds the partial functional forms of the qualitative input parameters (average engine speed and average engine load) using a simple regression analysis of the individual parameters against the output fuel consumption and emission factors. The second step combines the functional forms of the quantitative input parameters and the qualitative input parameters (fuel type and emissions regulation) into a single multi-parameter equation. The coefficients for the parameters, which indicate the sensitivity of the model to the input parameters are solved using the engine speeds, engine loads, fuel types, emissions regulations and the fuel consumption and emission factors from the 48 *base* engine-operating patterns.

The results of the simple regression analysis of the engine speed and engine load are represented as curve fits in APPENDIX J: *Sensitivity Analysis of Emissions Simulation Model: Curve fits*. From experimenting with different forms of curve fits, it was found that a second-order polynomial gave adequate fits for fuel consumption and emissions for both engine speed and engine load. The quality of the fit was best (typical R^2 value of 0.95) for CO_2 and fuel consumption vs. engine speed and engine load respectively. A second order polynomial fit also provided a suitable correlation for CO, HC and NO_x emissions. However, the relationship weakened with the most recent (Euro-3) emissions regulations considered. HC, followed by CO emissions, had the poorest correlation (R^2 between 0.004 and 0.66) to engine speed and engine load. The relationships between engine operation and emission factors (excluding CO_2 and fuel consumption) weaken because the improved efficiency of catalytic converters under the newer (Euro-3) emissions regulations are more influential on the overall vehicle emissions than emission controls which determine the exhaust gases entering the exhaust system (de Haan and Keller, 2004a).

As examples of the curve fits Figure 4.2 shows the relationships between CO_2 emissions and engine speed and Figure 4.3 shows the relationship between CO and engine load for the various types of vehicles.

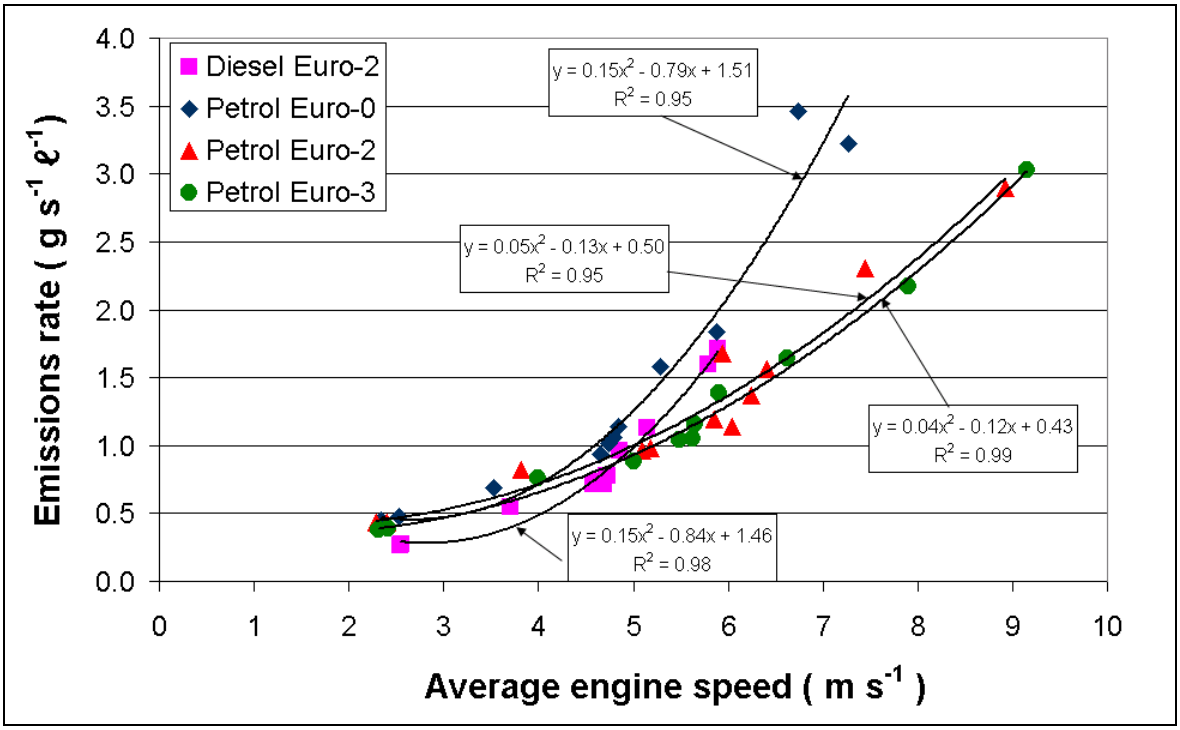

Figure 4.2: CO_2 **emissions per litre engine capacity vs. engine speed for different fuels and emissions regulations.**

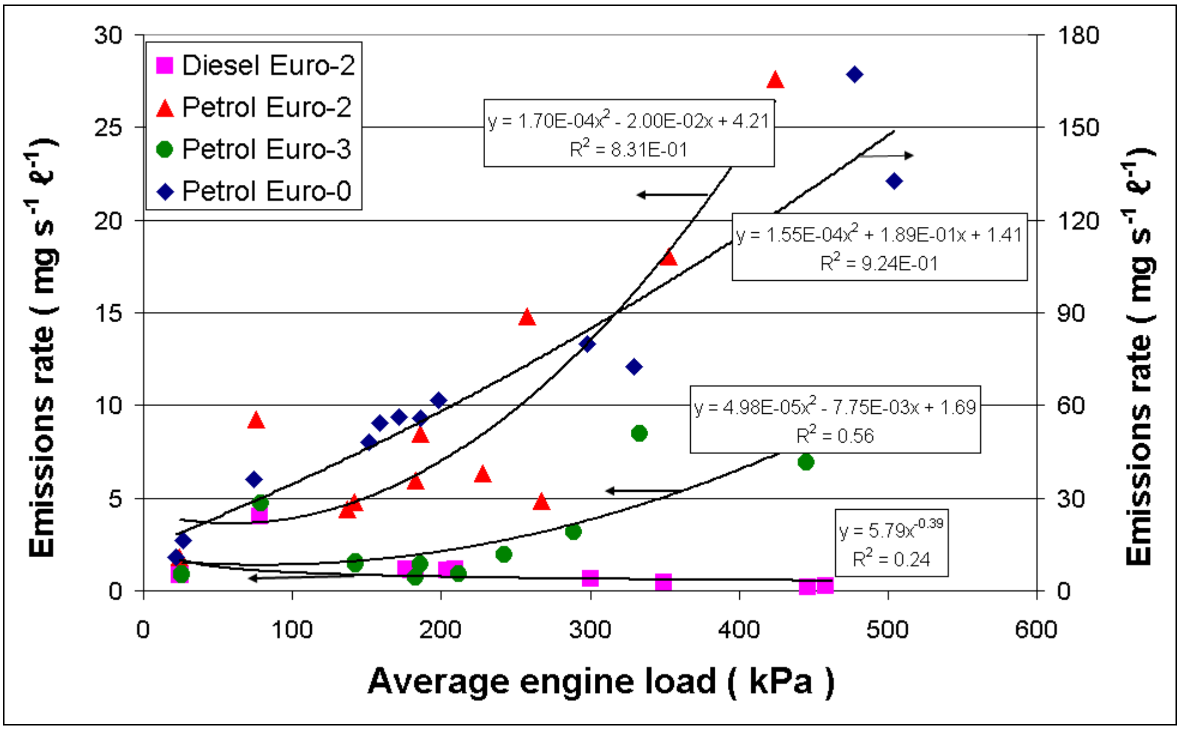

Figure 4.3: **CO emissions per litre engine capacity vs. engine load for different fuels and emissions regulations.**

Having determined the appropriate functional relationships between fuel consumption and emission factors for the input parameters, a multiple linear regression method, as defined by Stephens (2004), was used to determine which of the parameters has the most significant impact on the fuel consumption and emissions. The following relationship, Equation 11, was assumed based on the curve fits:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_1 x_3 + \beta_6 x_5 + \beta_7 x_6 + \beta_8 x_7 \qquad (11)$$

where y is the fuel consumption or emissions factor; x_1 is average engine speed; x_2 is average engine speed squared; x_3 is average engine load; x_4 is average engine load squared; x_5 is a dummy variable for fuel type (0 for diesel and 1 for petrol); x_6 and x_7 are dummy variables for the emissions regulation (x_6=1 and x_7=0 for Euro-0; x_6=0 and x_7=1 for Euro-2; and x_6=0 and x_7=0 for Euro-3 respectively); and β_1 *to* β_7 are coefficients to be fitted.

The analysis was performed using the regression analysis tool in Microsoft Excel. The summary outputs from the analysis, including the coefficients for Equation 11, their significance (*P*-values) and their 95% confidence intervals are given in APPENDIX J: *Sensitivity Analysis of Emissions Simulation Model*: Regression analysis. The coefficients are summarised in Table 4.4 below. Significant values (*P*-value <0.05) are in bold and power refers to the product of x_1 and x_3.

Table 4.4: Coefficients from regression analysis to determine the sensitivity of the simulation model.

	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8
Parameter	**Intercept**	**Diesel to Petrol**	**Euro-0 to Euro-2**	**Euro-2 to Euro-3**	**load**	**load^2 x10^{-5}**	**speed**	**speed^2**	**power**
Fuel Cons.	-0.73	**0.108**	0.0670	0.0245	**-0.0059**	**-0.446**	**0.517**	**-0.078**	**0.0017**
CO_2	-1.79	**0.323**	**0.0966**	0.0900	**-0.0146**	**-1.050**	**1.280**	**-0.190**	**0.0043**
CO	-0.20	0.014	**0.0456**	0.0073	**-0.0014**	**-0.116**	**0.127**	**-0.020**	**0.0004**
HC	-0.021	0.001	**0.0058**	0.0006	**-0.0002**	**-0.011**	**0.014**	**-0.002**	**<0.0001**
NO_x	-0.075	0.002	**0.0061**	0.0011	**-0.0006**	-0.032	**0.051**	**-0.008**	**0.0001**

Significant values (*P*-value <0.05) are in bold.

From Table 4.4 and Appendix J all the output parameters are significantly influenced by, in order of sensitivity, average engine speed, average engine speed squared, average engine load, average specific power and average engine load squared with respect to the other input parameters. The squared terms (i.e. engine speed squared and engine load squared) in and multi-linear regression are a result of the assumption that fuel consumption and emissions are second order functions of the engine speed and engine load. The inclusion of the term power indicates that the interaction between engine speed and engine load is significant in terms of the other input parameters.

The fuel type (difference between petrol and diesel) has the most significant impact on CO_2 and fuel consumption but no significant impact on the other output parameters. The shift from Euro-0 to Euro-2 (petrol vehicles only) emissions regulation has a significant impact on CO_2, CO, HC and NO_x emissions after engine speed; however, there is no significant change in emissions with respect to the other input parameters with a change from Euro-2 to Euro-3.

4.2.4. Conclusions

In this section, a fuel consumption and emissions simulation model was developed and presented. The software implementation of the model was discussed, the model was validated and a sensitivity analysis was performed.

The model was validated using a cross validation i.e. the *base* engine-operating patterns were used to simulate each other. The validation showed that the method used in the model provides good results for engine operation when compared to a similar statistical method using vehicle kinematics to produce the HBEFA. The HBEFA is used to develop national emissions inventories in Europe. The engine-operating patterns at each end of the engine operating envelope i.e. low speed - low load and high speed - high load, were predicted with less accurately.

The output of the simulation model was analysed with respect to the input parameters using a sensitivity analysis. The analysis showed that *CO_2 and fuel consumption* are most sensitive to fuel type, followed by engine speed, engine speed squared, a switch from Euro-0 to Euro-2 emissions regulation, engine load, engine power and engine load squared. The analysis also showed that *pollutant emissions* are most sensitive to engine speed followed by engine speed squared, a switch from Euro-0 to Euro-2 emissions regulation, engine load, engine power and engine load squared. A shift from Euro-2 to Euro-3 emissions regulation had no significant effect on the output parameters with respect to the other input parameters. Implementation of the Euro-2 regulation required use of catalytic converters to meet the emissions limits. This had a significant impact on emissions from previous emissions regulations. Improvements in emissions with the change from Euro-2 to Euro-3 regulation vehicles are not as great because there was only an incremental improvement in catalytic converter technologies and not a technology change. The changes to the specified emissions limits between Euro-0 and Euro-2 are also greater than the changes in the specified emissions limits from Euro-2 and Euro-3.

From the analysis, driving conditions, driving behaviour and driving styles have a significant impact on emission factors within the set of fuel types, emissions regulations and engine-operating patterns considered, because they determine engine speed and engine load. The sensitivity analysis suggests that the most effective way to reduce pollutant emissions is by managing driving behaviour and driving styles to encourage less aggressive driving with earlier gear changes. This would require modification to road infrastructure to promote smoother traffic flow, such as traffic light synchronisation and driver education and training. While it is generally understood that fuel consumption increases with increasing acceleration and speed, the relationship between emissions rates and fuel consumption is not proportional. Less aggressive driving styles would result in a significantly larger reduction in exhaust emissions compared to the reduction in fuel consumption.

Further development of the model should include validation of the model by using on-board measurement of emissions and engine operation from vehicles being used in the City of Johannesburg.

4.3. Results of the engine-operation and travel survey

In this section, results of the travel and engine operation survey are discussed. Vehicle activity by period of day, day of week, road type, vehicle fuel type and vehicle capacity class are presented for the sample of vehicles from the survey. The engine-operating patterns for the different combinations of these dimensions are also provided.

4.3.1. Overall results of survey

Thirty vehicles were sampled for approximately two weeks each between May 2006 and June 2007. This produced 716 hours and 29 587 km of data from 2 573 trips (excluding long distance trips – trips greater than 100 km, which made up a total of 1 909 km for the sample). Average trip duration during the survey was 17 min, average trip distance was 11.5 km and average speed was 41 km h^{-1}.

The sample size in terms of the number of vehicles monitored, distance travelled and hours of driving is at the same level as the number of vehicles and trips from the corresponding sections of the ARTEMIS project to determine real-world driving cycles in Europe. ARTEMIS used 77 vehicles in four European cities and produced approximately 2 200 hours and 80 000 km of driving data (Andre, 2004).

Area and road types travelled

The road network within the municipal boundary of the City of Johannesburg was illustrated in Figure 3.5. The subset of this network travelled by the sample vehicles for the survey is illustrated in Figure 4.4 (including third-tier residential streets). Routes travelled by the sampled vehicles are concentrated in the central, northern and western parts of the city.

From the density of subsections of the network, it is apparent that a good sample of the three tiers of road types, including all freeways, were sampled. No attempt was made to consider the socio-economic structure of the city – previously disadvantaged townships are concentrated in the south of the city and even 15 years after transition of government the apartheid infrastructure of the city persists. Consequent imbalances in traffic patterns between northern (relatively affluent) and southern suburbs traffic are likely to influence driving behaviours. However, consideration of this factor is beyond the scope of this thesis.

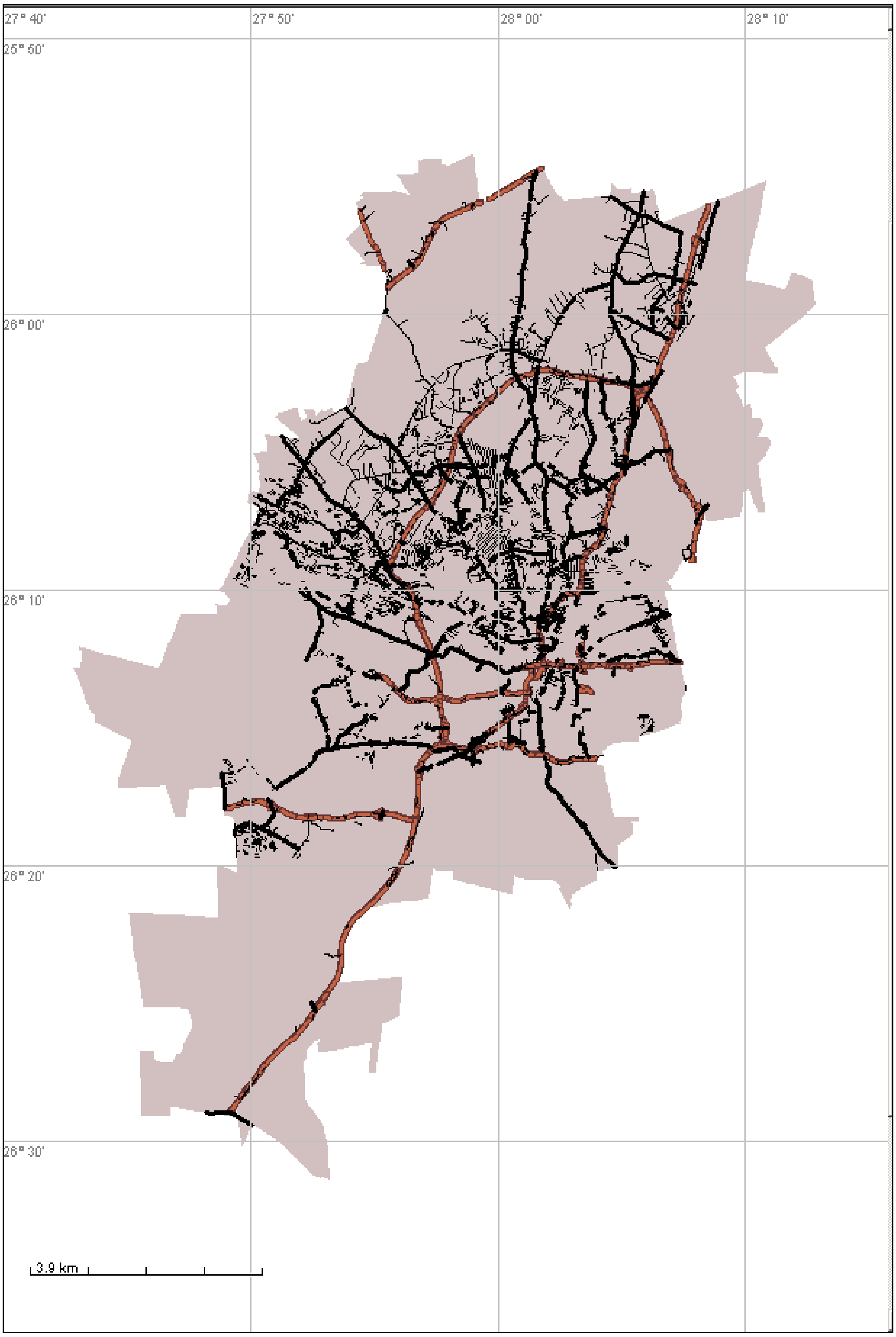

Figure 4.4: Roads within the Johannesburg municipal boundary travelled during the survey.

Vehicle activity by time of day and road types

The fraction of all trips and their *starting times* for the sample of vehicles are shown in the diurnal trip distribution in Figure 4.5. During the week most trips were made during morning and afternoon commute periods. On weekends, in contrast, most trips originated midmorning. The weekday morning rush-hour period is shorter than the evening period but more trips began between 07:00 and 08:00 than any other hour of the day, which is an antecedent condition for congestion. The period between 16:00 and 19:00 shows that the total number of trips travelled in the evening is considerably higher than for the same number of hours in the morning between 06:00 and 09:00. This is likely to be due to after-work chores such as shopping and extra mural activities.

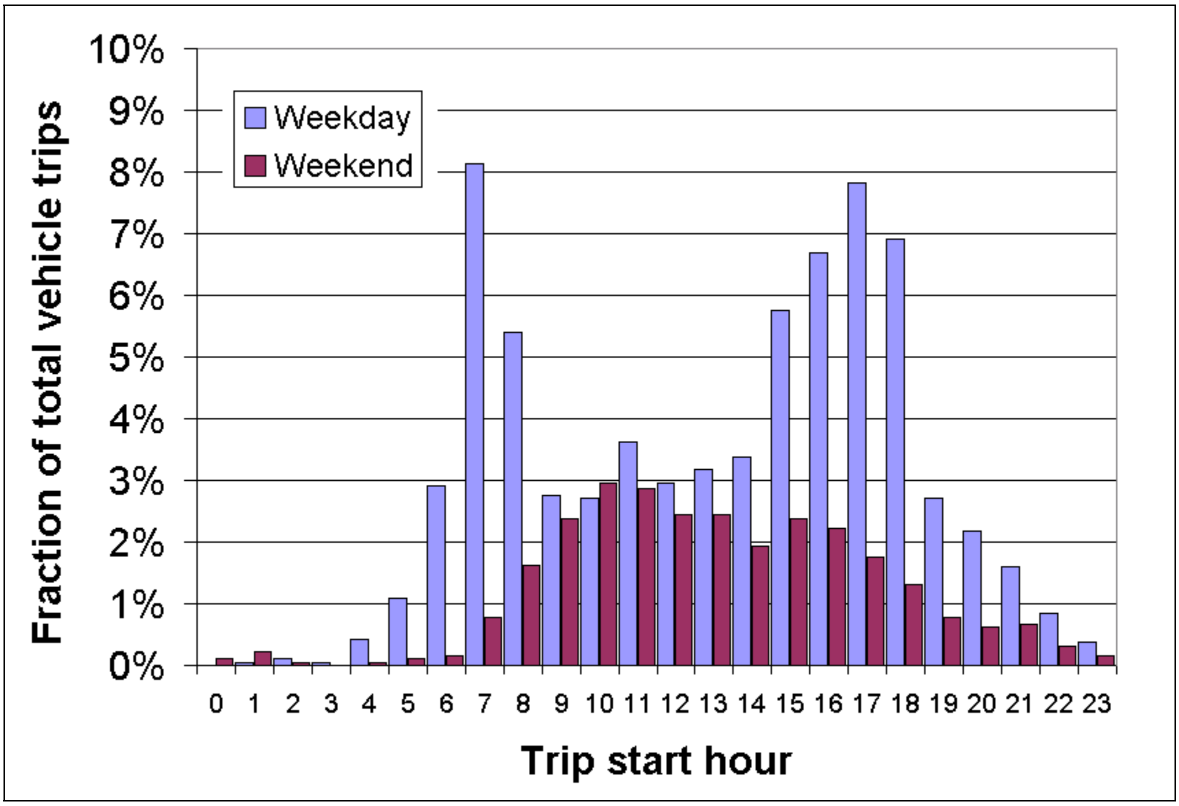

Figure 4.5: Diurnal trip distribution for the measured vehicle sample, sorted by weekday and weekend, normalised to total weekly trips.

While the numbers of trips starting within each hour of the day were shown in Figure 4.5, Figure 4.6 and Figure 4.7 give an indication of the fraction of total time and distance travelled on different road types by the vehicle sample. Relative distributions of all sample points (collected at one second intervals) by hour of day and road type are presented for weekdays and weekends respectively. The totals for weekdays and weekends are shown in Figure 4.8.

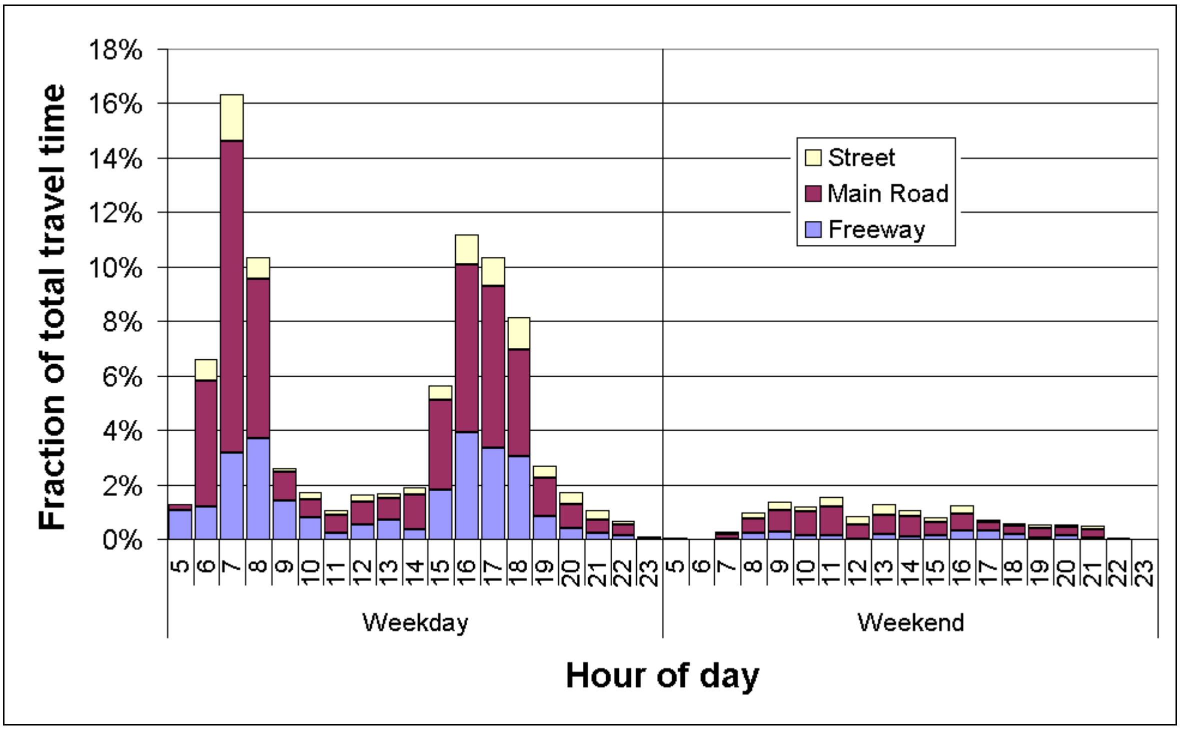

Figure 4.6: **Diurnal distribution of fraction of time spent on different road types.**

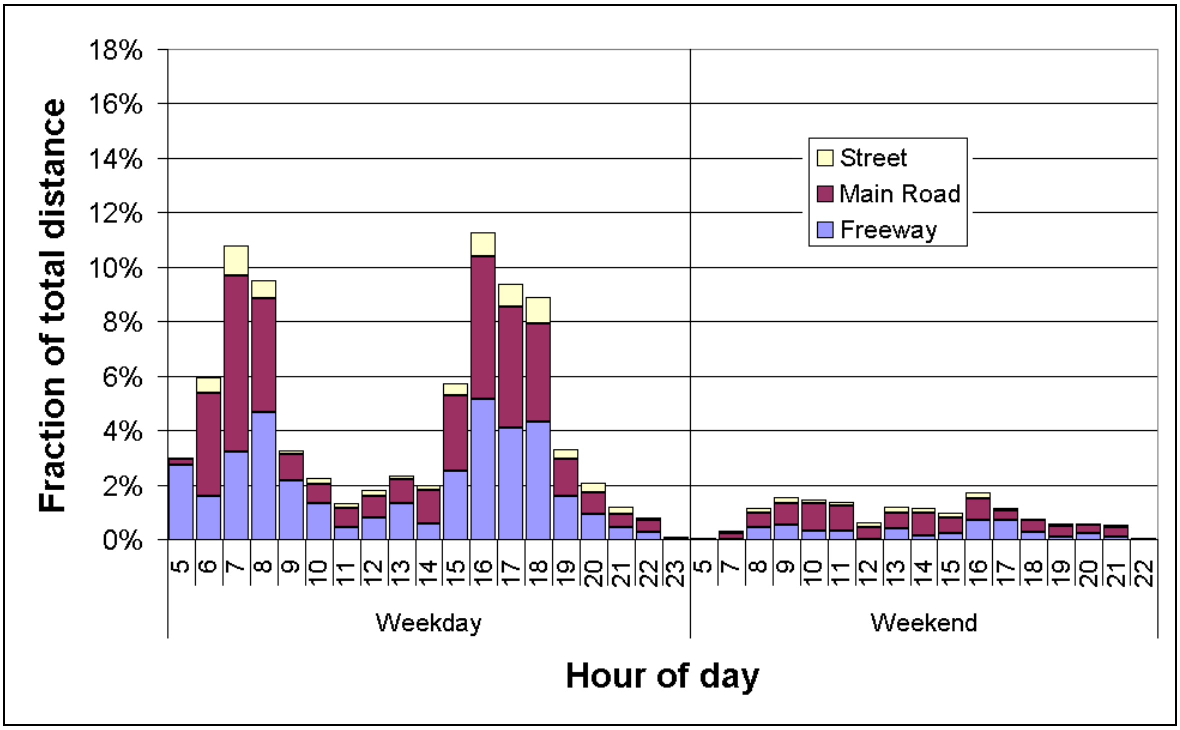

Figure 4.7: **Diurnal distribution of fraction of distance travelled by road types.**

The amount of *time* spent travelling (Figure 4.6) at specific times of the day coincides with the number of trips (Figure 4.5) starting at the same time of the day. The increased congestion as a result of the number of trips starting at the same time is evident in the distances travelled (Figure 4.7) for the fraction of time spent travelling (Figure 4.6). This is especially the case for the hours between 07:00 and 09:00, and is also apparent in the hour between 17:00 and 18:00 during weekdays.

Fifteen percent of the total vehicle distance travelled was on weekends, as shown in Figure 4.8. During the week freeways and main roads were used the same amount, at 45% each, while streets made up the remaining 10%. On weekends main roads were used 60% more than freeways suggesting that weekend trips are more likely to be local.

In terms of the overall time spent travelling, main roads were used most at 58% of the total time, freeways were used 29% of the time and streets were used 13% of the time. A larger fraction of the time was spent on main roads, as expected, due to their lower average speeds compared to freeways.

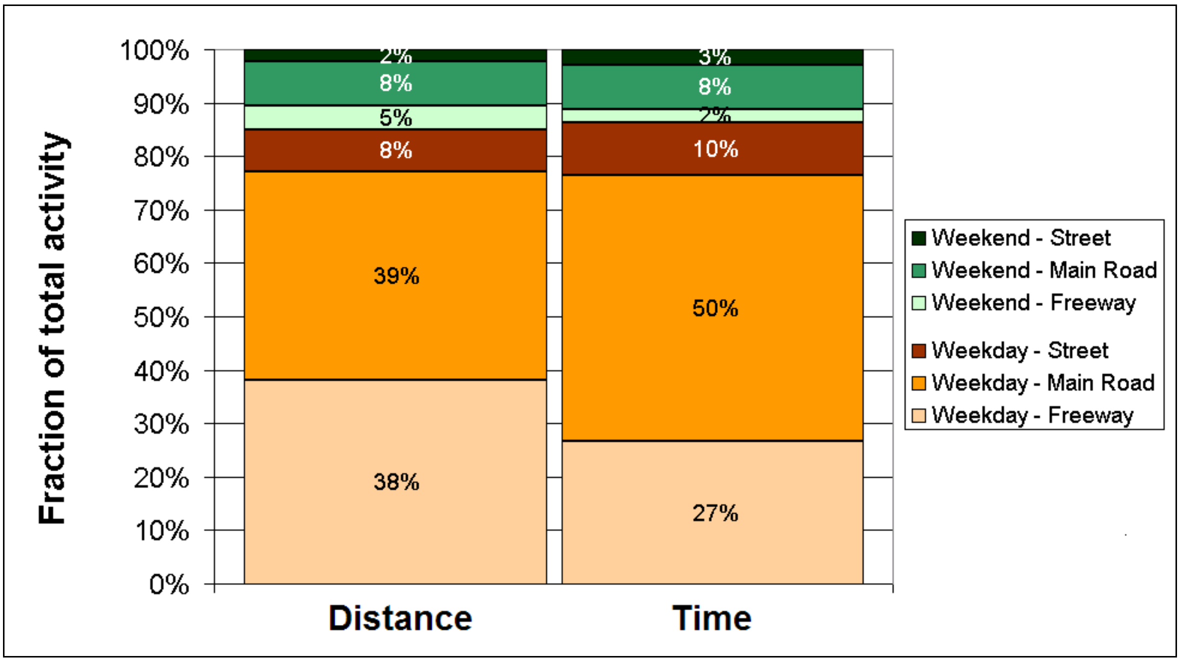

Figure 4.8: Diurnal distribution of proportion of distance travelled by road types.

Driving conditions by time of day and road type

Leading on from Section 1.7, where congestion is defined as the ratio the travel time in high activity conditions to ideal (free-flow) travel time, overall congestion is redefined here as the ratio of the average free-flow speed to the measured average trip speed. This ratio is referred to here as congestion index. Average free-flow speed is the average trip speed during free-flow conditions. For the purposes of this study, it is taken as the average speed for all trips between 20:00 and 05:00 for both weekdays and weekends from the surveyed vehicle sample, calculated to be 44 km h^{-1}.

The congestion index for weekdays was calculated by dividing the average free-flow speed by the average trip speed for each hour of the day from the survey (Figure 4.9). The most congested period is 06:00 to 08:00 with travel time being 37-40% longer than the free-flow time. The 16:00 to 18:00 period shows an increase of 31-32% in travel time and the 10:00 to 12:00 period shows an increase in travel time between 29% and 30%.

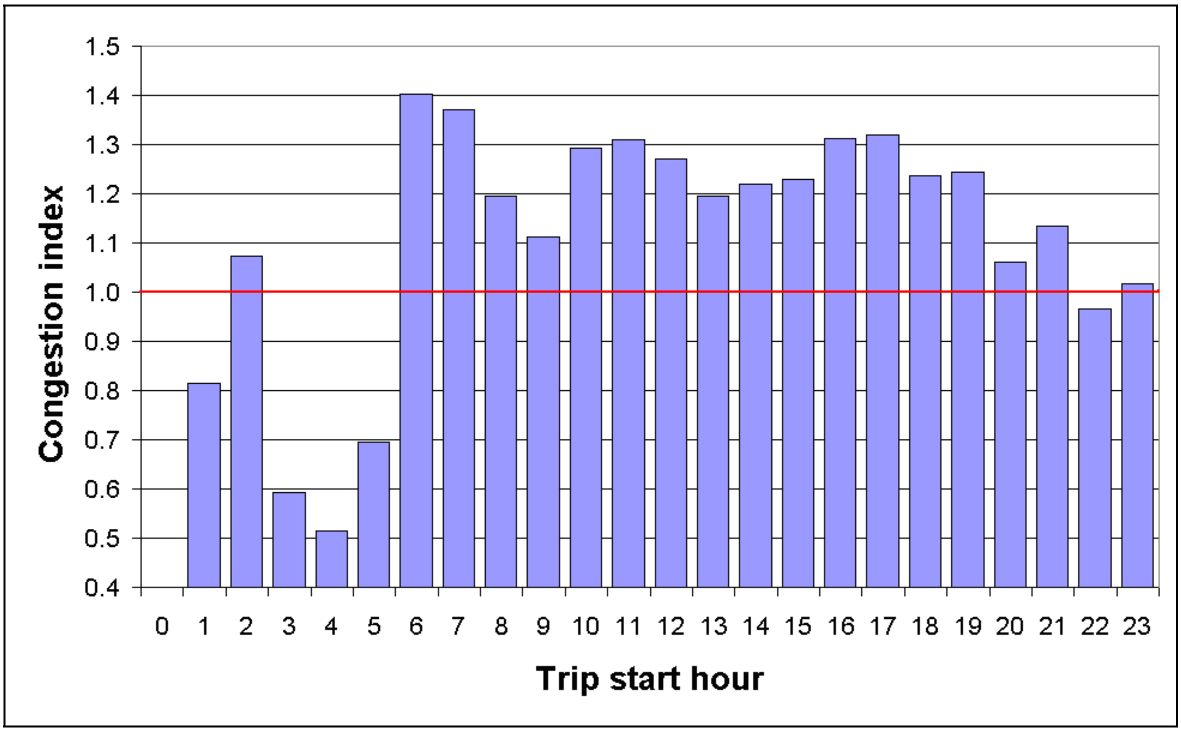

Figure 4.9: Overall congestion index by hour of day for weekdays (> 1.0 indicates average speeds are slower than the free flow speed).

The morning and evening commute periods were expected to be more congested than other periods, however, the 10:00 to 11:00 period was also found to be congested in terms of the overall index. The level of congestion from 10:00 to 12:00 can be explained from Figure 4.5 in terms of the increased number of trips starting in this period compared to the 08:00 to 10:00 period and from Figure 4.6 where the proportion of main road driving is higher compared to the other congested periods. The larger proportion of main road driving increases the congestion index for this period because main roads have a lower average speed than freeways. The index for the hours between 01:00 and 06:00 is distorted by the low number of trips during this period, as evident in Figure 4.5, and the high proportion of freeway driving as can be seen between 05:00 and 06:00 in Figure 4.6. During quiet periods, there is a tendency for speeding and not stopping at stop streets, which lowers the congestion index below one. This is evident for early hours of the morning.

The overall congestion index used above does not allow for changing proportions of vehicle activity on the various road types at different times of the day. Congestion on freeways, main roads and streets vary due to their structure and function, and require different management techniques. The different road types therefore require separate indices. Congestion on individual road types was considered by producing a congestion index for each road type. The free-flow speeds were calculated using the same hours as with the overall congestion index i.e. between 20:00 and 05:00 for both weekdays and weekends. Average free-flow speeds were calculated to be 95 km h^{-1} for freeways, 43 km h^{-1} for main roads and 33 km h^{-1} for streets.

Average speeds for the three different road types and hours of the day are shown in Figure 4.10 for weekdays and the corresponding congestion indices are shown in Figure 4.11. The average speeds for the 07:00 – 08:00 interval are 43, 24 and 28 km h^{-1} for freeways, main roads and streets respectively. Compared to these speeds the average speeds for 17:00 – 18:00 are 52, 31 and 33 km h^{-1} for freeways, main roads and streets respectively. Freeway speeds vary between 50 – 300% of main road speeds at similar times of the day. The speed in main roads and streets are similar with main roads being between -5% to 20% higher than for streets.

From the congestion indices in Figure 4.11 freeways are considerably more congested than the other two road types. Extreme congestion occurs in the 07:00 interval with freeway travel time being 120% longer than the ideal travel time and main road travel time being 78% longer than the ideal travel time. The freeway and main road travel times are not as severe during the evening commute as with morning commute but the travel times on freeways are still between 55% and 80% longer than the ideal travel times. Congestion on freeways is likely to be a result of two or more career homes where some members of the household work in one city and other members work in another city, such as Pretoria and Johannesburg.

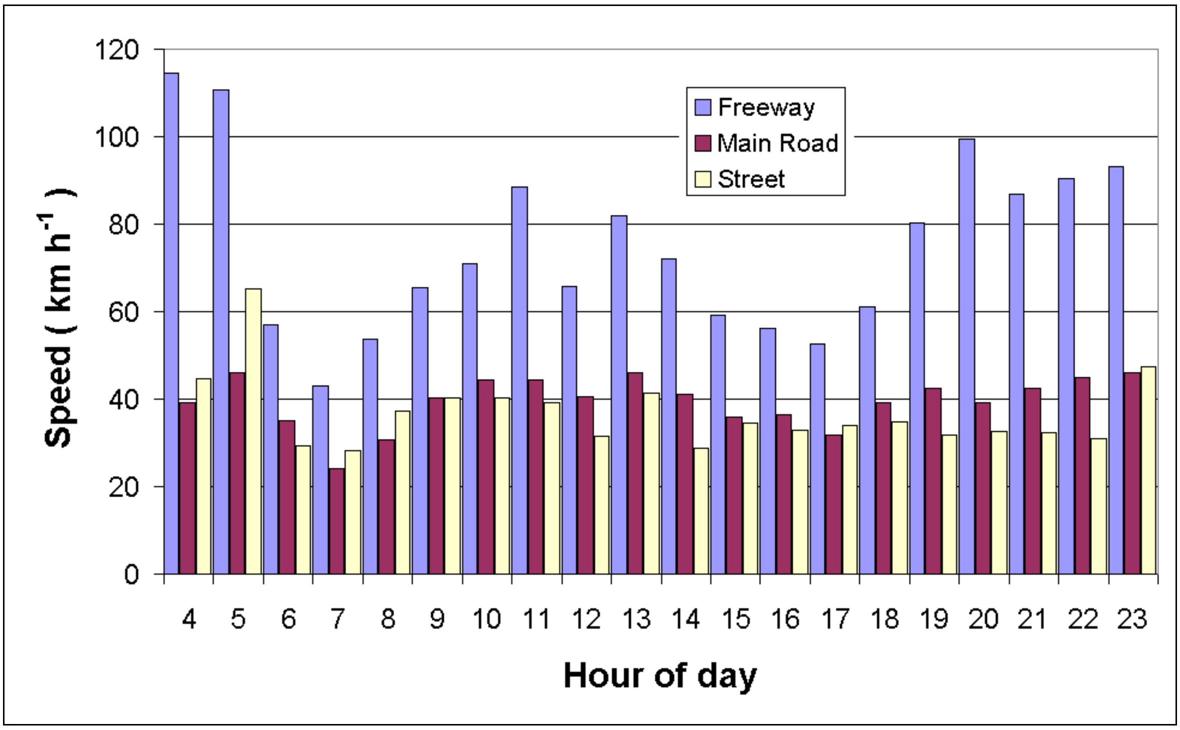

Figure 4.10: Average speeds by road type and hour of the day for weekdays.

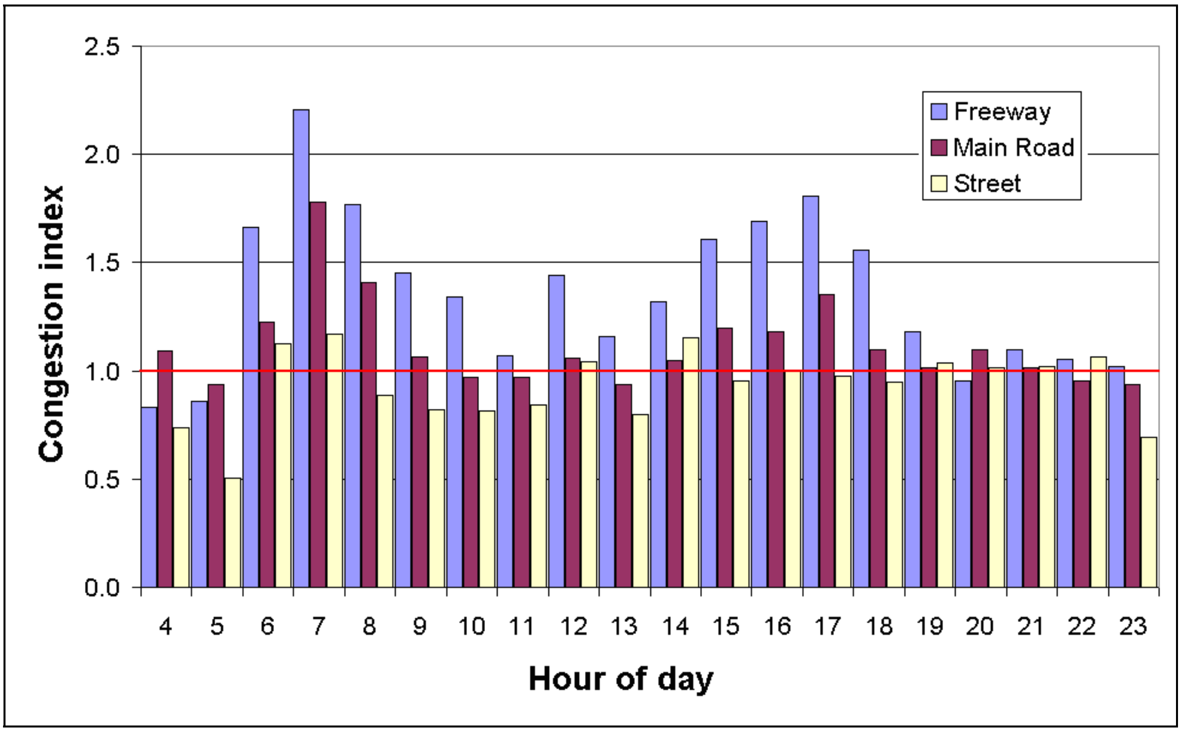

Figure 4.11: Congestion index by road type and hour of the day for weekdays (> 1.0 indicates average speeds are slower than the free flow speeds).

Congestion results in higher levels of fuel consumption and emissions. This is not only due to the lower speeds and less efficient use of the internal combustion engine but also due to the higher number of acceleration cycles. During congested traffic the number of acceleration, deceleration cycles increases. Stops per kilometre for different times and road types are shown in Figure 4.12. Streets have been excluded as there is a natural number of stops per kilometre due to stop streets at intersections. There is a clear increase in the number of stops in the 07:00 and 17:00 intervals. The number of stops per kilometre corresponds well with the congestion indices for the different hours of the day in Figure 4.11.

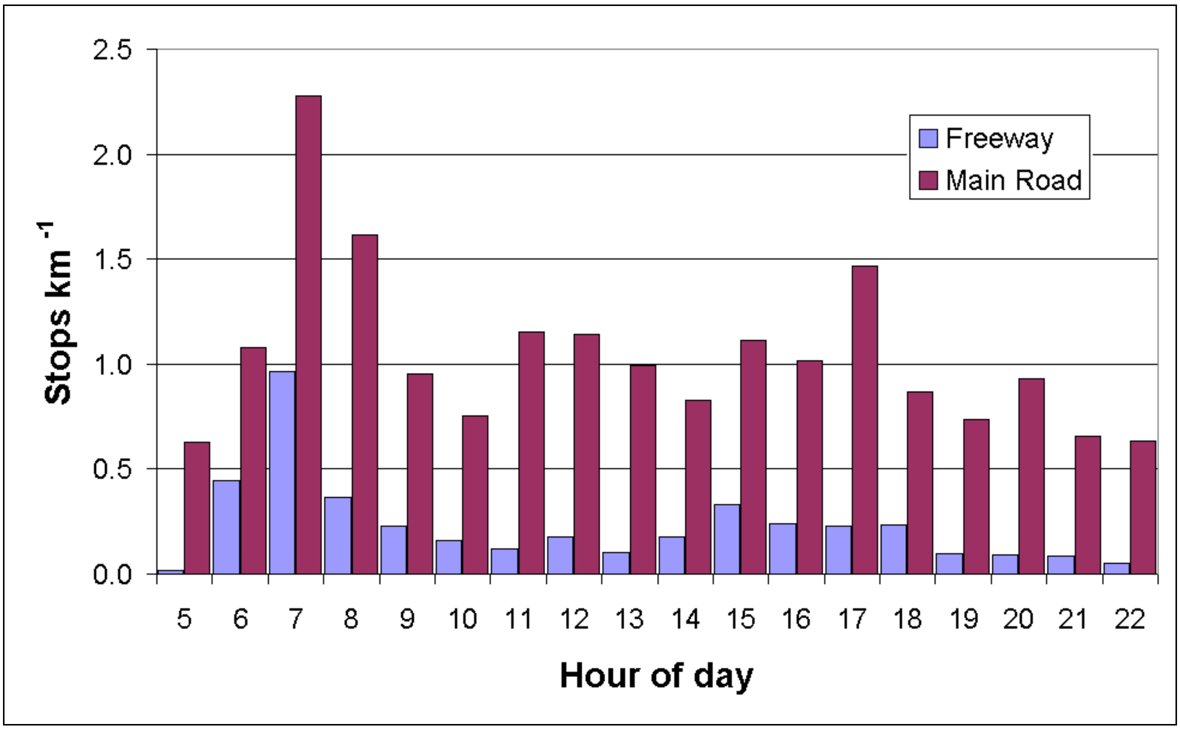

Figure 4.12: Stops per kilometre by hour of day and road type.

In order to identify the location of congested areas the average speeds from all the trips between 06:30 and 09:00 were aggregated and overlaid on a grid over the city, as shown in Figure 4.13. The most congested areas (red) are at the central business district, Sandton and roads leading onto the freeways.

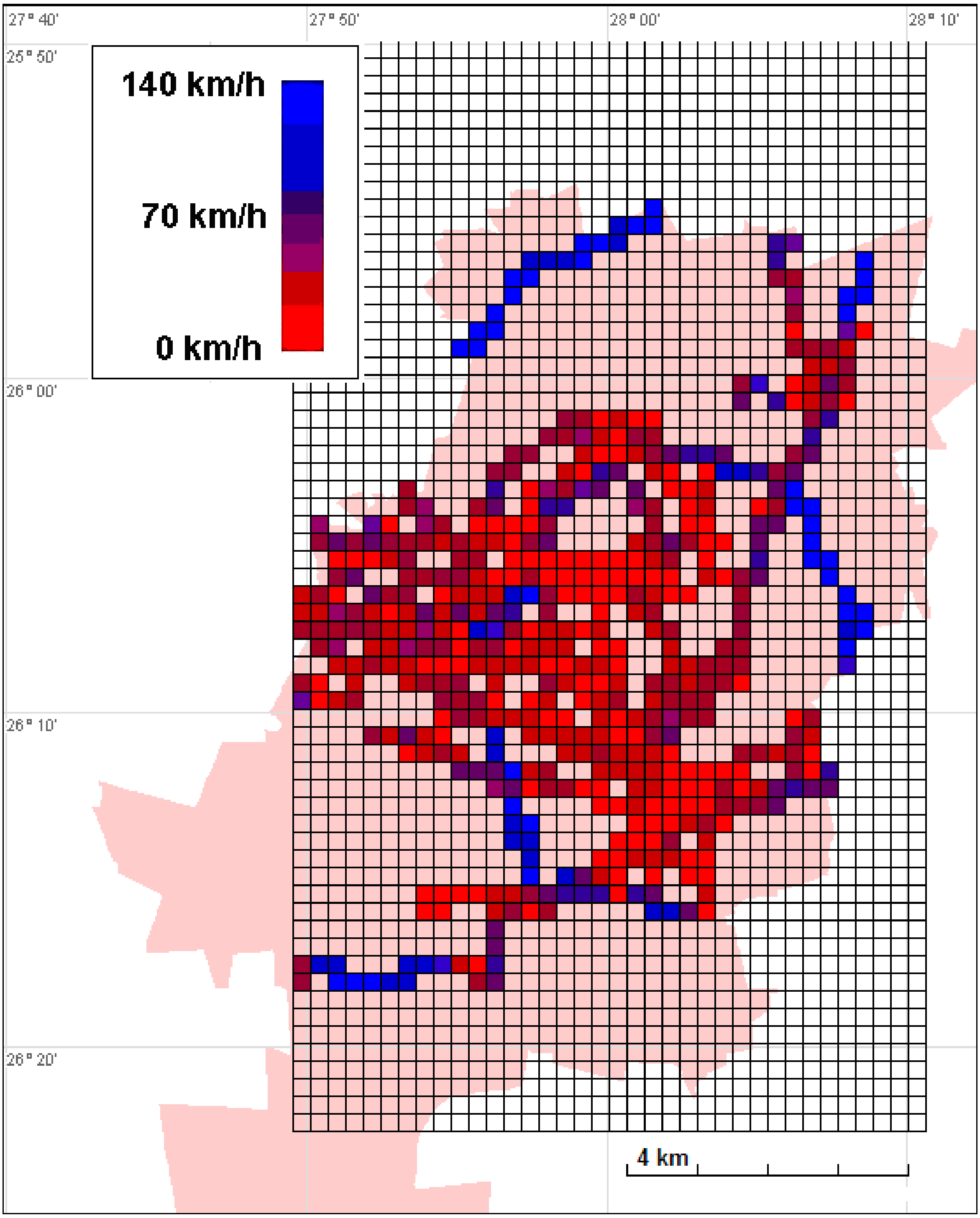

Figure 4.13: Average speeds for a 1 km x 1 km grid over Johannesburg between 06:30 and 09:00 in the morning.

4.3.2. Travel behaviour by vehicle fuel type and capacity class

The preceding data represents activity of the full set of surveyed vehicles. In this subsection, the sample is disaggregated into vehicles of different fuel types and capacity classes. Average daily distances travelled by each vehicle type are shown in Figure 4.14.

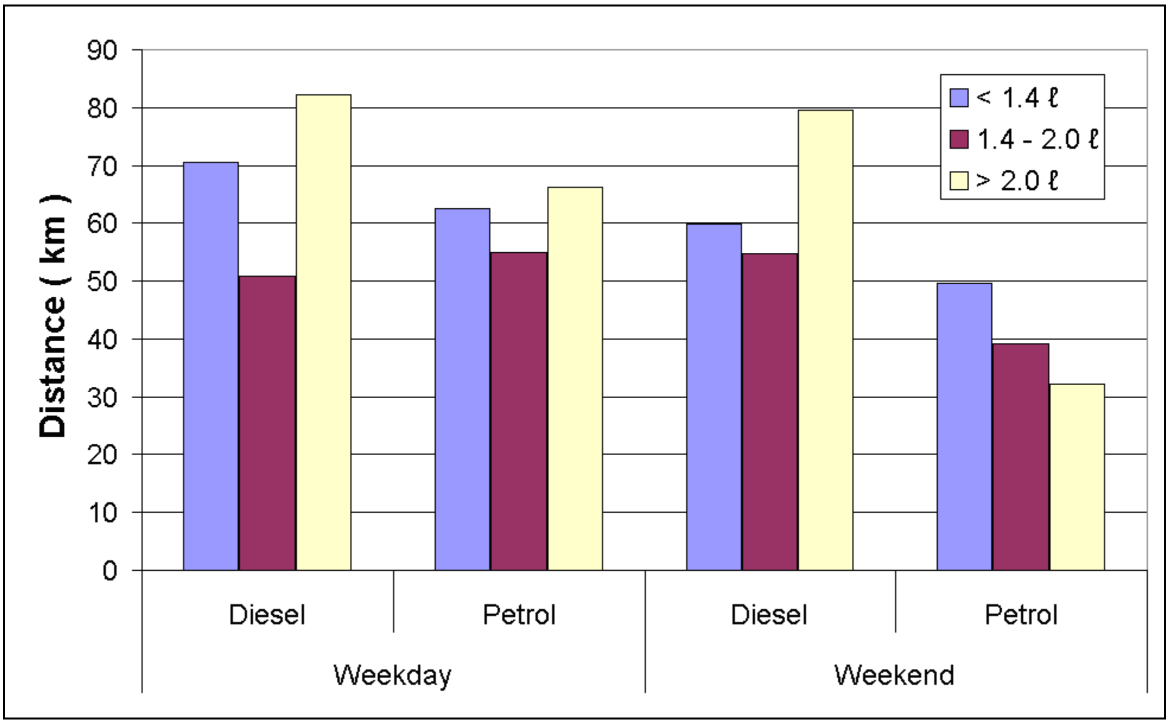

Figure 4.14: Average distance travelled per day by type of day, fuel type and engine capacity class.

The sample of diesel vehicles was too small (one < 1.4 ℓ capacity class vehicle, two 1.4 – 2.0 ℓ capacity class vehicles and two > 2.0 ℓ capacity class vehicles) to define any confidence. The petrol vehicle sample is made up of 25 vehicles (five in the < 1.4 ℓ capacity class, 13 in the 1.4 – 2.0 ℓ capacity class and seven in the > 2.0 ℓ capacity class.

The annual distance travelled for each vehicle fuel type and capacity class, calculated using the data in Figure 4.14 and based on 50 weeks per year, is presented in Table 4.5. Based on the sample, diesel vehicles are used more than petrol vehicles per year. For diesel vehicles, the > 2.0 ℓ capacity class was used the most and for petrol vehicles the < 1.4 ℓ capacity class was used the most. The 1.4 – 2.0 ℓ capacity class was used the least for both fuel types.

Table 4.5: Average annual distance travelled per fuel type and capacity class.

Fuel	Capacity class (ℓ)	Distance (km)
Diesel	< 1.4	23 600
	1.4 – 2.0	18 200
	> 2.0	28 500
Petrol	< 1.4	20 600
	1.4 – 2.0	17 700
	> 2.0	19 700

Diesel vehicles are inherently more fuel efficient than similar size and class petrol vehicles, and hence the cost-effective choice for drivers who travel higher total distances per year. Diesel vehicles, however, have a higher purchase price and the financial trade-off between running costs and capital costs depend on the travel demand per year. The trade-off of owning a diesel vehicle is also dependant on fuel prices. In Europe where the fuel prices are 60 – 80% higher than in South Africa the market share of diesel vehicles is more than 50% (WEC, 2007), whereas the market share of diesel vehicles in Johannesburg is only 13% (see Section 3.5.3). Increasing fuel prices have played a large part in the increased share of diesel passenger vehicles sales in South Africa since 1997. Fourteen petrol engine vehicle models and their diesel equivalents are compared in terms of their purchase price and fuel economy in APPENDIX K: *Comparison of Petrol and Diesel Vehicles*. The comparison shows that the break-even cost advantage of owning a diesel vehicle instead of a petrol vehicle occurs at travel distance of approximately 19 000 kilometres per year (assuming both petrol and diesel prices at R7 per litre).

The large capacity diesel vehicles are primarily 4x4 or SUV type vehicles whereas the large capacity petrol vehicles tend to be luxury sedans. With these types of vehicles, fuel costs are a smaller proportion of overall ownership costs in comparison to smaller capacity vehicles at the lower end of the vehicle market. Distances travelled per year are influenced by lifestyles and the additional distances travelled by larger capacity diesel vehicles (particularly on weekends) may suggest an outdoor lifestyle and the larger capacity petrol vehicles are likely to be used by executives for business trips.

The average annual vehicle kilometres travelled for *local trips* by private passenger vehicles in Johannesburg is estimated to be 19 200 km, weighted according to the proportions of different vehicles in Table 3.8 and average distances from Figure 4.14. From the survey, long distance trips (> 100 km) made up 6.5% of the distance of the local trips. The average vehicle kilometres travelled, including *long distance trips*, for Johannesburg private passenger vehicle population was estimated to be 20 448 km per annum based on the sample and fleet structure ignoring vehicle age distribution. It should be noted that newer vehicles are used more than older vehicles. Vehicle age was not considered while determining vehicle usage in this study but will need to be considered in further research.

The survey shows that the average annual distance travelled in South Africa (specifically in Johannesburg) is 2 700 km less per year than the 23 000 km in the United States (IEA, 2000:103) but 6 000 km more than the average distances travelled in Europe (European Peers) shown in Figure 4.15 (Jacobs, 2005).

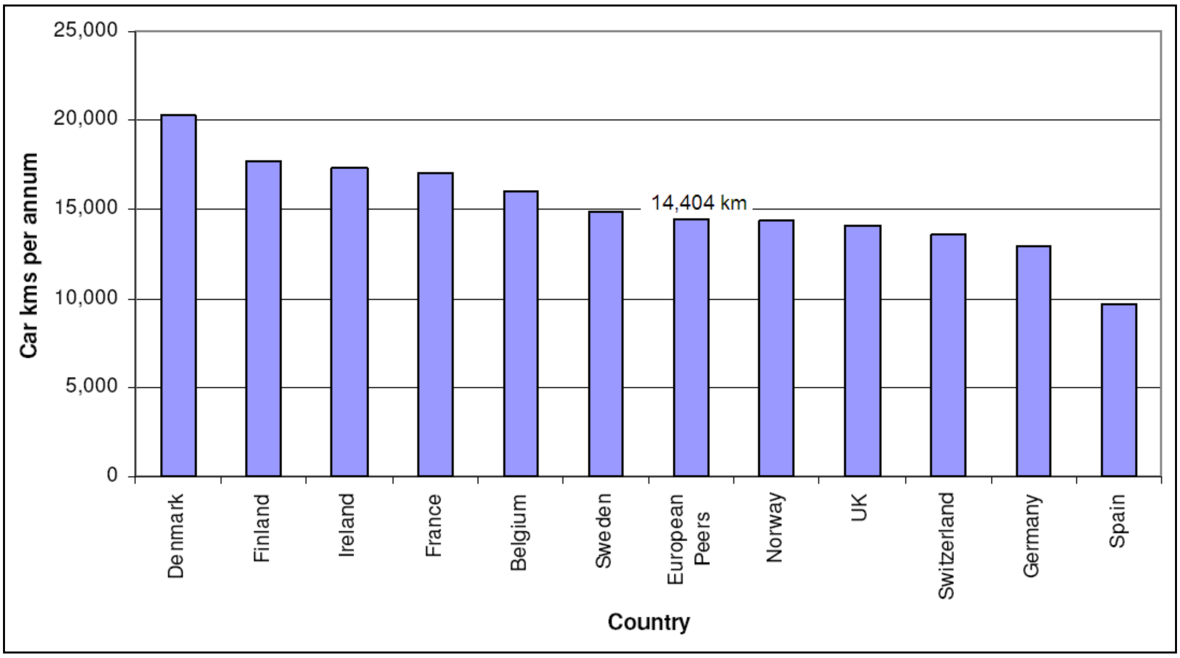

Figure 4.15: Average annual kilometres travelled per car in European countries (Jacobs, 2005)**.**

The vehicle kilometres travelled in Johannesburg in comparison to Europe and the United States can be explained by land use patterns and urban structure, availability and quality of public transport and vehicle usage costs (including fuel costs).

Land use in South Africa is dispersed and the structure of the cities is based on central business districts with widely dispersed residential suburbs (similar to US cities). Fuel consumption and the economic viability of public transport systems have often been attributed to urban density (Green and Mare, 1992). However, factors such as the distribution and distances between different land uses, location of services with respect to each other, vehicle ownership and the availability of public transport have been shown to play a larger role in transport energy demand than urban density (Mindali *et al*., 2004; Mirilees, 1993b). Vehicle ownership and use are large drivers of urban energy demand within cities. As vehicle ownership increases, the energy demand per capita increases.

The dependence on motorised transport in South Africa is aggravated by the legacy of apartheid, which separated land use functions and the allocation of different residential development areas to specific racial groups, with black townships further away from city centres and with less access than the white suburbs. Mining activity within Johannesburg has also contributed to the distribution of industrial, commercial and residential areas due to the natural distribution of mineral resources.

Travel demand is driven by household needs such as access to employment, education, shops and services depending on family structure and household income (Dix *et al*., 1983). As long as the household budget can afford one or more cars, the convenience it provides is difficult to beat with other modes of transport. Increased disposable incomes due to economic development are facilitating acquisition of vehicles by many who were previously able to afford one.

4.3.3. Share of driving conditions by vehicle type

Results of the survey were grouped to represent the set of driving condition dimensions (day of week, period of day and road type) and the vehicle dimensions (fuel type and capacity class) as defined in Table 3.5. These data are presented in APPENDIX L: *Driving conditions from travel survey by vehicle type*. Proportions of time spent by each fuel type and capacity class in the combinations of driving conditions are shown in Table L.1. The corresponding average vehicle speeds for the combinations of driving conditions and vehicle types in Table L.1 are presented in Table L.2. Selected intersections of these tables are presented here. Although the sample of diesel vehicles was too small for statistical significance, they have been included for completeness. The following discussion will focus on petrol vehicles.

The fraction of travel time spent by vehicles of different fuel types and capacities classes on various road types are shown in Figure 4.16, revealing that higher capacity (> 2.0 ℓ capacity class) vehicles use freeways more than the other vehicle capacity classes. This is as expected because larger capacity vehicles are designed for more comfort and are more suitable for longer trips, which are typically on freeways. Together with greater annual kilometres travelled by higher capacity class vehicles, this may indicate that the owners of such vehicles live further from work in outlying wealthier suburbs than owners of lower capacity vehicle types.

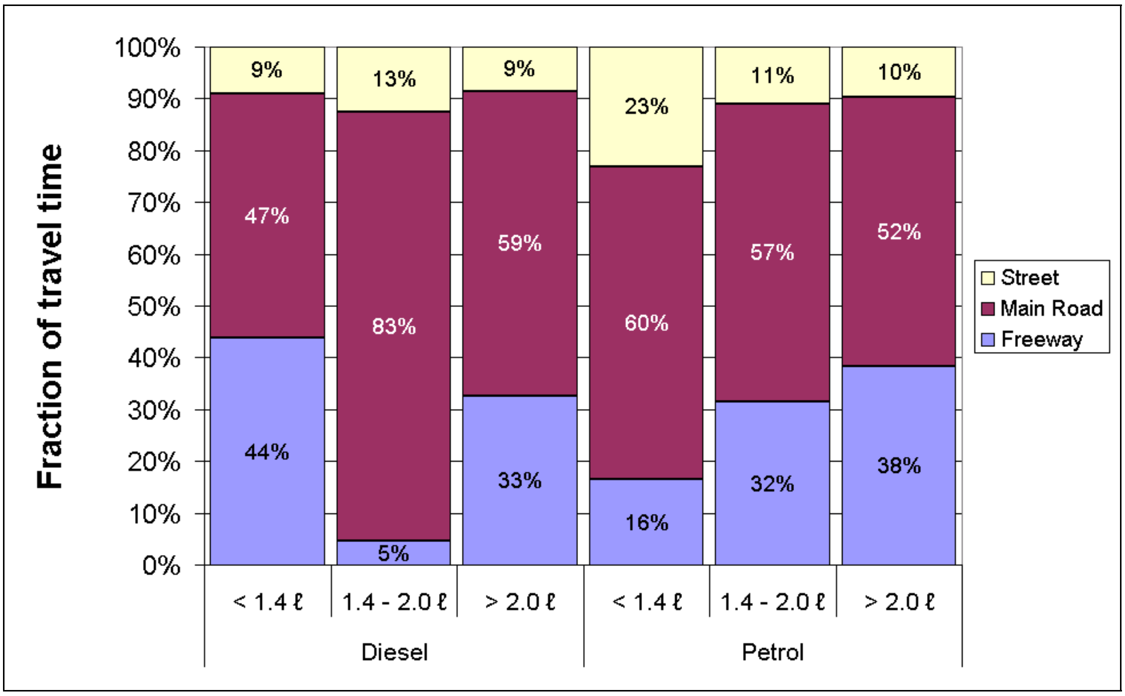

Figure 4.16: Fraction of travel time by vehicle type and road type.

The travel time shared between weekdays and weekends for petrol and diesel vehicles for different capacity classed are shown in Figure 4.17. The fraction of time spent travelling during weekdays is greater for the larger capacity vehicles.

Vehicle speed for the various driving conditions and vehicle capacity classes are shown for weekdays in Figure 4.18. The slowest speeds are for the 06:30 – 09:00 and the 16:00 – 18:30 periods. Larger capacity classes are generally driven faster than smaller capacity classes. Average speeds were calculated to be 38 km h^{-1}, 42 km h^{-1} and 49 km h^{-1} for the < 1.4 ℓ, 1.4 – 2.0 ℓ and >2.0 ℓ capacity classes respectively. From this analysis one deduces that standardised driving cycles are inadequate for determining real-world emissions factors for different capacity classes because the different capacity classes do not follow the same driving patterns in similar driving conditions.

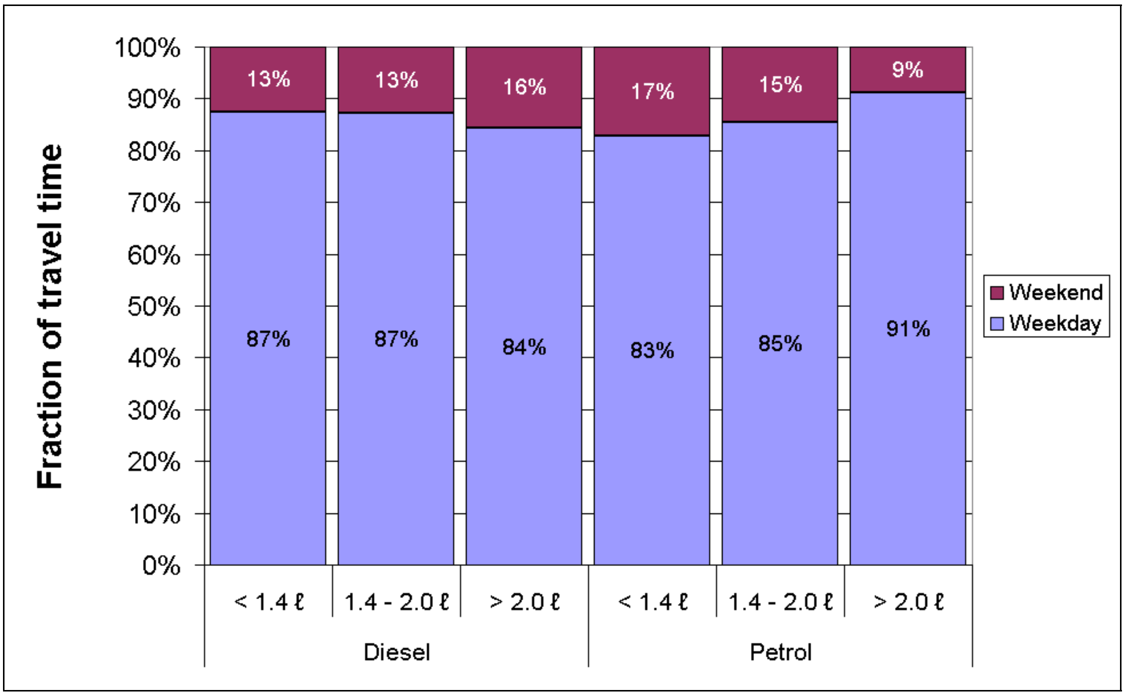

Figure 4.17: **Fraction of travel time for weekdays and weekends by vehicle type and road type.**

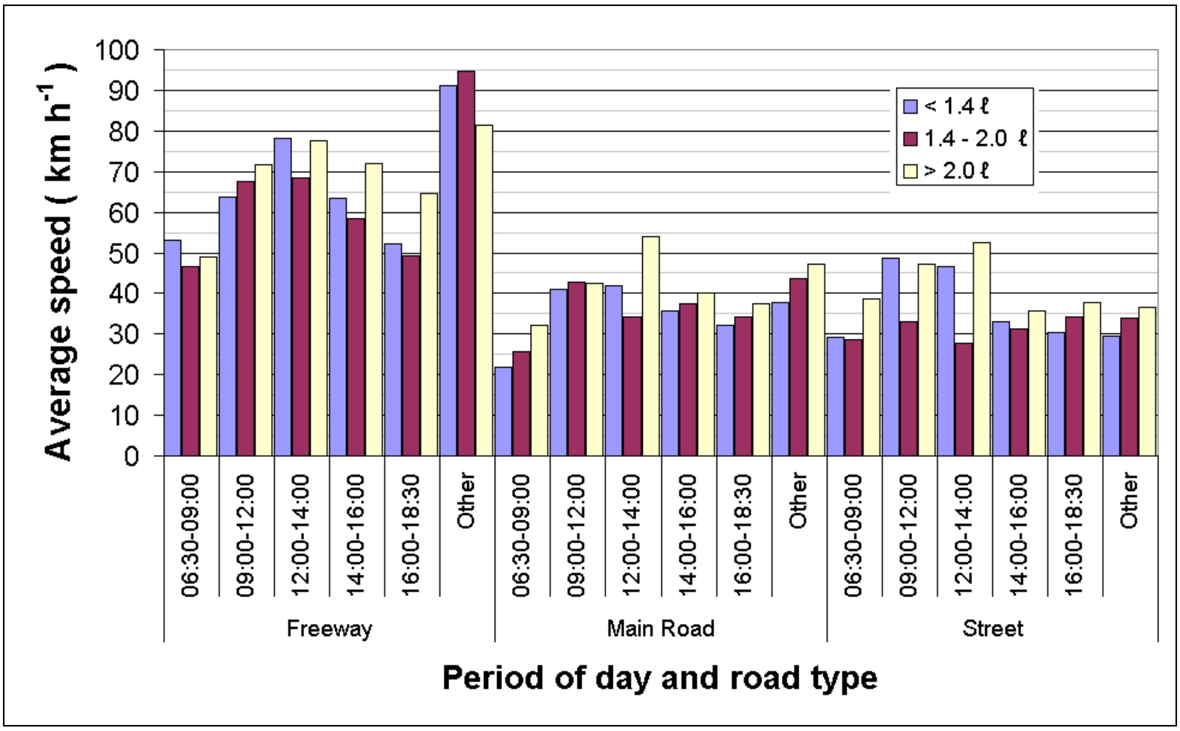

Figure 4.18: **Average speed by vehicle capacity class, road type and period of the day.**

4.3.4. Measured engine-operating patterns

A total of 1 080 engine-operating patterns are possible from the combination of the 30 sample vehicles and the operating environment dimensions considered in Table 3.5. Only

699 of the possible combinations occurred during the survey, limited due to the relatively small size of the vehicle sample. The missing patterns are primarily in the sectors *small capacity diesel vehicles* and in *weekend travel*, which make up a small proportion of the total vehicle activity.

The engine-operating patterns for vehicles of the same fuel type and capacity class were aggregated to produce 186 engine-operating patterns from a possible 216. A selected set of these engine-operating patterns are presented for detailed discussion to illustrate the underlying concepts. These selected patterns are the aggregated engine-operating patterns for petrol vehicles for three capacity classes, for the morning commute and for midmorning driving period, as shown in Figure 4.19 and Figure 4.20 respectively.

From Figure 4.19 the higher engine capacity vehicles operate at lower average speeds but tend to have slightly higher average loads (mean effective pressure). This suggests that drivers of larger engine capacity vehicles choose to increasing the throttle position rather than to change down a gear to achieve the desired acceleration or hill climbing ability whereas the drivers of smaller engine capacity vehicles only have the option to change down a gear because of their engine torque limitations. The larger range of part load operation of the larger capacity engines also allows for earlier gear changes with respect to the engine speed. The spare potential of the larger capacity engines will, however, be determined by the mass and size of the vehicle. During the morning commute, the engine-operating patterns are similar for the different road types. All three road types show a large percentage of time spent in low engine speed and low engine load patterns during the morning commute, indicating very slow speeds or idling conditions.

There is a peculiarity within the < 1.4 ℓ petrol capacity class during the morning commute period in that the engine-operating patterns are bimodal (there are two different patterns on top of each other). From further investigation the cause was found to be that one of the vehicles sampled had a continuously variable transmission. The engine-operating patterns of this vehicle indicate that the continuously variable transmission keeps the engine speed down by increasing the engine load. The sensitivity analysis of the simulation model explains the benefit of lower engine speed on fuel consumption and emissions resulting from this type of transmission. The use of continuously variable transmission and other advanced transmissions systems can play a significant role in improving the overall efficiency and reducing emissions from vehicles. While the data from the CVT vehicle provides for some interesting observations and a means to compare the influence this type of transmission to that of a conventional transmissions on engine operation, the inclusion of this data may skew the results for the estimated emissions and fuel consumption for the < 1.4 ℓ petrol capacity class vehicles within this study due to the low number of CVT vehicles in the actual vehicle population. Transmission type was not considered as one of the dimensions in the analysis but certainly requires further consideration. A larger sample of vehicles would need to be studied to better reflect the overall structure of the vehicle fleet with respect to the various types of transmissions in use.

In the midmorning patterns (Figure 4.20), the engine-operating patterns vary more for the different road types and there is less time spent at very slow engine speeds. Both the main road and freeway road types show an increase in maximum engine speed during this period.

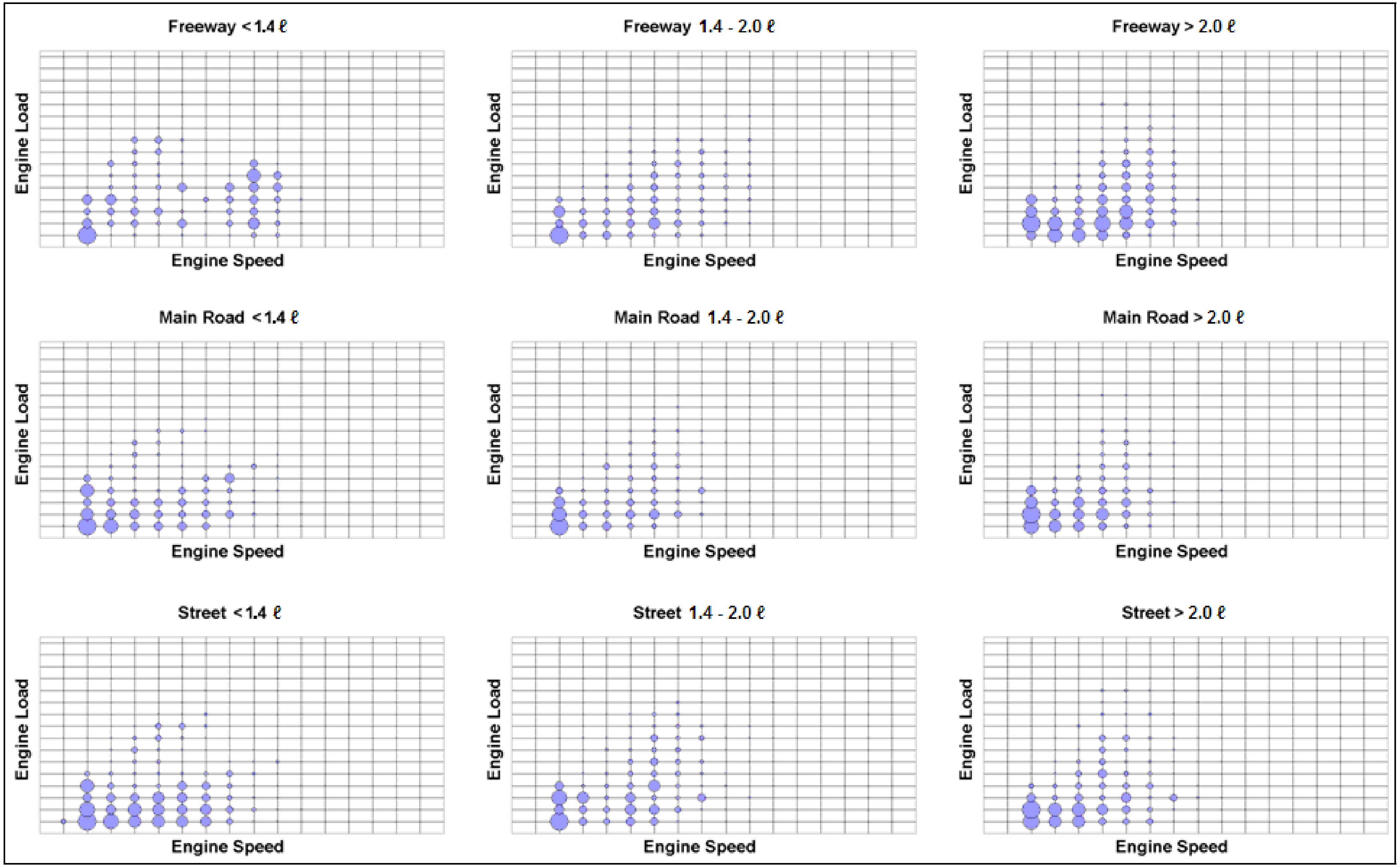

Figure 4.19: **Aggregated engine-operating patterns for morning commute period (6:30 – 9:00) for petrol vehicles (< 1.4 ℓ, 1.4 – 2.0 ℓ and > 2.0 ℓ capacity classes).**

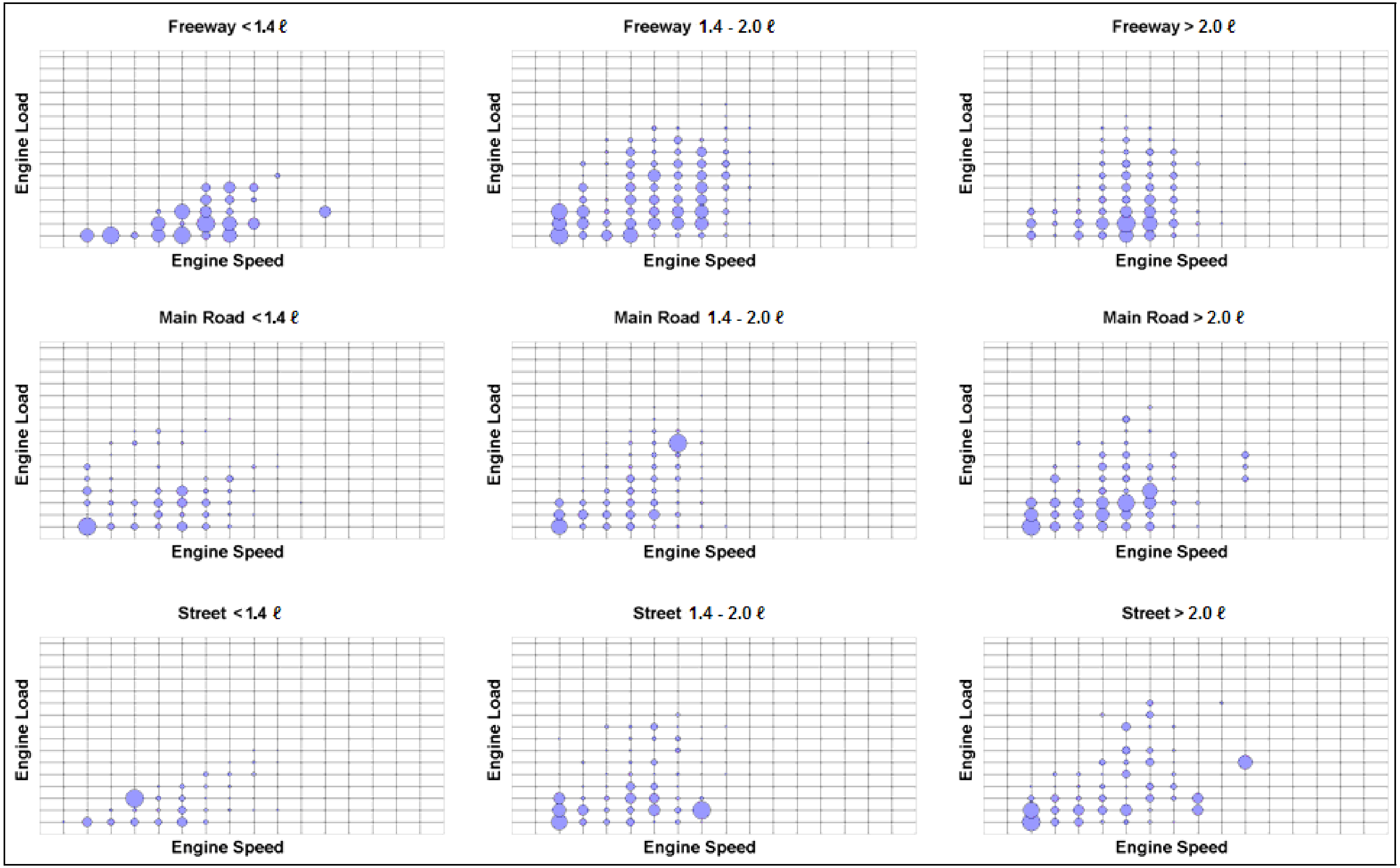

Figure 4.20: Aggregated engine-operating patterns for the midmorning period (9:00 – 12:00) for petrol vehicles (< 1.4 ℓ, 1.4 – 2 ℓ and > 2.0 ℓ capacity classes).

Uncertainty analysis of engine operation

Aggregated engine-operating patterns were used in the fuel consumption and emissions simulation model to determine the fuel consumption and emission factors for various vehicle types and driving conditions. Variations of the individual patterns, which make up the aggregated patterns, influence the uncertainty of the results. An uncertainty analysis was performed to show the variation of the measured engine-operating patterns within the aggregated patterns.

The average engine speed, average engine load and their corresponding standard deviations were determined for each combination of dimensions. In addition, the engine-operating patterns from each vehicle, which make up the aggregated engine-operating patterns, were compared to the aggregate pattern by calculating the *MI* (matching index). An average *MI* was then determined for each aggregated pattern. The average *MI* provides an overall indication of the similarity of the individual patterns to the aggregated pattern. The closer the *MI* is to one the less variation there is between the patterns that are used to produce the aggregated patterns and the greater the certainty of the fuel consumption and emission factors.

A statistical comparison between the patterns could only be determined for petrol vehicles as not enough diesel vehicles were sampled. The properties of the engine-operating patterns in Figure 4.19 and Figure 4.20 are summarised in Table 4.6. An analysis of all the possible engine-operating patterns is given in APPENDIX L: *Driving conditions from travel survey* by vehicle type.

The range of engine operation for the measured engine-operating patterns is quantified in Table 4.6. The trade-off between engine speed and engine load is once again evident in the standard deviation of the engine speed and engine load for different engine sizes. The smaller capacity vehicles use the engine-operating speed more while the larger capacity vehicles use the engine load range more. There is also a tendency for the larger capacity vehicles to exhibit similar engine-operating patterns to each other, particularly for freeway driving. This is evident from the *MI* being higher, on average, for the > 2.0 ℓ capacity class than the other capacity classes.

Table 4.6: Summary statistics for petrol vehicle engine-operating patterns for the morning commute (6:30 – 9:00) and midmorning travel (9:00 – 12:00).

			06:30 – 09:00			**09:00 – 12:00**		
			Capacity Class (ℓ)			**Capacity Class (ℓ)**		
Road type	**Parameter**	**Unit**	**< 1.4**	**1.4 – 2.0**	**> 2.0**	**< 1.4**	**1.4 – 2.0**	**> 2.0**
Freeway	Ave engine speed	$m\ s^{-1}$	5.91	5.29	4.76	6.48	5.66	5.96
	Stdev engine speed	$m\ s^{-1}$	2.50	1.43	0.84	0.24	1.51	0.16
	Ave Engine Load	kPa	342	320	298	172	348	308
	Stdev Engine Load	kPa	103	113	148	14	92	142
	Average MI		0.34	0.50	0.54	0.65	0.45	0.61
	Number of patterns		5	12	6	2	6	5
Main Road	Ave engine speed	$m\ s^{-1}$	4.55	4.33	4.08	4.82	4.96	5.21
	Stdev engine speed	$m\ s^{-1}$	1.40	0.64	0.69	1.26	0.89	0.86
	Ave Engine Load	kPa	250	272	266	256	347	290
	Stdev Engine Load	kPa	144	114	132	168	165	132
	Average MI		0.45	0.50	0.51	0.46	0.45	0.47
	Number of patterns		5	13	7	4	8	5
Street	Ave engine speed	$m\ s^{-1}$	4.56	4.76	4.31	5.10	4.92	5.42
	Stdev engine speed	$m\ s^{-1}$	0.98	0.78	0.83	1.19	1.41	2.27
	Ave Engine Load	kPa	233	315	275	206	266	315
	Stdev Engine Load	kPa	142	119	174	72	92	184
	Average MI		0.49	0.40	0.46	0.50	0.36	0.44
	Number of patterns		5	13	7	4	8	4

Ave - average, Stdev – standard deviation, MI – matching index

Shaded values indicate insufficient data to determine uncertainties

4.3.5. Costs of the survey

The only equipment costs associated with the survey were four sets of on-board diagnostics and GPS equipment. Each set of equipment cost R4 500, with the GPS data loggers costing the most at R2 100 each. The GPS sensor modules cost R600 each and the CarChip OBDII data loggers cost R1 800 each. The total cost for the four sets of equipment was R18 000. (Concessions were made by the equipment suppliers on the understanding that the equipment was being used for research purposes.) Technician time for negotiating, installing and retrieving equipment per vehicle sampled was 1 hour.

The cost of a single set of on-board emissions measurement equipment is in the order of US $100 000 (approximately R700 000). The cost benefit of simulating fuel consumption and emission factors based on low cost vehicle monitoring equipment and existing emission factors provides considerable savings to the development of local emission factors.

4.3.6. Conclusions

Proportions of different driving conditions in terms of road type and time of day have been determined for vehicles of different fuel types and capacity classes using OBD, GPS and the road information from the Johannesburg GIS database. Engine-operating patterns for various vehicle types and driving conditions were determined. The engine-operating patterns were needed to simulate the fuel consumption and emissions for the driving conditions using the fuel consumption and emissions simulation model.

The survey takes advantage of technologies built into newer vehicles, which allow engine operation to be monitored directly. This eliminates the need to estimate engine operation based on kinematics, properties of the vehicles, auxiliary equipment use and road gradient. The simpler process of determining engine-operating patterns reduces the costs of developing emissions inventories because only one survey needs to be performed, as opposed to the multiple surveys needed when using vehicle kinematics.

A private vehicle usage profile was determined in terms of the types of roads used by the various types of vehicles and the vehicle kilometres travelled by each type of vehicle per annum from the survey. It was shown that diesel vehicles and large capacity vehicle are used the most and that the larger capacity vehicles are used more on freeways than the smaller capacity vehicles in relation to the other road types.

The engine-operating patterns from the survey show that there is a larger variation in engine operation for smaller capacity vehicles. The patterns for all vehicle capacity classes also show more time is spent in the low speed and low loads during congested periods of the day, which is the least efficient mode of engine operation

4.4. An emissions inventory for Johannesburg

Data presented in the previous section are for the vehicles sampled during the survey. In this section results from the survey are projected onto the vehicle population of the City of Johannesburg and used to simulate local emissions factors to build an emissions inventory. The conceptual structure of the emissions inventory model was developed in Section 3.5.2 and illustrated in Figure 3.10.

The architecture of the implemented emissions inventory software application is presented in Figure 4.21. The emissions inventory integrates: (i) emission factors estimated using the simulation model; (ii) the proportion of driving conditions and a vehicle usage profiles from the survey; (iii) the size and structure of the Johannesburg vehicle population; and (iv) fuel sales to determine the total emissions from private passenger vehicles within the municipal boundaries of the city.

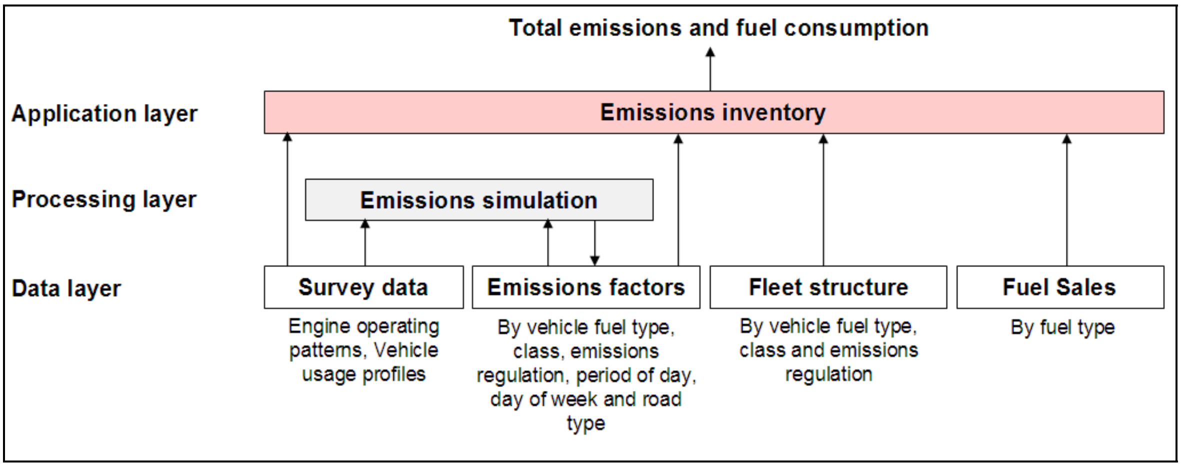

Figure 4.21: Architecture of the emissions inventory application.

The emissions inventory application consists of three layers: (i) a data layer containing vehicle usage profiles from the survey, emission factors for pre-calculated *base* engine-operating patterns, fleet structure and fuel sales; (ii) a processing layer, which calculates the emission factors from the engine operating patterns from the survey; and (iii) an application layer which integrates the data and calculation processes to provide useful information.

The data layer of the model was implemented in a Microsoft Access® database. The processing layer was implemented in Microsoft SQL Server® in preference to Access® due to the greater processing power. The application and presentation layer was implemented as a mixture of Access and Microsoft Excel®.

The intermediate steps to calculate the emission factors from the survey data and functions within the application layer are discussed in the following sections.

4.4.1. Emission factors from engine-operating patterns

Fuel consumption and emission factors were calculated using the procedure described in Section 3.5.4 and the coded implementation in APPENDIX H: *Transact SQL code for emissions simulation*. Due to the generic nature of the model and the normalised engine-operating patterns, results from the fuel consumption and emissions simulation model are returned as fuel consumption and emissions rates per litre engine capacity ($g\ s^{-1}\ \ell^{-1}$). To determine the final emission factors in grams per kilometre ($g\ km^{-1}$) the results from the simulation model were multiplied by the average speed for each of the driving conditions, vehicle type and average vehicle capacity for each vehicle fuel type and capacity class.

This was done using a query within an Access® database. Average engine capacities for each capacity class in the vehicle population were determined from the registration database, while the average speeds were provided from the survey results in Table L.2.

Four hundred and two sets of fuel consumption and emission factors were simulated using the measured engine-operating patterns from the survey. These are tabulated in APPENDIX N: *Emission Factors for Local Driving Conditions and Vehicles*. In the following paragraphs, selected features of this set of emission factors are highlighted. The focus of the discussion will be on petrol vehicles due to the small size of the diesel vehicle sample. The emissions factors for diesel vehicles based on the sample are included in Appendix N.

The impact that driving conditions (road type and period of the day) have on fuel consumption is shown in Figure 4.22 for weekdays and Euro-2 vehicles by capacity class. Fuel consumption is highest for the > 2.0 ℓ capacity class and lowest for the < 1.4 ℓ capacity class for most driving conditions. Freeways have the lowest fuel consumption factors with main roads being slightly higher than streets on average. The highest fuel consumption factors for the > 2.0 ℓ capacity class occurred during the 06:30 – 09:00 and *other* periods of the day for freeways, but during the 06:30 – 09:00 and 16:00 – 18:30 periods for main roads and streets. The high emissions rates for freeways in the *other* time period is due to high speed driving as evident in Figure 4.18, whereas the emissions in the 06:30 – 09:00 and 16:00 – 18:30 periods are due to congestion. The highest fuel consumption factors for the 1.4 – 2.0 ℓ capacity class occurred during the same periods of the day as the > 2.0 ℓ capacity class for freeways, but during the 06:30 – 09:00 and 12:00 – 14:00 periods for main roads and streets. The highest fuel consumption factors for the < 1.4 ℓ capacity class occurred during the 06:30 – 09:00 and 14:00 – 16:00 periods for all three road types.

Simulated CO_2 emissions were approximately proportional to the fuel consumption values with 10 ℓ/100 km equivalent to 240 g km^{-1} for petrol and 10 ℓ/100 km equivalent to 270 g km^{-1} for diesel based on typical Carbon/Hydrogen ratios of the two fuels (Heywood, 1988).

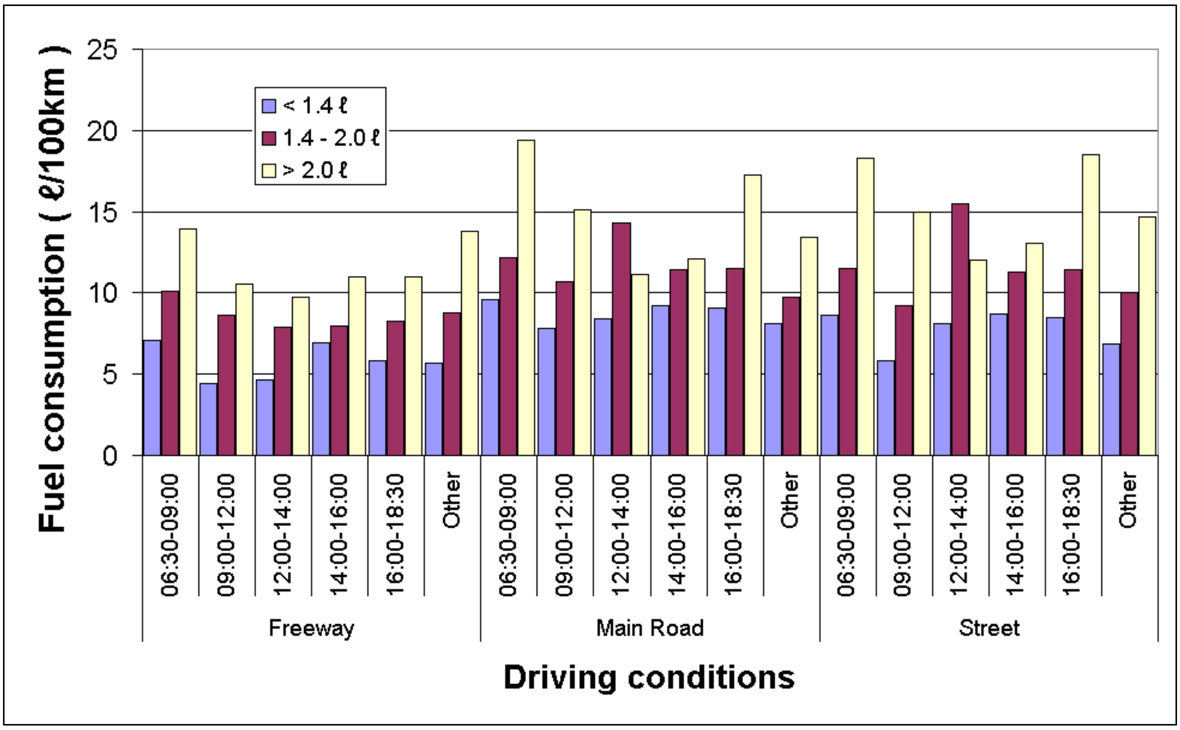

Figure 4.22: Fuel consumption factors for weekdays and Euro-2 vehicles by driving condition and capacity class.

CO and NO_x emission factors for the same driving conditions and vehicles in Figure 4.22 are shown in Figure 4.23 and Figure 4.24. Overall the CO and HC (Appendix N) emissions show similar trends to those of the CO_2 and fuel consumption factors.

The NO_x factors in Figure 4.24 show that in some circumstances (freeway and midday main road driving) the > 2.0 ℓ capacity class vehicles have lower emission factors than the 1.4 – 2.0 ℓ capacity class. This is likely to be due to the lower relative engine loads and engine speeds for the larger capacity vehicles in these conditions. This can be supported by the engine operating patterns in Figure 4.19 and Figure 4.20, and the tabulated values in APPENDIX M: *Variation of Measured Engine-operating Patterns*, which show that the average engine loads and engine speeds for the > 2.0 ℓ capacity class vehicles are indeed lower than those for the 1.4 – 2.0 ℓ capacity class for most driving conditions. There is also less gear changing required as the larger capacity engines have more usable torque than the smaller capacity vehicles, which allows for lower average engine speeds.

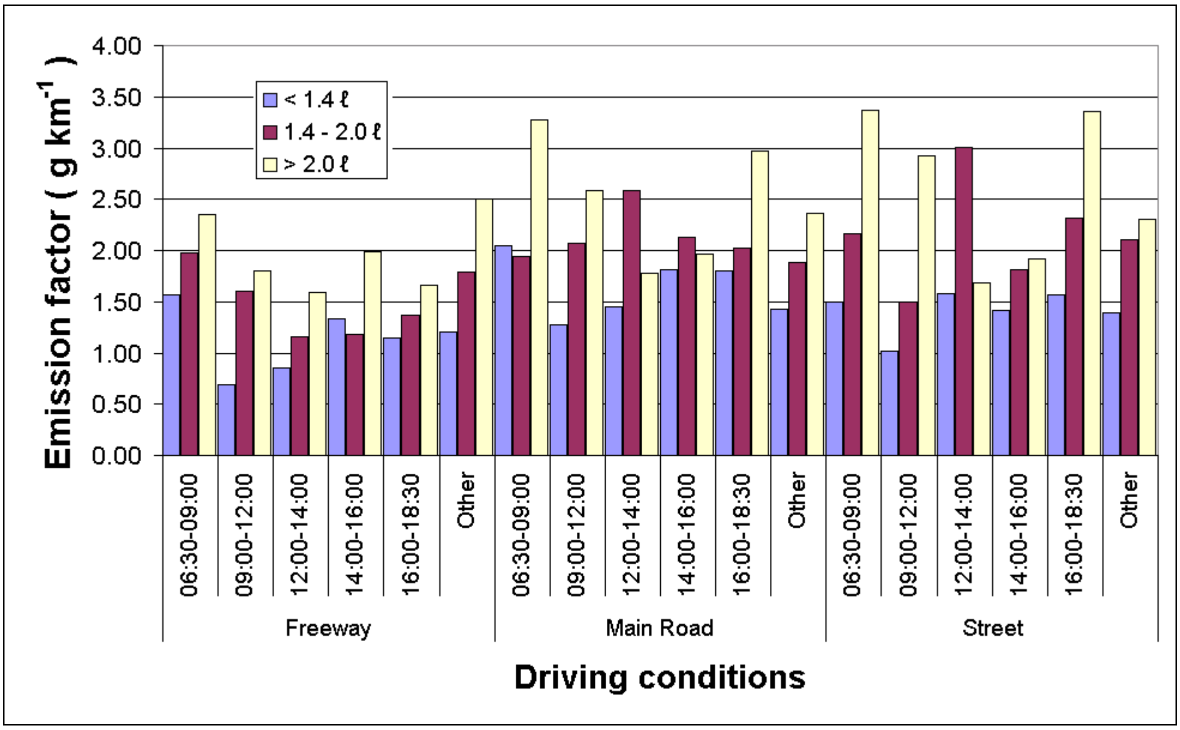

Figure 4.23: CO emission factors for weekdays and Euro-2 vehicles by driving condition and capacity class.

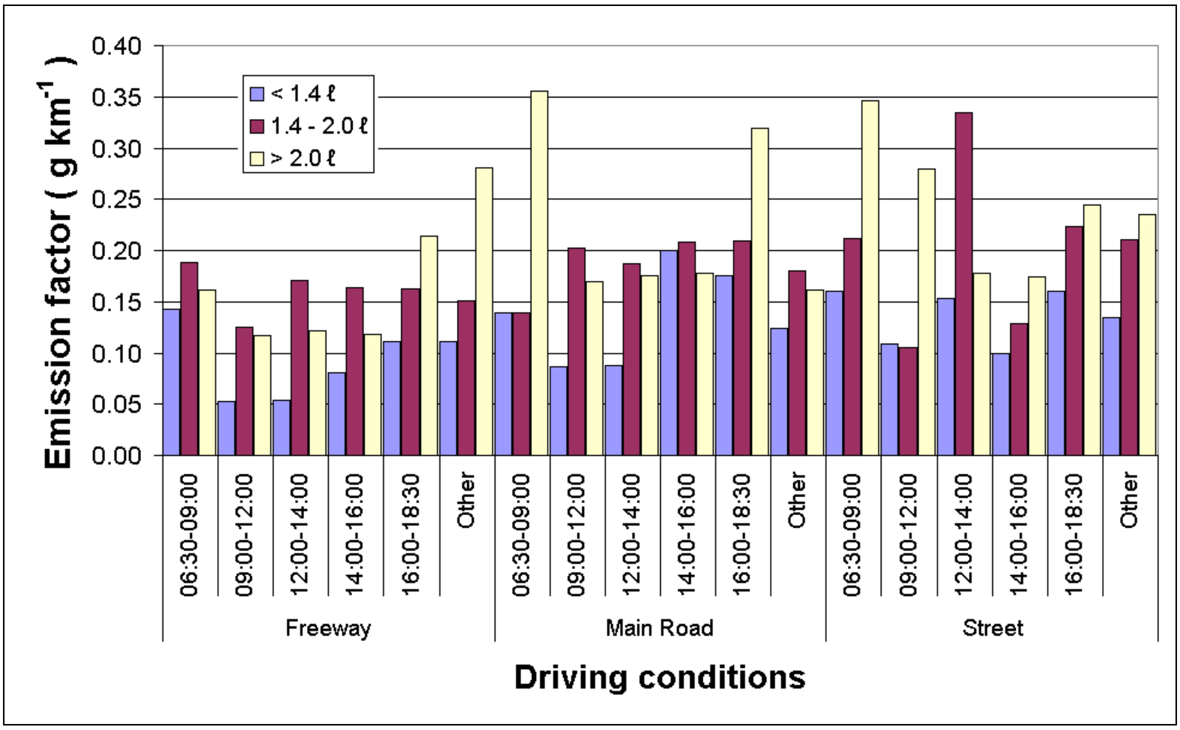

Figure 4.24: NO_x emission factors for weekdays and Euro-2 vehicles by driving condition and capacity class.

Average fuel consumption and emission factors by fuel type, capacity class and emissions regulation were calculated from the tables in APPENDIX N: *Emission Factors for Local Driving Conditions and Vehicles*. These are shown for fuel consumption, CO and NO_x factors in Figure 4.25, Figure 4.26 and Figure 4.27 respectively. (These averages have not been weighted according to the proportion of driving conditions travelled by each vehicle type, but are the numerical average of the values in the tables in Appendix N.) Fuel consumption data was not directly measured from the vehicles so no correlation between estimated fuel consumption and actual fuel consumption was possible. While a two week observation period was sufficient to determine typical engine operating patterns and driving cycles it was too short to determine accurate fuel consumption records without specialised equipment.

Based on the average fuel consumption factors in Figure 4.25, the change in age and technologies from Euro-0 to Euro-2 regulations results in reduced fuel consumption by 17%, 21% and 18% for the < 1.4 ℓ, 1.4 – 2.0 ℓ and > 2.0 ℓ capacity classes respectively. The change in age and technologies from Euro-2 to Euro-3 regulations reduced fuel consumption by 5%, 3% and 6% for the corresponding capacity classes. These fuel consumption improvements are not due to the stricter emissions regulation, which generally impose a fuel consumption penalty for reduced emissions, but due to the improved aerodynamics and other energy efficiency technologies in newer vehicles. The purpose of emissions regulations is to limit pollutant emissions; they do not specify fuel consumption limits so no correlation should be made between emissions regulations and fuel consumption. While the emissions control technologies in the EMPA source data correspond to certain body shapes due to vehicle age, the vehicle fleet profile in South Africa consists of older body shapes with newer emissions controls. This will certainly influence the actual fuel consumption factors in South Africa. The diesel fuel consumption is lower for the < 1.4 ℓ and > 2.0 ℓ capacity classes compared to the petrol vehicles, as expected due to the inherent efficiency of diesel engines. The fuel consumption of the diesel 1.4 – 2.0 ℓ capacity class is higher than that for the petrol vehicles of the same class and regulation. The lower fuel consumption in the diesel > 2.0 ℓ capacity class compared to diesel 1.4 – 2.0 ℓ capacity class the is likely to be due to the different profiles of the EMPA and the South African test fleets. The EMPA sample of large capacity diesel vehicles is dominated by large sedans whereas the South African sample of large diesels is

SUV/pickup type vehicles. There are insufficient sample data for this type of vehicle to make any definite conclusion.

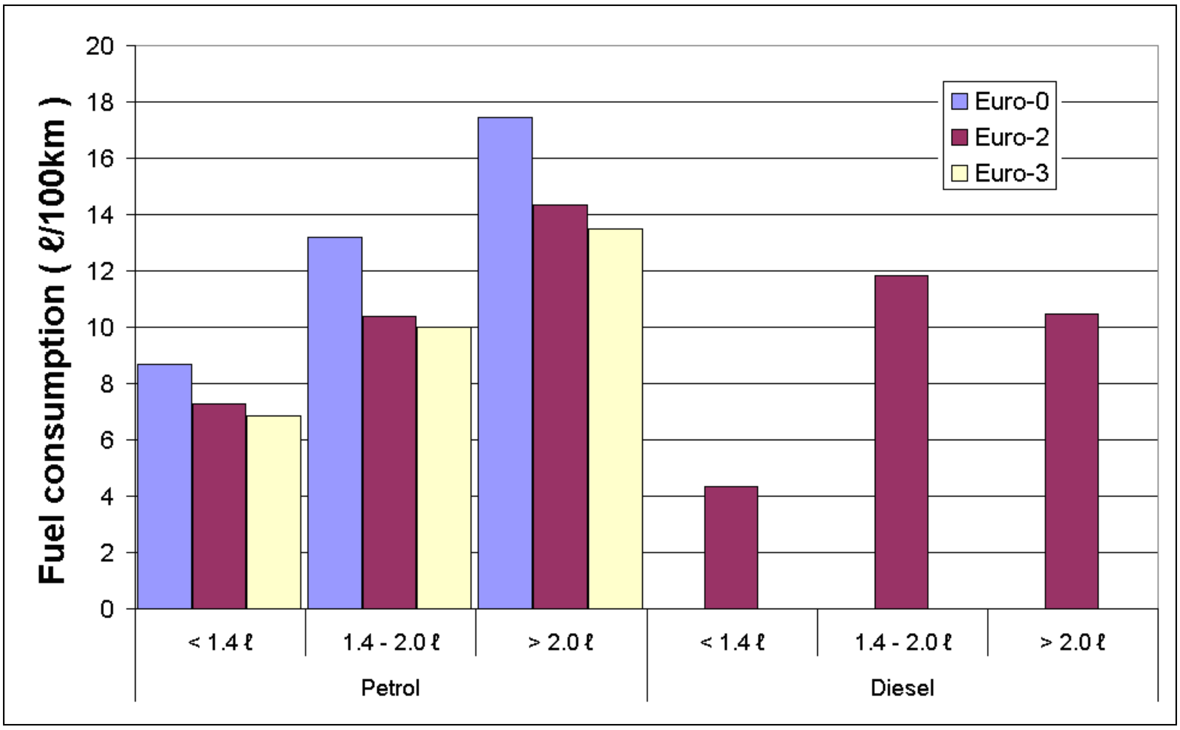

Figure 4.25: Average fuel consumption factors by vehicle fuel type, capacity class and emissions regulation.

Average CO and NO_x emissions factors are given in Figure 4.26 and Figure 4.27. The reduction of emissions from Euro-0 to Euro-2 are significantly larger than the change from Euro-2 to Euro-3 regulation vehicles, as already determined by the sensitivity of the emissions simulation model in Section 4.2.3. CO emissions factors are between 6 and 7 times higher for Euro-0 vehicles compared to Euro-2 vehicles, whereas Euro-2 vehicles are between 3 and 3.7 times higher. HC and CO emissions are lower, by a factor of about 10, for diesel vehicles compared to those from the petrol vehicles, both for Euro-2 compliant vehicles.

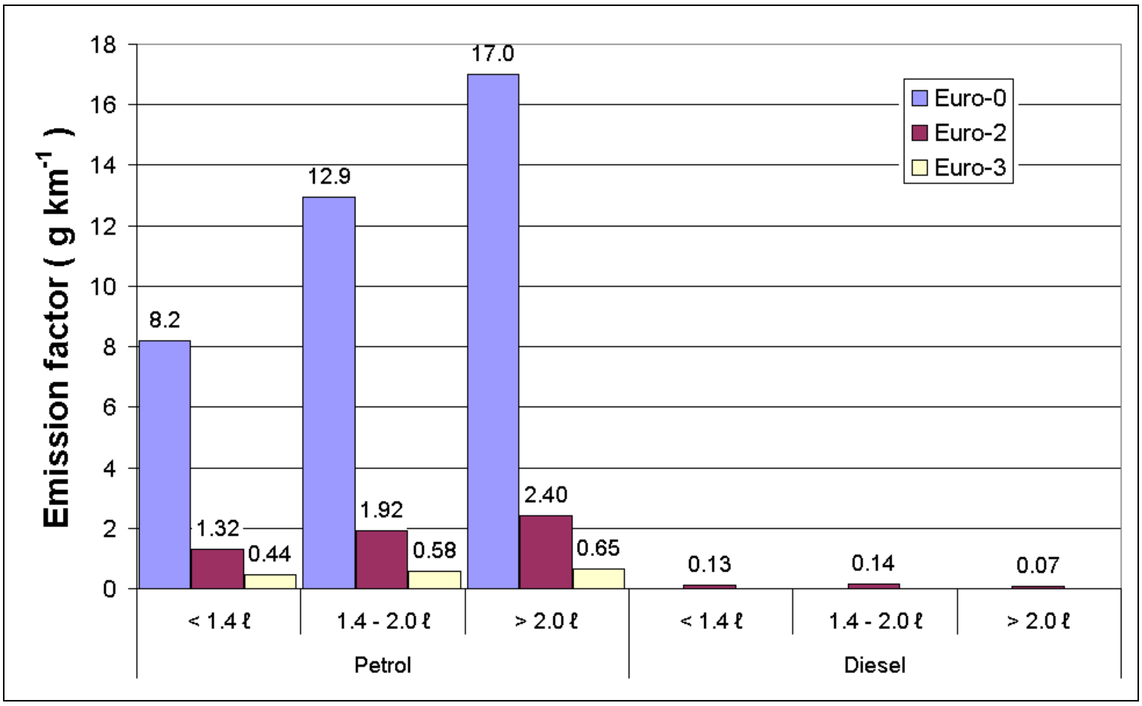

Figure 4.26: Average CO emission factors by vehicle fuel type, capacity class and emissions regulation.

NO_x emissions are a factor of 20 times higher for Euro-0 compared to Euro-2 and between 4 and 4.5 times higher for Euro-2 compared to Euro-3. NO_x emissions for diesel vehicles are between 4.3 and 8.0 times higher than for petrol vehicles of the same emissions regulation.

HC and CO emissions are lower for diesel vehicles due to the lean air fuel ratios, while NO_x emissions are higher due to the higher maximum temperature of the diesel combustion cycle. The NO_x emissions from the diesel engines are also more difficult to control using catalytic converters because the particulate matter from diesel engines accumulate in the catalytic substrates. Expensive particulate matter filters are required to prevent this from happening.

The emissions reductions from Euro-0 to Euro-2 and from Euro-2 to Euro-3 demonstrates the diminishing returns on emissions controls. The cost to reduce emissions from Euro-2 to Euro-3 are not justified by the reduced emissions within the South African context. Regular maintenance and removing older Euro-0 vehicle from the road should provide a more cost effective means to reduce ambient air pollution.

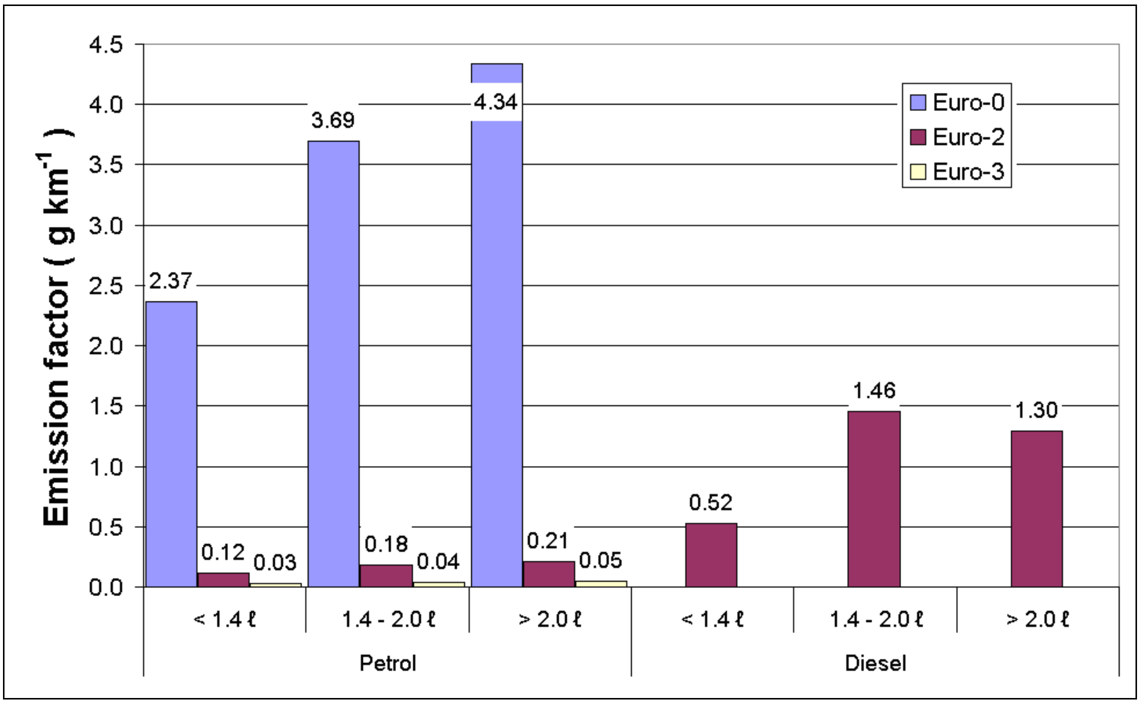

Figure 4.27: **Average NO_x emission factors by vehicle fuel type, capacity class and emissions regulation.**

4.4.2. Average fleet fuel consumption and emission factors by fuel type

Average fuel consumption and emission factors for petrol and diesel vehicles for the Johannesburg fleet were calculated, drawing on the following supporting data sets to weight the emission factors calculated from the engine-operating patterns:

- Structure of the vehicle population, in terms of capacity classes (Table 3.8);
- Proportions of petrol vehicles compliant with emissions regulations (45% Euro-0, 35% Euro-2 and 20% Euro-3);
- Proportion of driving conditions by vehicle type from Table L.1; and
- Annual average kilometres driven per year from Table 4.5.

Results are shown in Table 4.7.

Table 4.7: **Average fuel consumption and emission factors by fuel type.**

Parameter	Unit	Petrol	Diesel
Fuel cons.	ℓ/100 km	12.02	11.61
CO_2	g km^{-1}	269	306
CO	g km^{-1}	6.82	0.08
HC	g km^{-1}	0.75	0.04
NO_x	g km^{-1}	1.69	1.44
HC + NO_x	g km^{-1}	2.44	1.48

Various European emissions limits for passenger vehicles are shown in Table 4.8. A comparison of estimated emission factors in Table 4.7 and the European emissions regulations in Table 4.8 show that for petrol vehicles the emission factors calculated in this study (both CO and the combined NO_x and HC) are 2.5 times higher than the maximum limits for the Euro-1 emissions regulations. The tables also show that for Euro-2 diesel vehicles the CO emissions comply with the regulations, but the combined HC and NO_x emissions are 64% higher than the quoted emissions regulations. From this comparison, real-world vehicle operating environments and driving styles have a significant impact on overall vehicle emissions compared the standardised driving cycles used for emissions regulations.

Table 4.8: European emissions limits (based on the ECE driving cycle) (Robert Bosch GmbH, 2000).

Parameter	Unit	Petrol				Diesel	
EU Regulation		Euro-1	Euro-2	Euro-3	Euro-4	Euro-2	Euro-3
Year of introduction		1992	1996	2001	2005	1997	2000
CO	g km^{-1}	2.72	2.2	2.3	1.0	1.0	0.6
HC	g km^{-1}	-	-	0.2	0.1	-	-
NO_x	g km^{-1}	-	-	0.15	0.08	-	0.5
HC + NO_x	g km^{-1}	0.97	0.5	-	-	0.9	0.6

4.4.3. Total vehicle activity in the City of Johannesburg

Total vehicle activity by fuel type was determined from retail fuel sales, minus fuel used by taxis, divided by the average fuel consumption of petrol and diesel vehicles given in Table 4.7. This resulted in 2.8 billion vehicle kilometres for diesel vehicles and 12.1 billion kilometres for petrol vehicles, or a total annual distance driven in Johannesburg by private passenger vehicles for the study period of 14.9 billion vehicle kilometres.

4.4.4. Total emissions in the City of Johannesburg

Total emissions in Johannesburg were determined by summing the product of vehicle kilometres per fuel type and the average emission factors in Table 4.7. Results are shown in Table 4.9.

Table 4.9: Total fuel consumption and emissions from private passenger vehicles in Johannesburg per annum.

		Unit	Petrol	Diesel	Total
Fuel cons.		Giga-ℓ	1.46	0.325	1.78
Emissions	CO_2	Mt	3.27	0.86	4.13
	CO	kt	82.6	0.22	82.8
	HC	kt	9.05	0.10	9.15
	NO_x	kt	20.5	4.03	24.5

Total emissions of CO and HC are dominated by petrol vehicles (Table 4.9). Diesel vehicles, however, make a considerable contribution to NO_x emissions with emissions rates similar to petrol vehicles (see Table 4.7). Average diesel NO_x emissions per litre fuel are 12.4 g $ℓ^{-1}$ whereas average NO_x emissions per litre petrol are 14.1 g $ℓ^{-1}$. Diesel vehicles also make a significant (21%) contribution to total CO_2 emissions with an average of 306 g km^{-1} compared to the average petrol vehicle with a CO_2 emissions rate of 269 g km^{-1}.

No gross emissions estimates from the current emissions modelling process at the City of Johannesburg are available yet to perform a comparative study with the results presented here.

4.4.5. Break-down of total emissions by category

To determine which driving conditions and vehicle types produce the most emissions in the City of Johannesburg, for identifying where best to invest efforts to reduce emissions, it was necessary to combine the total vehicle activity for each combination of vehicle type and driving condition with the corresponding emission factors.

Total vehicle kilometres for each set of driving conditions and vehicle types were calculated using the following sets of data:

- Total distance travelled by private passenger vehicles in Johannesburg by fuel type, 2.8 billion vehicle kilometres for diesel vehicles and 12.1 billion kilometres for petrol vehicles;
- Distances travelled per year by vehicle type;
- Fleet structure by fuel type, capacity class and emissions regulation; and

- Fractions of driving conditions for each vehicle type (APPENDIX L: *Driving conditions from travel survey by vehicle type*).

The intermediate results are tabulated in APPENDIX O: *Breakdown of Total Vehicle Activity*.

Total fuel consumption and emissions for each driving condition and vehicle type were calculated by multiplying the results in APPENDIX O: *Breakdown of Total Vehicle Activity* by the corresponding emissions factors in APPENDIX N: *Emission Factors for Local Driving Conditions and Vehicles*. Selected intersections of these results are presented in terms of the fraction of total fuel consumption and emissions by various categories:

- Vehicle fuel type, emissions regulation and capacity class in Figure 4.28;
- Road type in Figure 4.29;
- Period of day for weekdays in Figure 4.30; and
- Period of day for weekends in Figure 4.31.

The structure of the private passenger vehicle population in Johannesburg in terms of fuel type, capacity classes and emissions regulations is presented in Figure 4.28 for convenience, so that the fraction of total fuel consumption and emissions by fuel type, emissions regulation and capacity can be compared to the fleet structure.

- Diesel vehicles, which constitute 10% of the private passenger vehicle fleet, do not contribute significantly to the total CO and HC emissions from private passenger vehicles in Johannesburg, but they produce 19% of the total CO_2 emissions and emit 14% of the total NO_x emissions. Diesel vehicles consume 17% (by volume) of total retail fuel sales, which is more per vehicle than petrol fuel consumption. This is because diesel vehicles travel more per year than petrol vehicles.
- Euro-3 petrol vehicles consumed 14% of the retail fuel sales. They also emitted 15% of the CO_2 emissions, 2% of the CO emissions, 0.5% of the HC emissions and 0.4% of the NO_x emissions, but constitute 17% of the total vehicles. These pollutant emissions are insignificant compared to those from the other petrol vehicles.
- Euro-2 petrol vehicles, which were assumed to make up 30% of the private passenger fleet, consume 26% of the fuel and produce 27% of the CO_2 but only produce 10% of the CO emissions, 5% of the HC emissions and 3% of the NO_x emissions.

- Although Euro-0 compliant petrol vehicles were assumed to make up 39% of both petrol and diesel vehicles (45% of the petrol vehicle fleet) they were estimated to consume 42% of the fuel, produce 40% of the CO_2, 88% of the CO emissions, 93% of the HC emissions and 82% of the NO_x emissions.

From these data there is a clear benefit from stricter vehicle emissions regulations. Implementation of the Government strategy for control of exhaust emissions should have a significant impact on total emissions within the City of Johannesburg because this strategy required all new homologations to be compliant to Euro-2 regulations from January 2007 and all new cars to be Euro-2 compliant from January 2008.

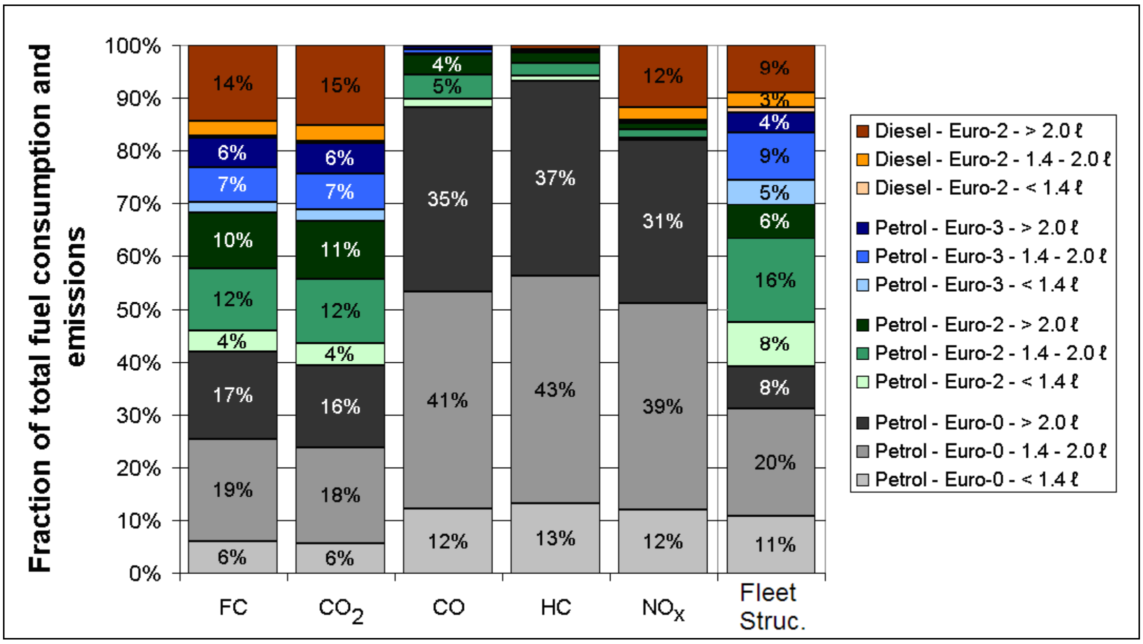

Figure 4.28: Fraction of total fuel consumption and emissions for private passenger vehicles by fuel type, emissions regulation and capacity class. (The fleet structure is included for clarity.)

The fraction of total fuel consumption and emissions for streets, main roads and freeways are presented in Figure 4.29. 48% of the fuel consumed in Johannesburg was on main roads followed by freeways with 42% and streets with 11%. The fraction of CO_2 emissions for each of the three road types correlate well with fuel consumption. Total pollutant emissions are the highest for main roads (49% of the CO, 50% of the HC and 46% of the NO_x) followed by freeways (with 39% of the CO, 39% of the HC and 43% of the NO_x). The share of total CO and HC emissions by road type are the same. NO_x emissions, although still highest for the main road category, are higher for freeways than the other pollutant emissions. This indicates that freeways represent conditions which promote NO_x

production, that is high vehicle speeds require higher engine loads resulting in higher maximum combustion temperatures, whereas constant smooth engine operation reduces HC and CO emissions.

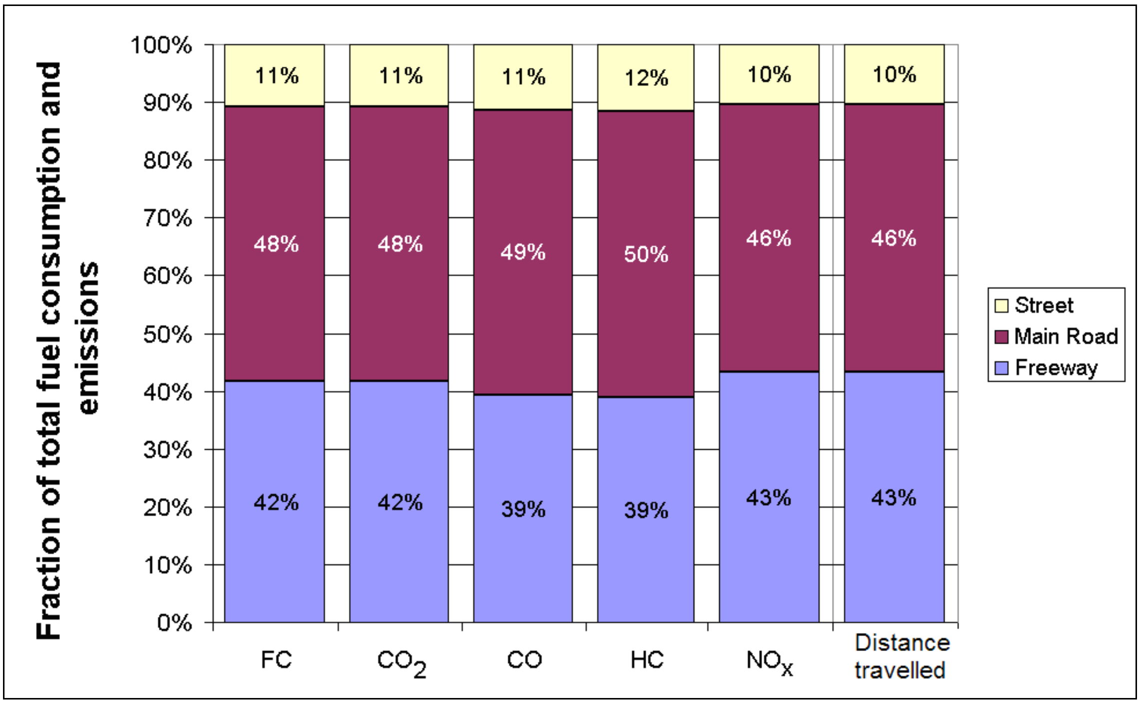

Figure 4.29: Fraction of total fuel consumption and emissions for private passenger vehicles in Johannesburg by road type and the proportion of total distance travelled by road type.

The fraction of total fuel consumption and emissions for private passenger vehicles in Johannesburg by period of day for weekdays and weekends are shown in Figure 4.30 and Figure 4.31 respectively. For weekdays the combination of vehicle activity and emissions factors for the various driving conditions result in the 06:30 – 09:00 period contributing most to total fuel consumption and emissions followed by the 16:00 – 18:30 and then the *other* period of the day. In the periods between 09:00 and 16:00 the same amount of fuel was consumed as the 16:00 – 18:30 period, however, CO and HC emissions were 12% lower. This suggests that the emissions per litre fuel consumed is higher in congested periods and can be confirmed by the ratio of emissions to fuel consumed in the 06:30 – 09:00 period. The highest potential for reducing emissions and congestion would be during this period, using traffic management techniques and public transport.

On weekends the travel patterns vary to those during the week. This results in a different distribution of total fuel consumption and emissions throughout the day during weekends.

Most of the emissions are emitted during the 09:00 – 12:00 period followed by the 16:00 – 18:30 period. The remainder of the emissions are roughly evenly distributed over the other periods of the day.

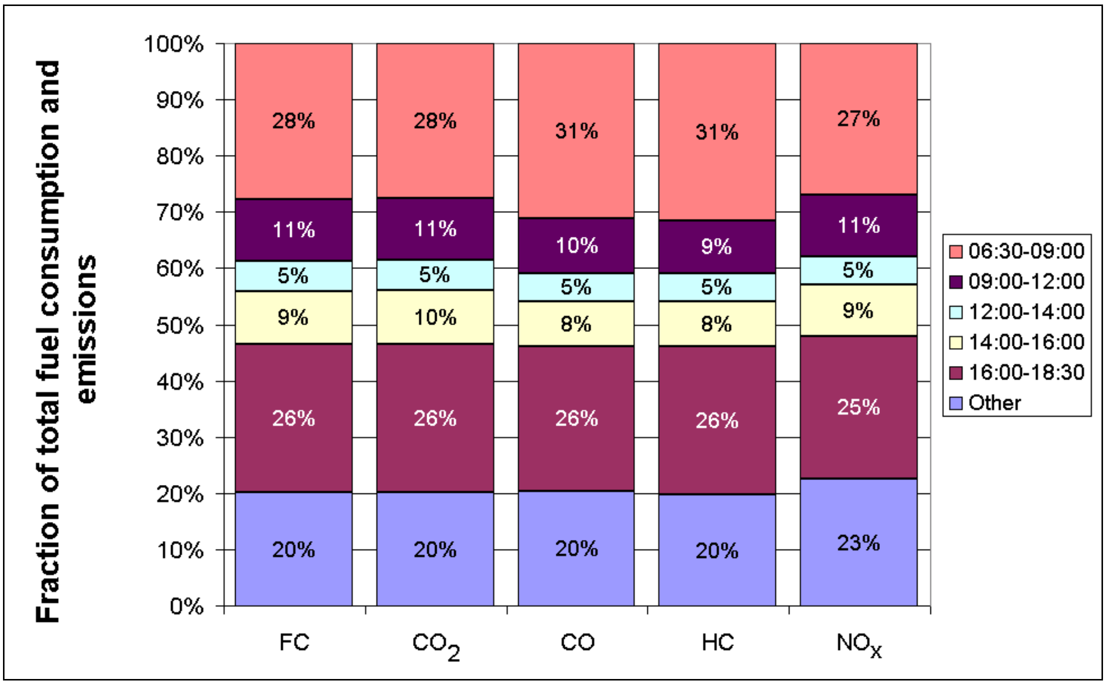

Figure 4.30: Fraction of total fuel consumption and emissions for weekdays for private passenger vehicles in Johannesburg by period of day.

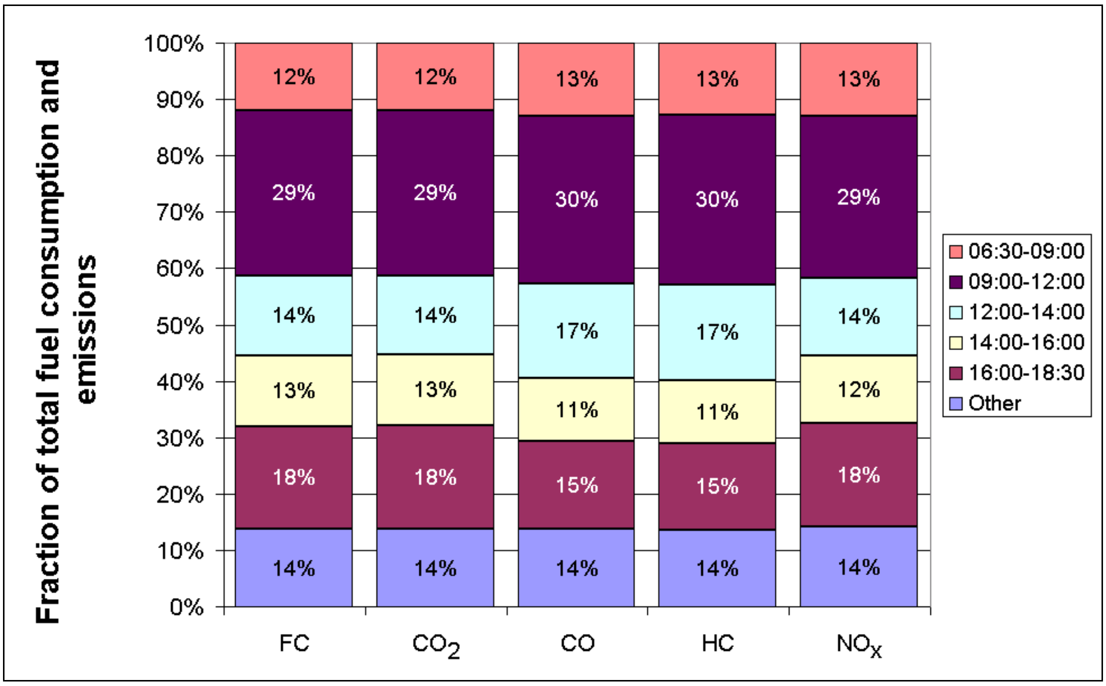

Figure 4.31: Fraction of total fuel consumption and emissions for weekends for private passenger vehicles in Johannesburg by period of day.

4.4.6. Conclusions

Emission factors were calculated using data from the vehicle usage and engine operation survey, and the developed emissions model for vehicles of various emissions regulations, fuel types and capacity classes and driving conditions that occur in Johannesburg as a proof of concept. The method of combining these data with information about the vehicle fleet structure, fuel sales and private vehicle usage has been demonstrated with the aid of a new software application developed during this study. The method relies on European emissions factors and fleet characteristics. A larger dataset is needed to characterise emissions for the South African vehicle fleet.

Fuel consumption and emission factors have been shown to be worse for congested and high speed driving. In general, the fuel consumption and emissions for the larger capacity vehicles are higher. There were some circumstances, however, where the > 2.0 ℓ capacity class has lower NO_x emissions than the 1.4-2.0 ℓ capacity class. This is due to the average engine loads and engine speeds being relatively lower for the larger capacity class vehicles in certain circumstances which lowers NO_x emission rates.

The total private passenger vehicle activity was estimated to be 14.9 billion vehicle kilometres based on the total fuel sales in Johannesburg and average fuel consumption factors calculated by the emissions simulation model, the shares of the driving conditions and the structure of the vehicle fleet.

The emissions inventory programme allows one to vary the share vehicles of different fuel types, engine capacities and emissions regulations to study the impact of the fleet structure on total emissions. In addition, the impact of the different driving conditions and vehicle usage profiles can be considered.

The combination of a new emissions simulation model and its integration within a larger decision support systems provides an original contribution to the methods and tools used to developed emissions inventories.

4.5. Chapter summary

In this chapter the implementation, uncertainties and sensitivity of the fuel consumption and emissions simulation model were presented, the results of the travel survey were summarised, and the model and survey results were used together to demonstrate how they can be used together to produce an emissions inventory. Both the emissions simulation and emissions inventory models were implemented as original software programs.

The simulation model was shown to have favourable prediction ability in comparison to the kinematic model used to produce emission factors for the HBEFA.

The travel survey was shown to be an effective method to collect both travel behaviour and engine operation information. The survey demonstrated the impact of different driving conditions on engine operation. The variation of the engine-operating patterns for different vehicle types and driving conditions were also considered.

Engine-operating patterns from the survey were used in the simulation model to produce emission factors for the emissions inventory. Average fuel consumption and emission factors were produced from the structure of the vehicle population and the activity per vehicle type from the survey. Total vehicle kilometres for each fuel type were calculated from the average fuel consumption and fuel sales. Total emissions for the City of Johannesburg were calculated from the total distance and the average emission factors for each fuel type.

Examples of total emissions by vehicle type, road type and different periods of the day were given to highlight which driving conditions and vehicle types make the largest contributions to the overall emissions burden in the City of Johannesburg.

5. CONCLUSION

The aim of this study was to provide a proof of concept that fuel consumption and emission factors could be developed for urban emissions inventories in South Africa without intensive and costly dynamometer or on-board emissions measurement programmes. The objectives were thus: to develop a new fuel consumption and emissions simulation model based on engine-operating patterns developed from data published in Europe and adapted for South African driving conditions; to survey vehicle usage profiles and engine-operating patterns in the City of Johannesburg as a case study; and to integrate the model and survey data to demonstrate how these two sub-projects could be used to develop an emissions inventory for Johannesburg. The limitations are related both to the size of the sample of vehicle monitored in Johannesburg and the mismatch in the vehicle vintage and emissions controls in South Africa and Europe. A considerable set of local emissions measurements need to be executed based on the local fleet and driving conditions to validate to presented model.

5.1. Summary of findings

5.1.1. Emissions simulation model

A generic fuel consumption and emissions model based on engine-operating patterns was developed using details of real-world driving cycles, vehicle properties and emission factors from the Swiss Institute of Materials Science and Technology (EMPA) emissions testing programme. The model was validated and a sensitivity analysis was performed. The model provided good predictability in comparison to the Germany-Swiss-Austrian Handbook of Emission factors, which is used to develop national vehicle emissions inventories in Europe.

A sensitivity analysis of the new emissions simulation model showed that CO_2 and fuel consumption are sensitive to the input parameters in the following order: fuel type, engine speed, engine speed squared, a switch from Euro-0 to Euro-2 emissions regulation (for petrol vehicles), engine load, engine power and engine load squared. Pollutant emission (NO_x, CO, HC - hydrocarbons) are most sensitive to engine speed, engine speed squared, a switch from Euro-0 to Euro-2 emissions regulation, engine load, engine power and engine load squared. A shift from Euro-2 to Euro-3 emissions regulation had no significant effect on the emission factors with respect to the other input parameters. While fuel consumption and CO_2 emissions appear to decrease with emissions regulation this is not the case as emissions controls generally increase fuel consumption due to catalytic converters requiring richer air fuel ratios to operate at the correct temperatures. The improvements are primarily due to better aerodynamics and engine technologies implemented in the newer vehicles which also happen to have tighter emissions regulation compliance.

Analysis of the fuel consumption and emissions simulation model demonstrated the impact engine operation has on fuel consumption and emission factors. The analysis suggests that the most effective way to control vehicle emissions (and fuel consumption beyond fuel switching) from a technical perspective is to manage engine speed. Engine speed and engine load are both determined by driving conditions and driving styles. Driving conditions can be managed using traffic management techniques such as traffic light synchronisation and congestion management, while driving styles can be influenced by driver training and education to encourage less aggressive driving with earlier gear changes, for all vehicle capacity classes.

5.1.2. Travel behaviour and engine operation survey

A detailed travel and vehicle operation survey of vehicles used in their normal day-to-day journeys within the City of Johannesburg was performed to determine private vehicle usage profiles, proportions of different driving conditions and corresponding engine-operating patterns.

The survey used technologies available in newer vehicles, which allow engine operation to be monitored directly. This eliminated the need to estimate engine operation based on kinematics, properties of vehicles, auxiliary equipment use and road gradient. The simpler process of determining engine-operating patterns reduced the costs and complexity of developing an urban vehicle emissions inventory. Multiple surveys to determine local driving cycles, auxiliary equipment use, road gradient and gear change styles were not required because the total engine load was measured during the survey using on-board diagnostics (OBD).

Diurnal trip distributions and proportions of different driving conditions, in terms of road type and time of day, have been determined from the survey. Morning and evening commute periods experience the most congested traffic, with the morning commute being more intense but over a shorter period than the evening commute. Average speed and number of stops per kilometre, that influence emission rates, have also been determined for various road types and times of day.

An overall congestion index for the City of Johannesburg was developed for each hour of the day. The different proportions of road usage at different times of the day required separate indices for the different road types. To consider congestion in more detail an index was calculated for each road type and hour of the day. Corresponding fractions of total fuel consumption by fuel type and vehicle capacity class were derived and presented.

Distances travelled per annum for various vehicle fuel types and capacity classes were estimated from the survey data. Diesel vehicles and large capacity vehicles travel more per year than the other vehicle types. Larger capacity vehicles are used more on freeways than smaller capacity vehicles relative to the other road types.

Engine-operating patterns from the survey show that there is a larger variation in engine operation for smaller capacity vehicles. The engine-operating patterns showed a greater variation in engine speed and engine load during congested periods of the day.

The diesel vehicle sample was too small to categorise diesel vehicle activity with any certainty. Any future survey should include a larger fraction of diesel vehicles to ensure that the sample fairly represents the average vehicle by fuel type and capacity class.

5.1.3. Local fuel consumption and emission factors for an emissions inventory

Emission factors were developed for the local driving conditions and vehicle types using the engine-operating data from the survey and the fuel consumption and emissions simulation model.

Total fuel consumption and emissions were estimated for the City of Johannesburg based on the calculated local emission factors, distances travelled and proportions of driving conditions experienced by each fuel type and capacity class of vehicle in the survey and total fuel sales within the City.

The emissions inventory is dependant on data from the simulation model and the vehicle survey. Engine operating patterns measured from petrol vehicles in this study can be regarded as representative of actual engine operating patterns in Johannesburg. However, the emissions simulated from the engine operating patterns are dependant on the EMPA reference fleet which does not match the local fleet structure. Local emissions measurements for real world driving is needed to fill the gaps between the two fleets. Results for diesel vehicles should be treated with caution due to the small sample size.

5.2. Conclusions

This study involved the development of new methods including database applications for emissions simulation and integration of a diverse set of information to derive actual emission factors for the City of Johannesburg. These models realistically take into account the city topology, congestion, driving styles and fleet structure. The method is relatively cost effective in terms of equipment and human resource allocation required for the task compared to dynamometer and on-board emission measurement techniques currently in use in Europe and North America.

The emissions model was shown to provide better accuracy than the Germany-Swiss-Austrian Handbook of Emission factors with average absolute prediction errors of 21% for CO, 5% CO_2 and fuel consumption, 20% for HC and 21% for NO_x using a cross validation procedure.

The survey showed that the most congested period of the day is 0:7:00 – 0:800 followed by 17:00 – 18:00. The average speeds for the 07:00 – 08:00 interval are 43, 24 and 28 km h^{-1} for freeways, main roads and streets respectively. The average speeds for 17:00 – 18:00 are 52, 31 and 33 km h^{-1} for freeways, main roads and street respectively. For reference purposes, free flow speeds on the same road segments during non-congested periods are 95, 43 and 33 km h^{-1} respectively.

The survey also showed that petrol vehicles did an average of 19 200 km per year and the diesel vehicles did an average of 26 000 km per year. For both fuel types the > 2.0 ℓ capacity class travelled the most followed by the < 1.4 ℓ capacity class. The larger capacity vehicles used the freeways more than the other road types whereas the other capacity vehicles used main roads more than the other road types.

Emission factors simulated using the engine-operating patterns weighted according distances travelled per year, proportions of driving condiditions experienced, shares of engine capacities and emissions regulations in the vehicle population are summaried in Table 5.1.

Table 5.1: Average fuel consumption and emission factors by fuel type.

Parameter	Unit	Petrol	Diesel
Fuel cons.	ℓ/100 km	12.02	11.61
CO_2	g km^{-1}	269	306
CO	g km^{-1}	6.82	0.08
HC	g km^{-1}	0.75	0.04
NO_x	g km^{-1}	1.69	1.44
HC + NO_x	g km^{-1}	2.44	1.48

Results from the emissions inventory estimated that 15 billion vehicle kilometres were driven in Johannesburg by private passenger vehicles per year; total CO_2 emissions were 4.13 Mt; total CO emissions were 82.8 kt; HC emissions were 9.15 kt; and total NO_x emissions were 24.5 kt. These values are based on the structure of the fleet in terms of fuel type, capacity class, emissions regulation and the proportion of distances travelled by each vehicle type in the different driving conditions.

Total fuel consumption and emissions were disaggregated to consider the largest contributors to fuel consumption and emissions. Most of the pollutant emissions (82% of the NO_x, 88% of the CO and 93% of the HC) were from the older Euro-0 petrol vehicles, which were estimated to be 39% of the private passenger vehicle population. Almost half of the vehicular emissions were emitted on main roads. For weekdays between 27 and 30% of the pollutant emissions were emitted during the 06:30 – 09:00 period and another 26% were emitted during the 16:00 – 18:30 period.

This study has shown that it is possible to cost effectively produce an accurate emissions inventory by monitoring engine operating patterns of engine speed and engine load, and usage profiles of a group of vehicles using on-board diagnostics, Global Positioning system sensors and a fuel consumption and emissions simulation model.

5.3. Contribution

Effective transport, energy and environmental policies depend on the accurate assessment of vehicle fuel consumption and emissions. Underestimating emissions would place the health of citizens and the environment at risk whereas overestimating emissions might incur unnecessary economic burdens due to excessive emissions and fuel efficiency controls (TRB, 2000). There is, however, a trade off between accuracy and cost of acquiring accurate data. This study attempts to provide appropriate data to guide urban transport energy and emissions control policies at a low cost.

Original software tools were created, one implements a new fuel consumption and emissions simulation model and the other integrates simulated emission factors and vehicle activity from a survey of engine-operating patterns for local operating enviornments and driving styles in an emissions inventory model.

From this study, a new fuel consumption and emissions simulation model has been developed. The model allows for a simplified data collection process for the development of real-world emission factors by using engine-operating patterns, which can be measured directly using on-board diagnostics. The adaptation of fuel consumption and emission factors from emissions measurements made elsewhere were used as an alternative to performing physical emissions tests because of the high costs of conducting such tests.

The main significance of this study is that it provides an improved method of calculating local vehicle emissions inventories by taking into account the local operating environment, driving conditions and driving styles, without requiring extensive studies of different aspects of vehicle use. The new method makes use of modern electronic instruments such as on-board vehicle diagnostic data loggers and global positioning system receivers. Innovative use of these instruments has enabled the new method to incorporate relatively low cost surveys of a large number of vehicles, with low number of hours of effort.

The engine-operating patterns from the survey and the simulation model produced fuel consumption and emission factors for local driving conditions and driving styles for different types of vehicles. The survey also provides a private vehicle usage profile. Data from the survey was suitable to determine detailed driving cycles in Johannesburg. Driving cycles, however, do not provide all of the information needed to determine accurate real-world emission factors because they only represent the forward motion of the vehicle. Engine-operating patterns were developed as an alternative to driving cycles as they provide a means to consider all the engine loads including road gradient, auxiliary equipment use and driving styles. Although hot and cold start emissions were not considered in this study, the number of hot and cold starts can be determined from the data collected during the vehicle usage survey.

The final total emissions provide a set of emission factors, developed by considering local driving conditions, to replace the inappropriate emissions factors and emissions models currently considered by the authorities at City of Johannesburg in the cities mobile emissions inventory. The City of Johannesburg was considering using the average emissions factors from the South African Vehicle Emissions Project and the COPERT emissions factors for Euro-2 vehicles at the time of writing this thesis, but no definite average emissions factors were available from the city.

Overall, the method offers a complete solution from the monitoring of vehicles to the estimation of total emissions and a framework to build scenarios of different shares of vehicle fuel types, capacity classes and emissions regulations.

5.4. Limitations

This study was limited to a technical study of fuel consumption and emission factors for private passenger vehicles based on driving conditions and driving styles in the City of Johannesburg. While the new emissions simulation model is generic in nature because it is based on engine-operating patterns, its application within the novel emissions inventory model also developed here is specific to the City of Johannesburg. Additional surveys would need to be run to collect engine-operating patterns and vehicle usage profiles if the emissions inventory model were to be used for other cities

Simulation of the emission factors is dependant on the base engine-operating patterns developed from published data. The model is thus confined to simulate fuel consumption and emissions for a range of engine operations as a result of these studies. While the European vehicle fleet is a closer match to the South African vehicle fleet than many other countries with emissions factor databases, the EMPA data does not provide an exact match to the local vehicle fleet. This is particularly the case in terms of vehicle age and emissions regulation alignment. Extensive local emissions measurement programmes are needed to determine accurate local emissions factors and to develop local emissions estimation tools.

The current study did not consider the economic impacts of implementing certain emissions controls or driver training. The recently imposed emissions regulation (Euro-2) should result in an order of magnitude reduction in emissions factors for new vehicles at a relatively low cost. Further work should include a study of the economic instruments available to manage vehicle kilometres driven, fuel consumption and emissions factors such as higher fuel prices or greater investment in public transport.

Other modes of transport are significant in Johannesburg, particularly taxis and buses. This study did not consider these modes of transport.

Particulate matter was not included in this study. This was due to lack of source data to include it in the emissions simulation model.

5.5. Recommendations for further work

5.5.1. Emissions simulation model

The fuel consumption and emissions simulation model needs to be validated using actual emissions measurements made during real-world driving in Johannesburg. On-board emissions measurements would provide a suitable mechanism to perform such a validation because they directly measure the emissions due to all the loads imposed on engines of vehicles being used in their usual routines. The characterisation of local emissions factors is vital to producing reasonably accurate and appropriate emissions inventories in South African cities. Particulate matter should also be included in the emissions simulation and emissions inventory models as it is of particular health concern when considering the total ambient emissions in the city.

5.5.2. Measurement programmes and surveys

During this project, data were collected manually using four sets of equipment. The process thus only allowed for data collection from four vehicles at a time. The data collection can be enhanced by using telemetry via the cell phone network and a centralised database to automate the process. In this way, a larger sample of vehicles could be monitored continuously and access to the vehicle for manual data downloads would not be needed. This would allow emissions to be modelled in more detail and will provide a near real-time traffic monitoring tool.

Further research is needed to better determine diesel vehicle usage profiles and emissions factors, as the sample used in this study was too small and the differences between the EMPA reference fleet and the local vehicle fleet are too large.

5.5.3. Emissions inventory development

Further development of the proposed emissions inventory should allow scenarios to be developed by changing the structure of the vehicle fleet and the proportion of different driving conditions. Scenarios of vehicle fleet structure need to studied in terms of the proportions of fuel types, engine capacities and emissions regulations so that the impact of encouraging policies such as free bates and fuel pricing can be considered. Other scenarios may include various proportions of different driving conditions such that the implementation of congestion charging or shifting of working hours can be studied.

Accurate records of vehicle registrations are a prerequisite to the development of emissions inventories. Access to this information should be made available for research purposes. The South African National Department of Transport has an electronic national transport information system (eNATIS), which can provide valuable information in the modelling and assessment of fuel consumption and emissions if studies of this type were to have freely available access to it.

5.5.4. Software development

The software developed within this study was for research purposes and as such is more a set of program modules which were integrated using the authors information technology skills and knowledge of various computer programming tools. The applications developed here are thus subject to further development for user friendliness and usability before they can be used by city authorities.

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APPENDIX A: Driving Cycles from the EMPA Testing Programme

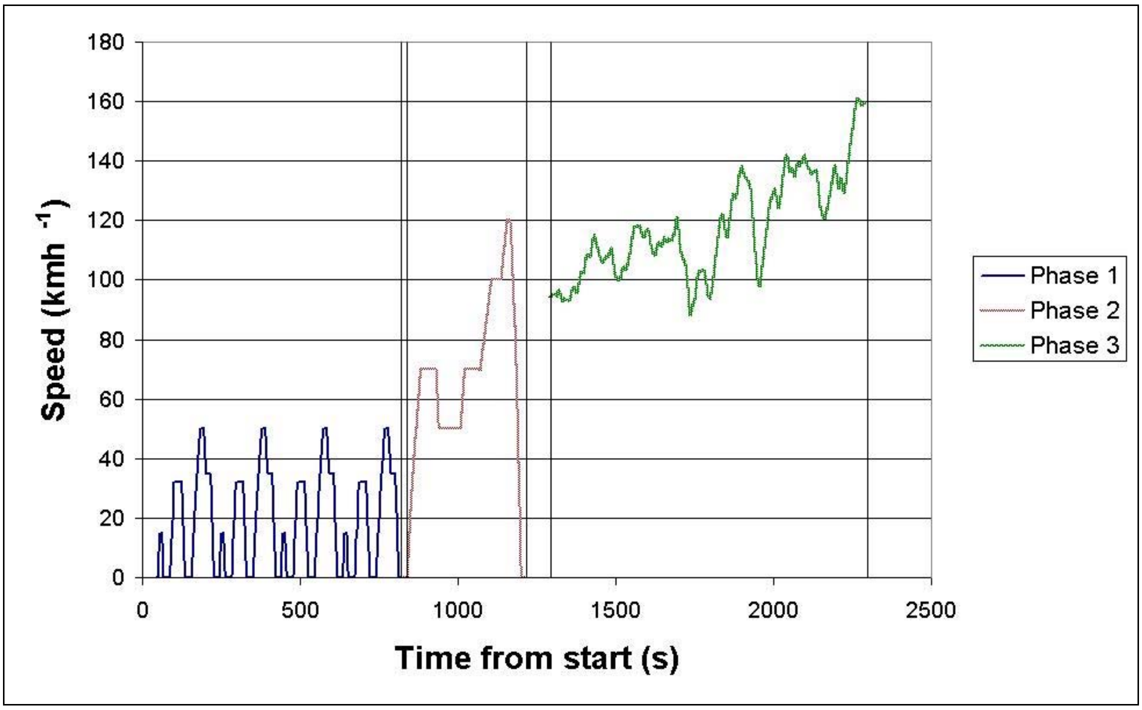


Figure A.1: **New European driving cycle (Phase 1 and 2) and the German autobahn cycle (Phase 3).**

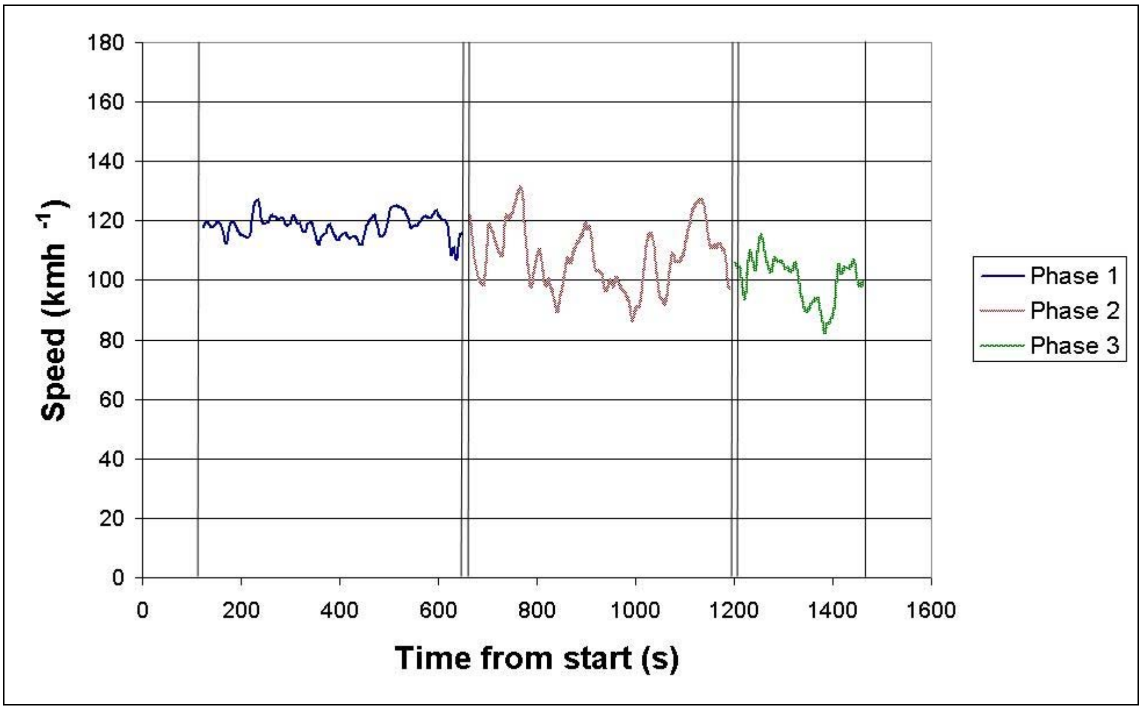


Figure A.2: **EMPA cycle R1 (speed profiles are only shown for the part of the cycle where emissions are sampled).**

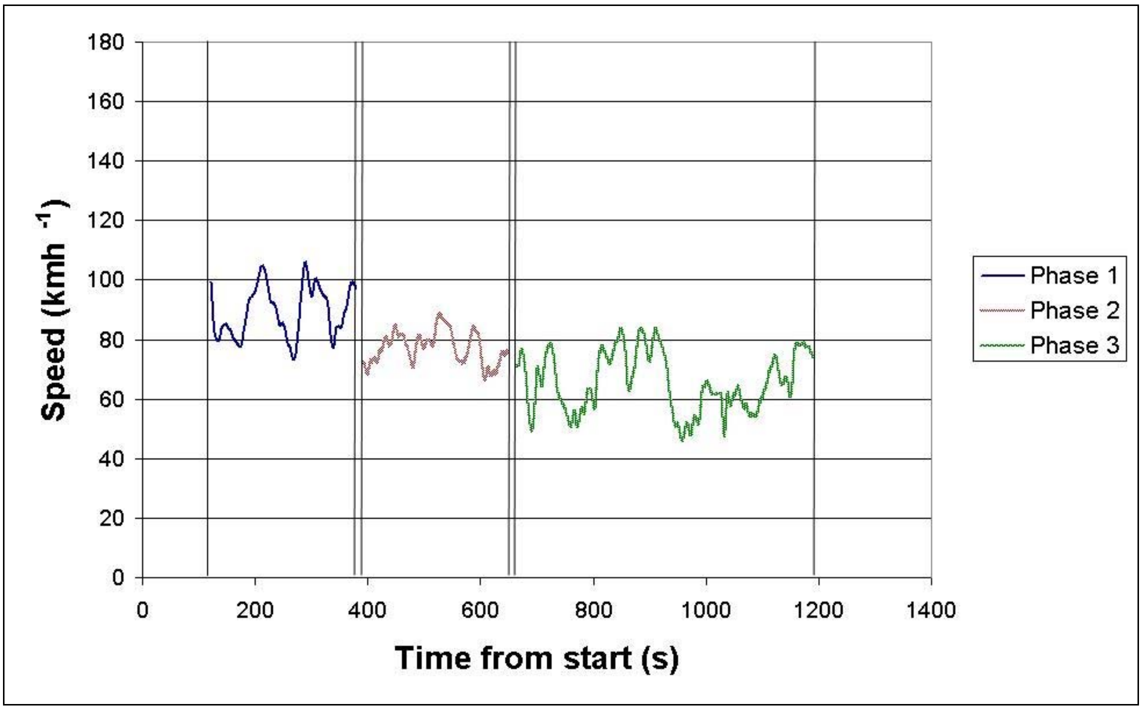


Figure A.3: EMPA cycle R2.

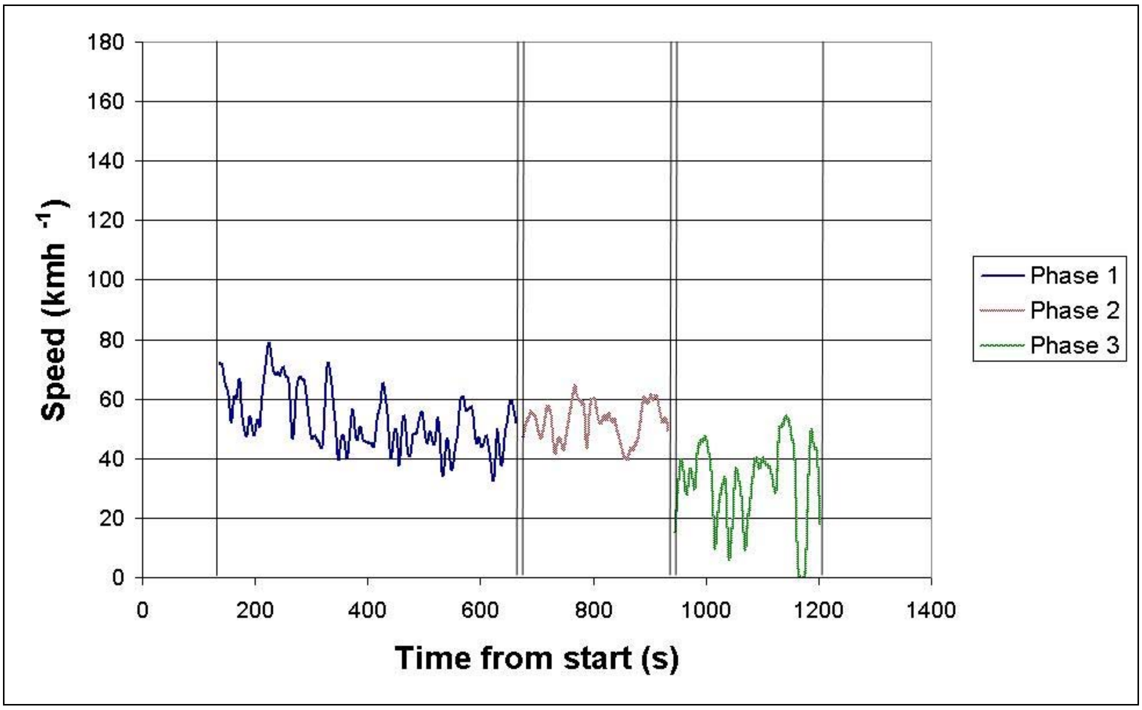


Figure A.4: EMPA cycle R3.

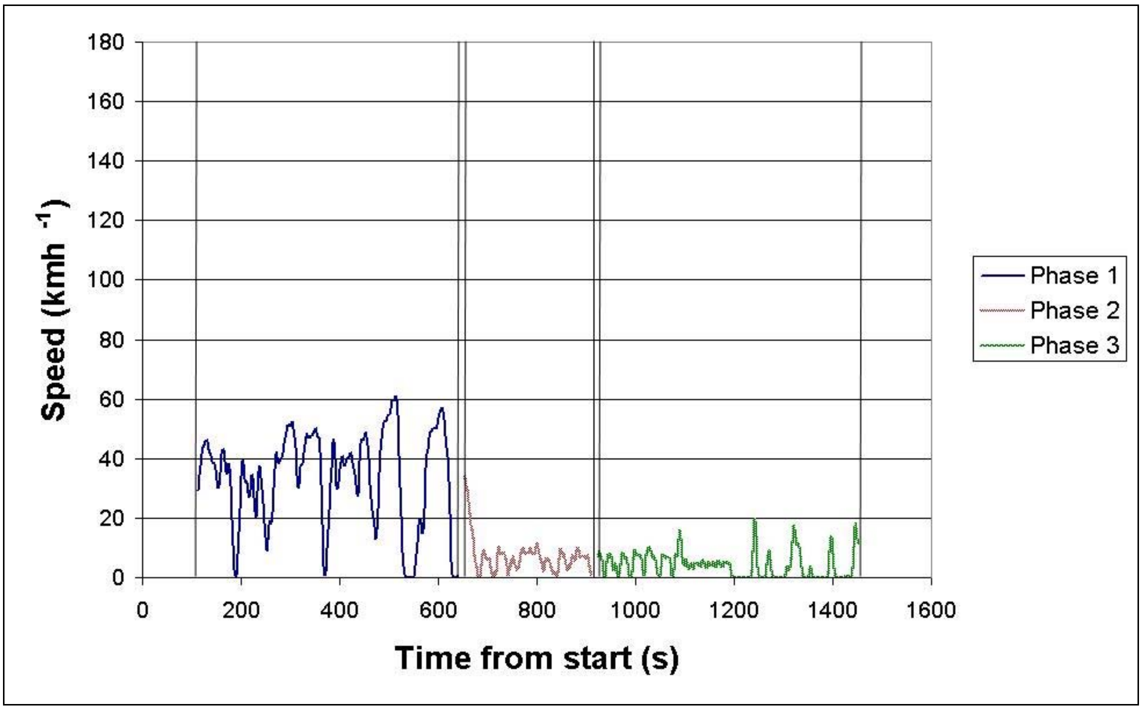


Figure A.5: EMPA cycle R4.

APPENDIX B: Vehicles from the EMPA Emissions Testing Programme

Table B.1: Vehicles from the EMPA emissions testing programme.

Fuel	Regulation	Make	Model	Model Year	Engine Capacity (CC)
Diesel	Euro-2	Alfa	156 2.4 JTD	1998	2 387
Diesel	Euro-2	Ford	Focus 1.8 TD	2000	1 753
Diesel	Euro-2	Mercedes	C 250 TD	1997	2 497
Diesel	Euro-2	Mitsubishi	Pajero 2.8 TDI	1999	2 835
Diesel	Euro-2	Opel	Zafira A 20 TD	1999	1 995
Diesel	Euro-2	Peugeot	406 1.9 DT	1997	1 905
Diesel	Euro-2	Seat	Ibiza GT TDI	1999	1 896
Diesel	Euro-2	VW	Passat	1997	1 896
Petrol	Euro-0	BMW	635 CSI	1985	3 430
Petrol	Euro-0	Fiat	Uno 45	1986	999
Petrol	Euro-0	Honda	Accord 2.0i Katalysator	1985	1 954
Petrol	Euro-0	Opel	Kadett D 1300	1984	1 296
Petrol	Euro-2	BMW	Z3	1997	1 796
Petrol	Euro-2	Ford	Ka 1.3	1997	1 299
Petrol	Euro-2	Ford	Mondeo 2	1997	1 988
Petrol	Euro-2	KIA	Pride 1.3	1997	1 324
Petrol	Euro-2	Mercedes	A 160	1998	1 598
Petrol	Euro-2	Mitsubishi	Charisma 1.8 GDI	1997	1 834
Petrol	Euro-2	Nissan	Terrano II 2.4	1997	2 389
Petrol	Euro-2	Porsche	Boxster	1997	2 480
Petrol	Euro-2	Renault	Twingo	1997	1 149
Petrol	Euro-2	Skoda	Felicia 1.3	1997	1 289
Petrol	Euro-2	Subaru	Impreza	1997	1 994
Petrol	Euro-2	VW	Polo	1997	1 390
Petrol	Euro-3	Alfa	147 2l TS 16V	2001	1 970
Petrol	Euro-3	Audi	A4	2001	1 781
Petrol	Euro-3	BMW	323 Ci	2000	2 494
Petrol	Euro-3	Chrysler	300M	2003	3 518
Petrol	Euro-3	Citroen	Xsara 1.4i	2001	1 360
Petrol	Euro-3	Daihatsu	YRV 1.3	2001	1 298
Petrol	Euro-3	Fiat	Punto 1.8 HGT	2000	1 747
Petrol	Euro-3	Ford	Focus 1.6 16V	2000	1 596
Petrol	Euro-3	Ford	Mondeo 2	2001	1 999
Petrol	Euro-3	Honda	Accord 2.0i VTEC	2000	1 997
Petrol	Euro-3	Hyundai	Accent 1.3 GS	2000	1 341
Petrol	Euro-3	Mazda	Demio	2001	1 498
Petrol	Euro-3	MCC	Smart	2000	599
Petrol	Euro-3	Mitsubishi	Galant 2.5 V6	2000	2 498
Petrol	Euro-3	Opel	Zafira 1.8 16V	2000	1 796
Petrol	Euro-3	Peugeot	206	2001	1 997
Petrol	Euro-3	Peugeot	306 1.8 16V	2001	1 762
Petrol	Euro-3	Renault	Mégane 1.6 16V	2001	1 598
Petrol	Euro-3	Renault	Megane Scenic 2	2001	1 998
Petrol	Euro-3	Toyota	Yaris 1	2000	998
Petrol	Euro-3	Volvo	S60	2002	2 435

APPENDIX C: Comparison of *MI* to *SDS*

The matching index *MI* was used in this study to quantify how similar two engine-operating patterns are to each other. The *MI* was designed in preference to the *SDS* (sum of differences squared) used in the development of the HBEFA. The reason for this is that the *SDS* does not clearly define the similarity between two patterns and in some cases can produce misleading results. This is demonstrated by comparing the two methods in the examples below:

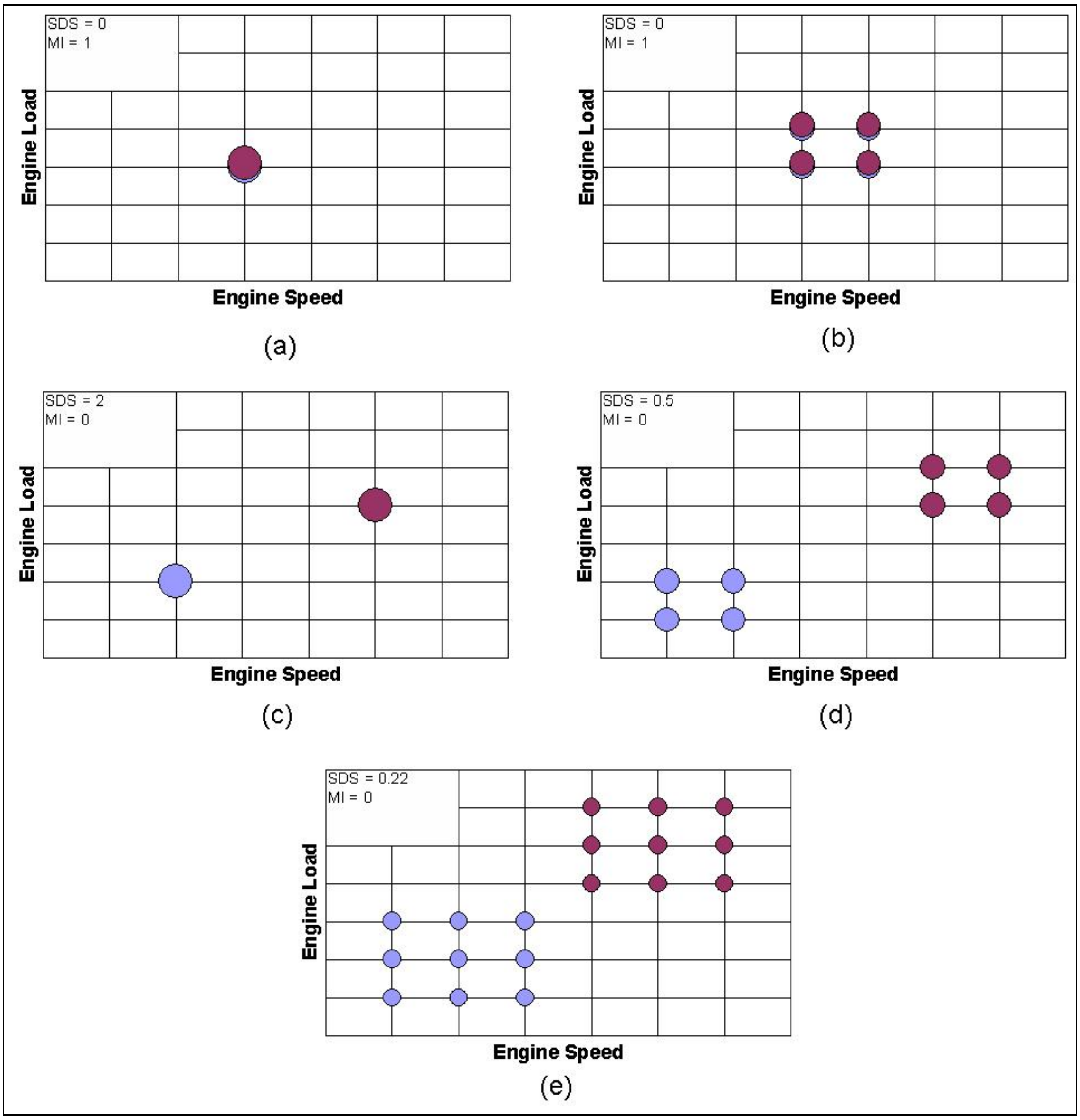


Figure C.1: Sum of differences squared and matching index comparison for exact match (a) and (b) and no intersection (c), (d) and (e).

When there is an exact match of two patterns as in Figure C.1 (a) and (b), the *SDS* is consistently zero and the *MI* is consistently one irrespective of the number of intervals (i.e. the number of bubbles in each pattern) that contain data. When there is no intersection between two patterns, as in (c), (d) and (e), the *MI* is always zero, but the *SDS* decreases with the number of intervals that have data. The significance of this is considered further in Figure C.2.

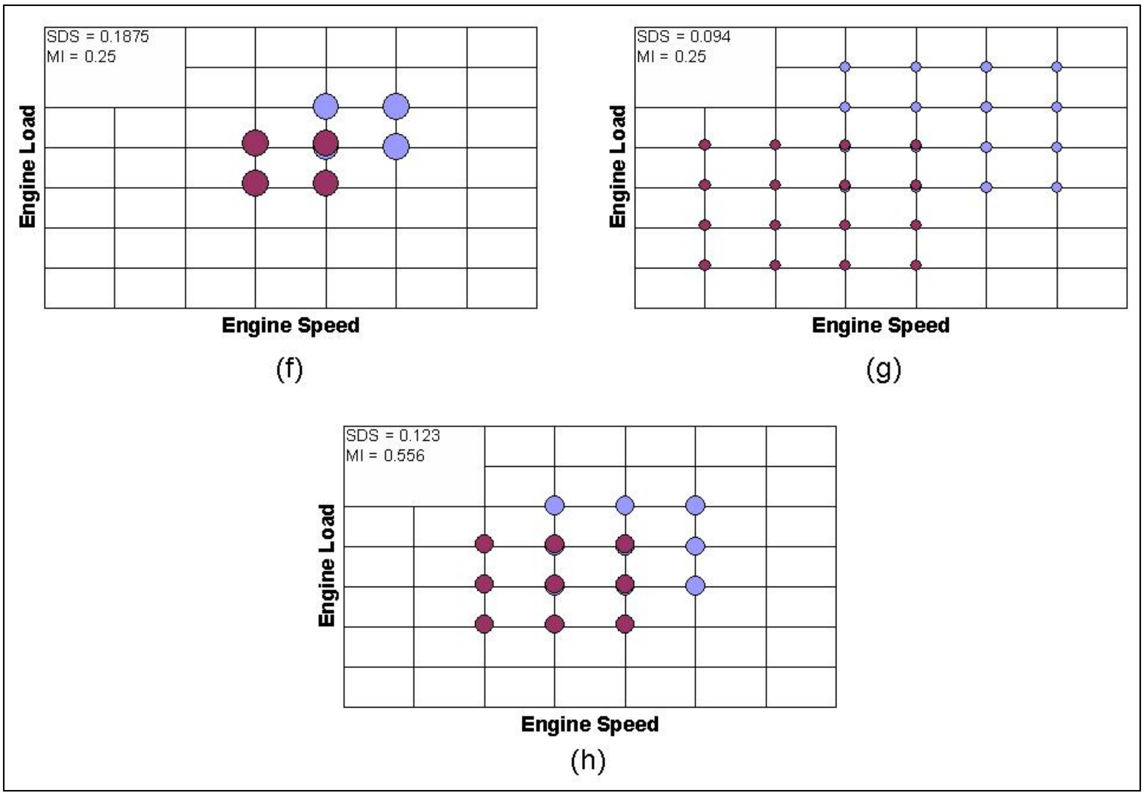


Figure C.2: Sum of differences squared and matching index comparison for partially matching patterns.

From Figure C.2 (f) and (g) have an equivalent overlap from a visual inspection. This is evaluated as a 25% overlap using the *MI* in both cases. The *SDS* method, however, indicates that the patterns in (g) have a better match than (f) due to the smaller *SDS*. The comparison in (h) has a better match (larger overlap) than both (f) and (g) but the *SDS* indicates that (g) is a better match, but we know this is not the case from a visual inspection of the figures.

In the de Haan and Keller (2004) method the minimum *SDS* value is used to find the best match of a new driving pattern to existing driving patterns. From the above analysis, this can produce incorrect results.

APPENDIX D: *Base* Engine-operating Patterns and Emission Factors

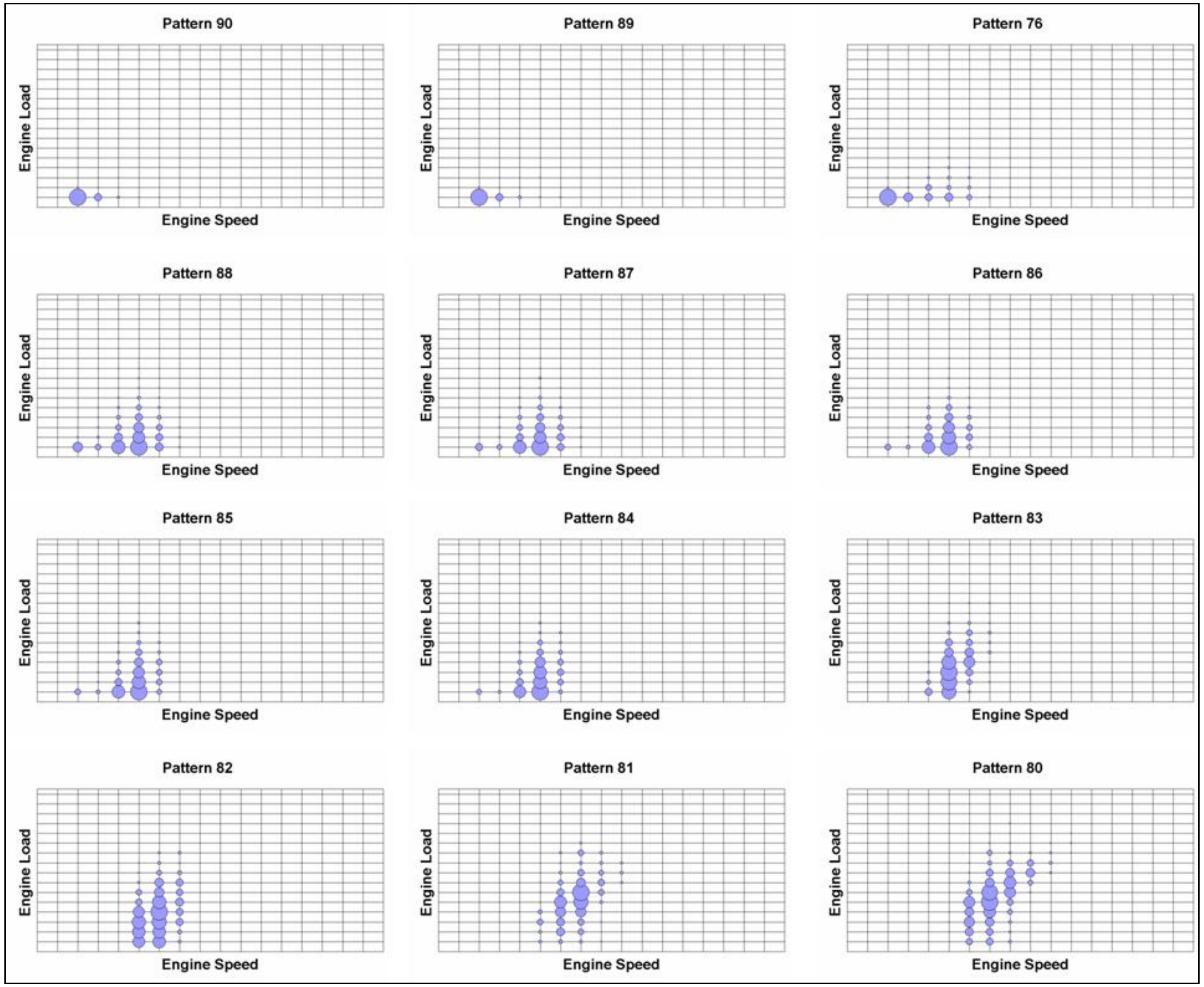


Figure D.1: ***Base*** **engine-operating patterns for Euro-0 petrol vehicles.**
(In all the figures and tables, the patterns are ordered in terms of increasing average specific power.)

Table D.1: Fuel consumption and emission factors for Euro-0 petrol *base* engine-operating patterns.

			Pattern ID											
Parameter	**Value**	**Unit**	**90**	**89**	**76**	**88**	**87**	**86**	**85**	**84**	**83**	**82**	**80**	**81**
Fuel cons.	Average value	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.15	0.17	0.25	0.34	0.37	0.37	0.39	0.41	0.57	0.64	1.14	1.24
	Standard deviation	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.03	0.05	0.10	0.11	0.15	0.13	0.14	0.16	0.23	0.25	0.35	0.48
	Standard error	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.01	0.02	0.03	0.03	0.04	0.04	0.04	0.05	0.09	0.10	0.16	0.24
	Number of patterns		7	8	12	14	13	12	13	12	6	6	5	4
CO_2	Average value	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.45	0.47	0.69	0.94	1.01	1.02	1.06	1.14	1.58	1.84	3.22	3.46
	Standard deviation	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.08	0.11	0.25	0.27	0.35	0.32	0.36	0.41	0.62	0.62	0.88	1.24
	Standard error	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.03	0.04	0.07	0.07	0.10	0.09	0.10	0.12	0.25	0.25	0.40	0.62
	Number of patterns		7	8	12	14	13	12	13	12	6	6	5	4
CO	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	10.79	16.13	36.08	47.93	54.31	56.44	55.86	61.76	79.74	72.39	132.79	167.12
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	8.71	14.49	31.03	43.18	62.62	53.42	46.63	56.21	69.74	92.31	130.78	170.62
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	3.29	5.12	8.96	11.54	17.37	15.42	12.93	16.23	28.47	37.68	58.49	85.31
	Number of patterns		7	8	12	14	13	12	13	12	6	6	5	4
HC	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	1.96	2.65	5.03	6.02	6.87	6.86	7.44	7.36	9.30	7.88	15.02	17.80
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	1.48	2.33	3.80	3.80	5.96	2.47	3.85	3.40	4.44	7.40	9.36	9.40
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.56	0.83	1.10	1.01	1.65	0.71	1.07	0.98	1.81	3.02	4.18	4.70
	Number of patterns		7	8	12	14	13	12	13	12	6	6	5	4
NO_x	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.69	0.78	2.33	5.15	5.64	6.80	7.66	8.47	17.39	20.53	53.28	53.52
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.18	0.26	1.50	2.84	2.76	3.86	4.41	4.81	8.22	12.60	27.98	19.03
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.07	0.09	0.43	0.76	0.76	1.11	1.22	1.39	3.35	5.14	12.51	9.51
	Number of patterns		7	8	12	14	13	12	13	12	6	6	5	4

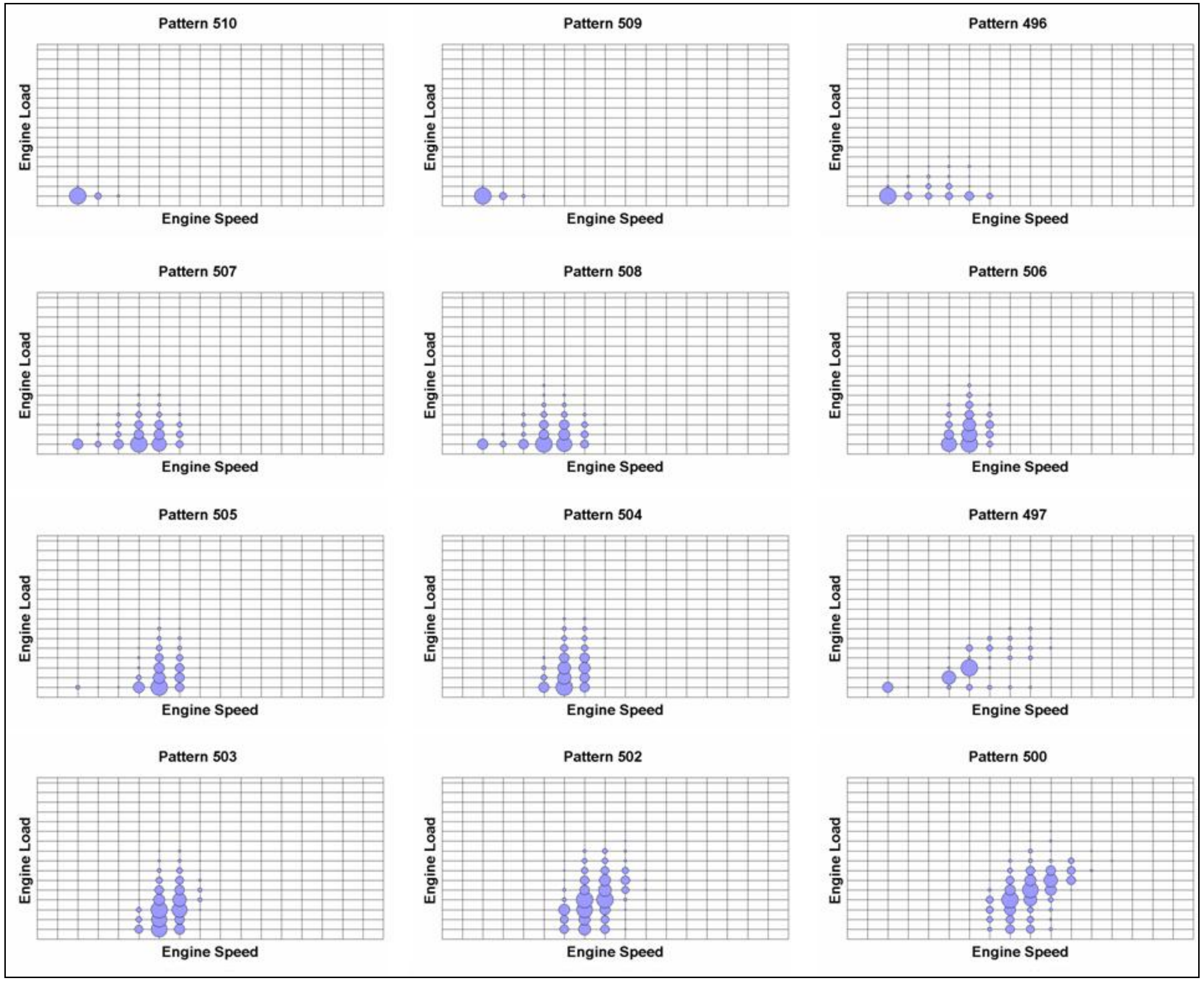

Pattern 510
Pattern 509
Pattern 496
Pattern 507
Pattern 508
Pattern 506
Pattern 505
Pattern 504
Pattern 497
Pattern 503
Pattern 502
Pattern 500

Figure D.2: *Base* engine-operating patterns for Euro-2 petrol vehicles.

Table D.2: Fuel consumption and emission factors for Euro-2 petrol *base* engine-operating patterns.

			Pattern ID											
Parameter	**Value**	**Unit**	**510**	**509**	**496**	**507**	**508**	**505**	**506**	**504**	**503**	**497**	**502**	**500**
Fuel cons.	Average value	g s^{-1} ℓ^{-1}	0.13	0.13	0.26	0.30	0.31	0.36	0.38	0.43	0.50	0.53	0.74	0.94
	Standard deviation	g s^{-1} ℓ^{-1}	0.02	0.02	0.02	0.03	0.04	0.06	0.05	0.11	0.13	0.05	0.13	0.19
	Standard error	g s^{-1} ℓ^{-1}	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.04	0.03	0.05	0.08
	Number of patterns		19	23	11	18	21	13	10	17	14	4	7	5
CO_2	Average value	g s^{-1} ℓ^{-1}	0.43	0.43	0.82	0.96	0.98	1.14	1.20	1.36	1.56	1.68	2.30	2.89
	Standard deviation	g s^{-1} ℓ^{-1}	0.05	0.05	0.07	0.11	0.12	0.20	0.17	0.35	0.41	0.20	0.42	0.57
	Standard error	g s^{-1} ℓ^{-1}	0.01	0.01	0.02	0.02	0.03	0.06	0.05	0.08	0.11	0.10	0.16	0.25
	Number of patterns		19	23	11	18	21	13	10	17	14	4	7	5
CO	Average value	mg s^{-1} ℓ^{-1}	1.84	1.83	9.25	4.38	4.79	5.94	8.44	6.31	4.84	14.78	18.04	27.61
	Standard deviation	mg s^{-1} ℓ^{-1}	2.60	2.39	4.65	4.16	5.80	5.98	10.73	8.28	7.75	24.46	15.48	36.08
	Standard error	mg s^{-1} ℓ^{-1}	0.60	0.50	1.40	0.98	1.27	1.66	3.39	2.01	2.07	12.23	5.85	16.13
	Number of patterns		19	23	11	18	21	13	10	17	14	4	7	5
HC	Average value	mg s^{-1} ℓ^{-1}	0.20	0.21	1.36	0.33	0.34	0.49	0.47	0.46	0.48	0.83	0.86	1.36
	Standard deviation	mg s^{-1} ℓ^{-1}	0.22	0.23	0.61	0.40	0.43	0.48	0.50	0.46	0.47	0.98	0.62	0.88
	Standard error	mg s^{-1} ℓ^{-1}	0.05	0.05	0.18	0.10	0.09	0.13	0.16	0.11	0.13	0.49	0.23	0.39
	Number of patterns		19	23	11	18	21	13	10	17	14	4	7	5
NO_x	Average value	mg s^{-1} ℓ^{-1}	0.11	0.12	0.77	0.65	0.63	0.99	0.79	1.19	1.55	0.68	0.94	2.49
	Standard deviation	mg s^{-1} ℓ^{-1}	0.14	0.15	0.26	0.77	0.73	1.02	1.00	1.23	1.69	0.89	1.26	3.31
	Standard error	mg s^{-1} ℓ^{-1}	0.03	0.03	0.08	0.18	0.16	0.28	0.32	0.30	0.45	0.45	0.48	1.48
	Number of patterns		19	23	11	18	21	13	10	17	14	4	7	5

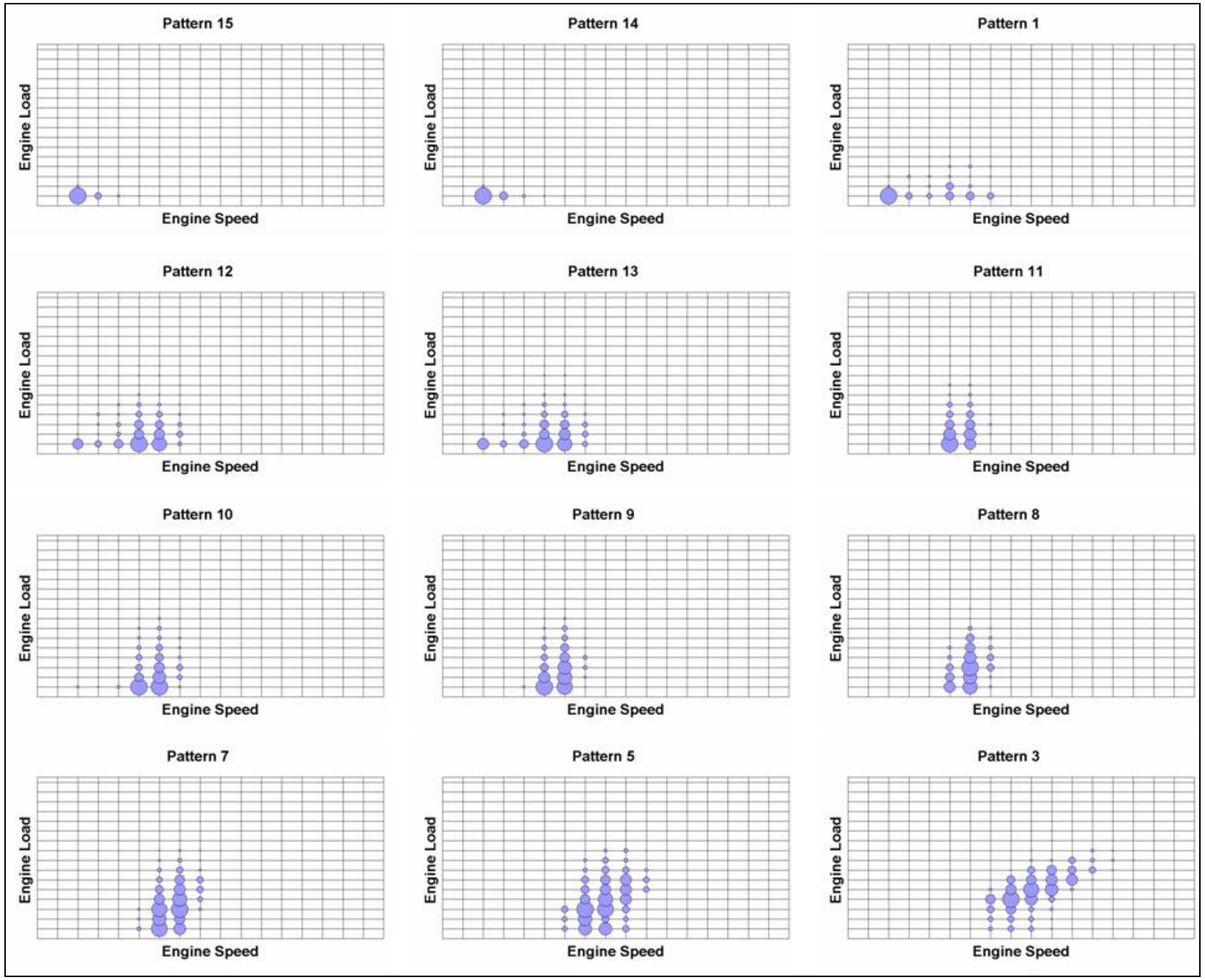


Figure D.3: ***Base*** **engine-operating patterns for Euro-3 petrol vehicles.**

Table D.3: Fuel consumption and emission factors for Euro-3 petrol *base* engine-operating patterns.

			Pattern ID											
Parameter	**Value**	**Unit**	**15**	**14**	**1**	**12**	**13**	**11**	**10**	**9**	**8**	**7**	**5**	**3**
Fuel cons.	Average value	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.12	0.13	0.25	0.29	0.29	0.34	0.34	0.37	0.45	0.53	0.70	0.98
	Standard deviation	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.09	0.10	0.05	0.11
	Standard error	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.02	0.04	0.03	0.02	0.06
	Number of patterns		33	39	14	20	21	7	15	15	6	12	7	4
CO_2	Average value	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.38	0.39	0.76	0.88	0.88	1.04	1.05	1.16	1.38	1.64	2.18	3.03
	Standard deviation	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.06	0.06	0.08	0.09	0.09	0.14	0.15	0.19	0.28	0.31	0.15	0.36
	Standard error	$\mathrm{g\ s^{-1}\ \ell^{-1}}$	0.01	0.01	0.02	0.02	0.02	0.05	0.04	0.05	0.11	0.09	0.06	0.18
	Number of patterns		33	39	14	20	21	7	15	15	6	12	7	4
CO	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.89	0.84	4.70	1.53	1.43	0.69	1.40	0.92	1.92	3.14	8.45	6.93
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	1.16	1.08	2.08	1.67	1.64	0.82	2.51	0.87	3.01	3.50	10.33	7.90
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.20	0.17	0.55	0.37	0.36	0.31	0.65	0.22	1.23	1.01	3.90	3.95
	Number of patterns		33	39	14	20	21	7	15	15	6	12	7	4
HC	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.05	0.05	0.66	0.03	0.03	0.05	0.05	0.06	0.08	0.08	0.19	0.17
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.10	0.09	0.24	0.02	0.02	0.05	0.06	0.08	0.12	0.15	0.28	0.05
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.02	0.02	0.06	0.00	0.00	0.02	0.01	0.02	0.05	0.05	0.11	0.03
	Number of patterns		32	38	14	20	20	7	15	15	5	11	7	4
NO_x	Average value	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.04	0.03	0.32	0.21	0.20	0.23	0.32	0.24	0.10	0.20	0.47	0.32
	Standard deviation	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.07	0.06	0.21	0.22	0.21	0.20	0.24	0.15	0.08	0.30	0.36	0.19
	Standard error	$\mathrm{mg\ s^{-1}\ \ell^{-1}}$	0.01	0.01	0.06	0.05	0.05	0.07	0.06	0.04	0.03	0.09	0.14	0.09
	Number of patterns		31	37	14	20	21	7	14	14	6	12	7	4

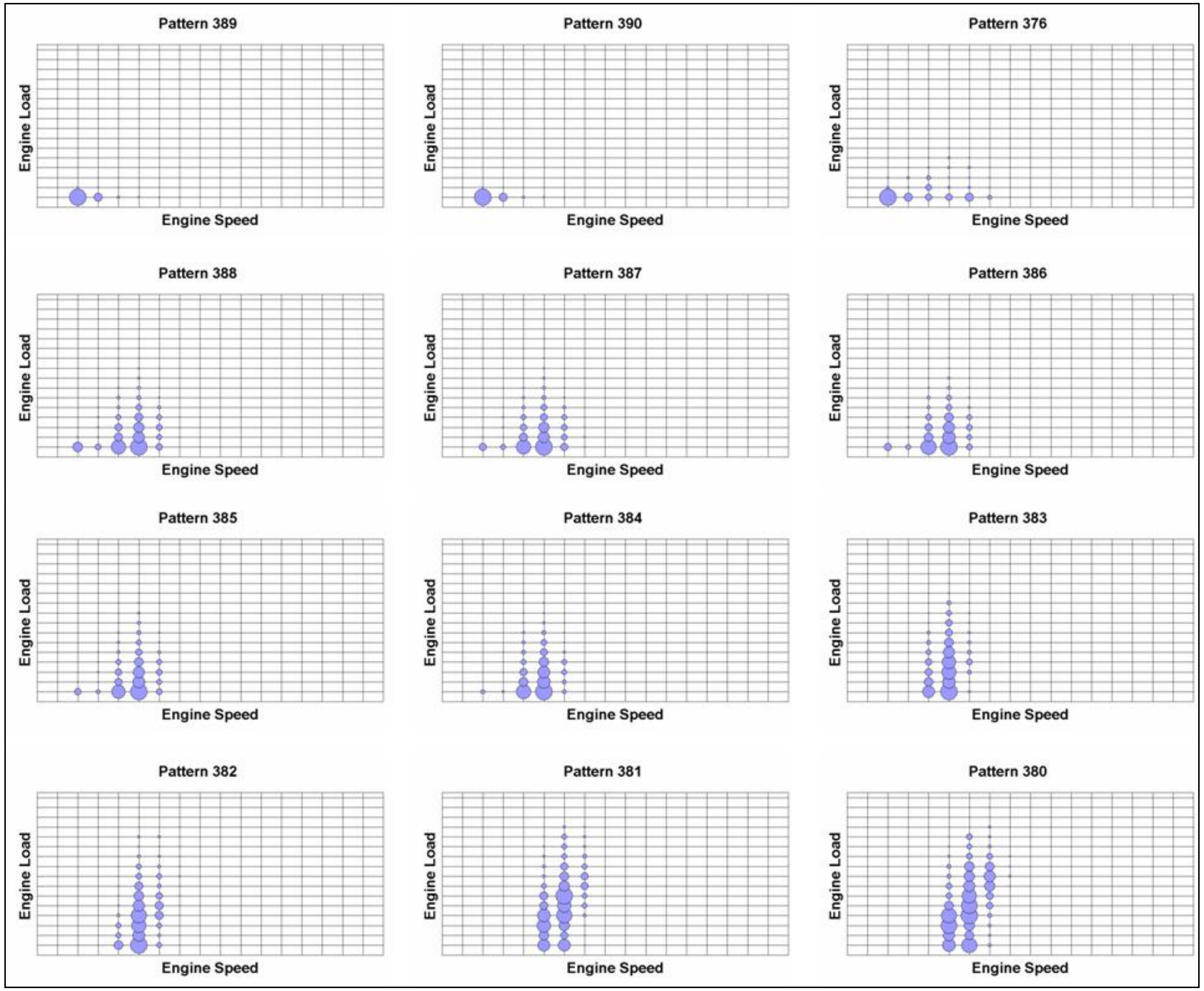


Figure D.4: *Base* engine-operating patterns for Euro-2 diesel vehicles.

Table D.4: Fuel consumption and emission factors for Euro-2 diesel *base* engine-operating patterns.

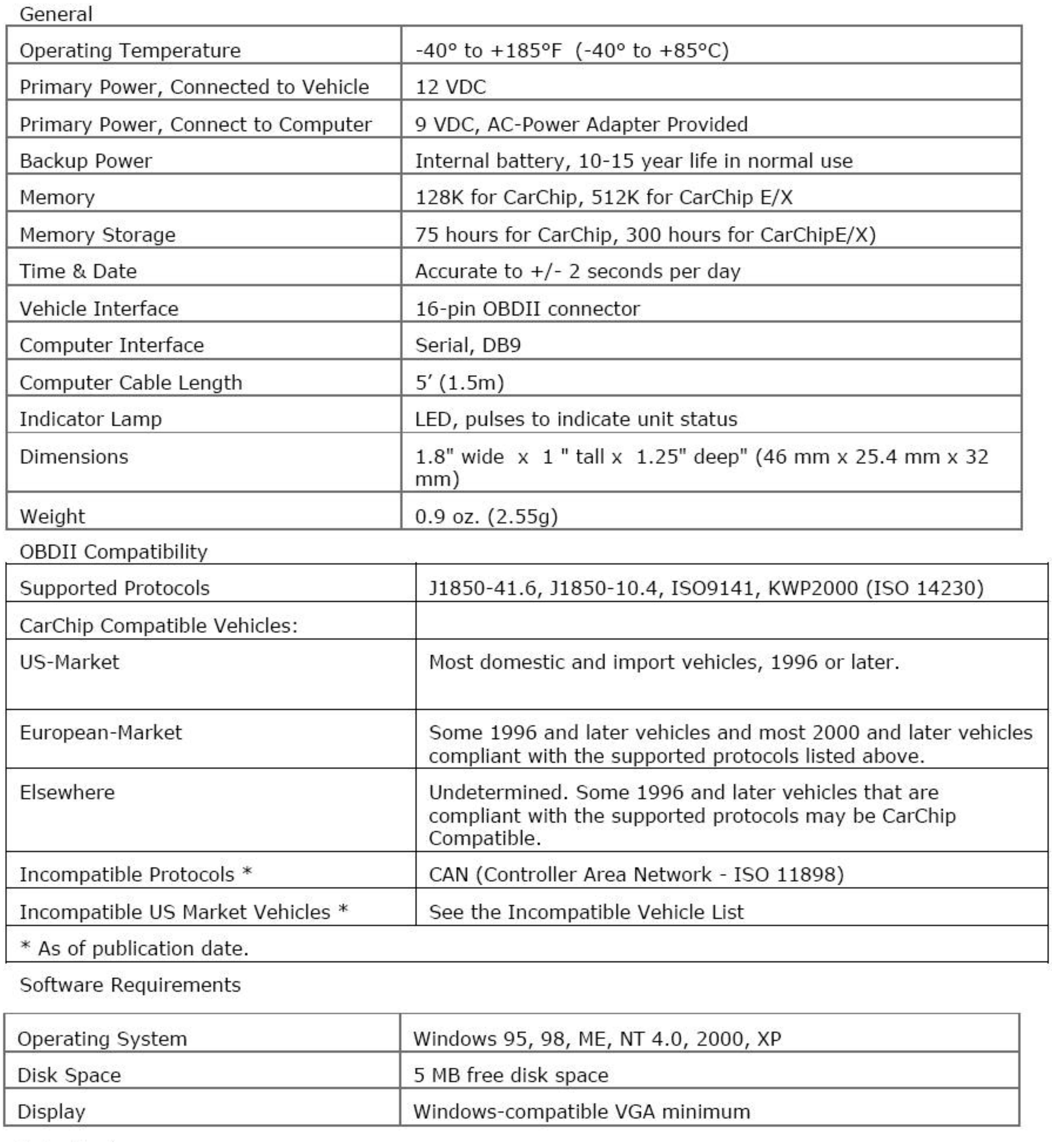
			Pattern ID											
Parameter	**Value**	**Unit**	**390**	**389**	**376**	**387**	**388**	**386**	**385**	**384**	**383**	**382**	**381**	**380**
Fuel cons.	Average value	$g\ s^{-1}\ \ell^{-1}$	0.09	0.09	0.17	0.22	0.23	0.23	0.24	0.25	0.30	0.36	0.50	0.54
	Standard deviation	$g\ s^{-1}\ \ell^{-1}$	0.01	0.01	0.04	0.03	0.03	0.03	0.04	0.03	0.05	0.09	0.07	0.14
	Standard error	$g\ s^{-1}\ \ell^{-1}$	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.07
	Number of patterns		13	13	8	18	18	17	21	10	5	9	4	4
CO_2	Average value	$g\ s^{-1}\ \ell^{-1}$	0.27	0.27	0.54	0.71	0.72	0.73	0.78	0.78	0.96	1.13	1.60	1.71
	Standard deviation	$g\ s^{-1}\ \ell^{-1}$	0.04	0.04	0.12	0.10	0.10	0.10	0.14	0.10	0.18	0.27	0.24	0.43
	Standard error	$g\ s^{-1}\ \ell^{-1}$	0.01	0.01	0.04	0.02	0.02	0.02	0.03	0.03	0.08	0.09	0.12	0.22
	Number of patterns		13	13	8	18	18	17	21	10	5	9	4	4
CO	Average value	$mg\ s^{-1}\ \ell^{-1}$	0.85	0.84	4.01	1.12	1.17	1.15	1.07	1.18	0.66	0.48	0.21	0.24
	Standard deviation	$mg\ s^{-1}\ \ell^{-1}$	0.35	0.36	2.27	0.59	0.59	0.57	0.62	0.58	0.55	0.45	0.18	0.18
	Standard error	$mg\ s^{-1}\ \ell^{-1}$	0.10	0.10	0.80	0.14	0.14	0.14	0.13	0.18	0.24	0.15	0.09	0.09
	Number of patterns		13	13	8	18	18	17	21	10	5	9	4	4
HC	Average value	$mg\ s^{-1}\ \ell^{-1}$	0.23	0.23	0.76	0.31	0.36	0.33	0.29	0.24	0.16	0.15	0.15	0.16
	Standard deviation	$mg\ s^{-1}\ \ell^{-1}$	0.13	0.13	0.39	0.14	0.20	0.13	0.15	0.10	0.10	0.09	0.09	0.10
	Standard error	$mg\ s^{-1}\ \ell^{-1}$	0.04	0.04	0.15	0.04	0.05	0.03	0.04	0.04	0.06	0.04	0.05	0.06
	Number of patterns		13	13	7	13	13	13	15	7	3	5	3	3
NO_x	Average value	$mg\ s^{-1}\ \ell^{-1}$	1.38	1.39	1.82	3.15	3.07	3.10	3.45	3.62	4.70	5.60	7.43	8.05
	Standard deviation	$mg\ s^{-1}\ \ell^{-1}$	0.35	0.34	0.64	1.20	1.28	1.34	1.38	1.38	0.87	0.85	0.20	1.42
	Standard error	$mg\ s^{-1}\ \ell^{-1}$	0.10	0.09	0.23	0.28	0.30	0.33	0.30	0.44	0.39	0.28	0.10	0.71
	Number of patterns		13	13	8	18	18	17	21	10	5	9	4	4

APPENDIX E: Vehicles Sampled During Survey

Table E.1: List of vehicles from survey

Fuel	Capacity class (ℓ)	Make	Model	Year
Diesel	< 1.4	Citroen	C3 Diesel 1.4	2005
Diesel	1.4 - 2.0	VW	Polo 1.9 TDI comfortline	2005
Diesel	1.4 - 2.0	VW	Polo 1.9 TDI sportline	2005
Diesel	> 2.0	Hyundai	Terracan	2006
Diesel	> 2.0	Nissan	Navara	2006
Petrol	< 1.4	Honda	140 cvt	2006
Petrol	< 1.4	Hyundai	Getz 1.3	2003
Petrol	< 1.4	Hyundai	Getz 1 400	2006
Petrol	< 1.4	Smart	SmartCar 600	2004
Petrol	< 1.4	Toyota	Corrola 140i	2004
Petrol	1.4 - 2.0	Ford	Focus 1.6	2006
Petrol	1.4 - 2.0	Honda	170i VTEC	2005
Petrol	1.4 - 2.0	Honda	170i VTEC	2005
Petrol	1.4 - 2.0	Mercedes	C180 kompressor	2006
Petrol	1.4 - 2.0	Mercedes	C200 kompressor	2005
Petrol	1.4 - 2.0	Toyota	Verso	2005
Petrol	1.4 - 2.0	Toyota	Verso	2006
Petrol	1.4 - 2.0	Volvo	S40 1.8i	2005
Petrol	1.4 - 2.0	VW	Polo 1.6 pet	2005
Petrol	1.4 - 2.0	VW	Polo 1.6 pet	2004
Petrol	1.4 - 2.0	VW	Polo 1.6 pet	2005
Petrol	1.4 - 2.0	VW	Polo 1.6 pet	2006
Petrol	1.4 - 2.0	VW	Polo 1.6 pet	2006
Petrol	> 2.0	BMW	325i	2006
Petrol	> 2.0	BMW	330i	2001
Petrol	> 2.0	BMW	530i	2005
Petrol	> 2.0	Mercedes	C230 V6	2005
Petrol	> 2.0	Volvo	S40 T5	2006
Petrol	> 2.0	Volvo	S80 T6	2001
Petrol	> 2.0	Volvo	V50	2006

APPENDIX F: CarChip OBDII Data Logger Specifications



General

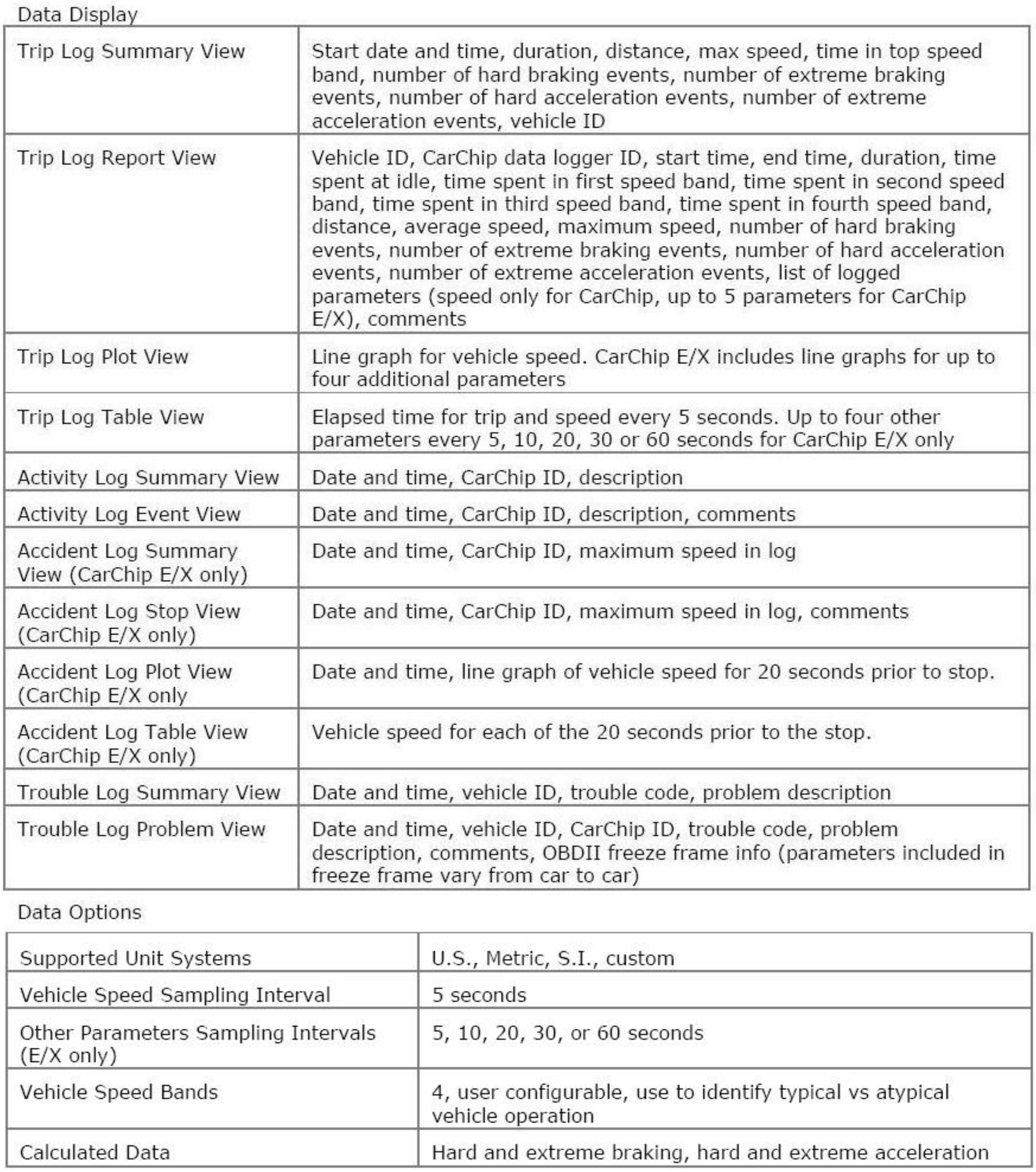
Operating Temperature	-40° to +185°F (-40° to +85°C)
Primary Power, Connected to Vehicle	12 VDC
Primary Power, Connect to Computer	9 VDC, AC-Power Adapter Provided
Backup Power	Internal battery, 10-15 year life in normal use
Memory	128K for CarChip, 512K for CarChip E/X
Memory Storage	75 hours for CarChip, 300 hours for CarChipE/X)
Time & Date	Accurate to +/- 2 seconds per day
Vehicle Interface	16-pin OBDII connector
Computer Interface	Serial, DB9
Computer Cable Length	5′ (1.5m)
Indicator Lamp	LED, pulses to indicate unit status
Dimensions	1.8" wide x 1 " tall x 1.25" deep" (46 mm x 25.4 mm x 32 mm)
Weight	0.9 oz. (2.55g)

OBDII Compatibility

Supported Protocols	J1850-41.6, J1850-10.4, ISO9141, KWP2000 (ISO 14230)
CarChip Compatible Vehicles:	
US-Market	Most domestic and import vehicles, 1996 or later.
European-Market	Some 1996 and later vehicles and most 2000 and later vehicles compliant with the supported protocols listed above.
Elsewhere	Undetermined. Some 1996 and later vehicles that are compliant with the supported protocols may be CarChip Compatible.
Incompatible Protocols *	CAN (Controller Area Network - ISO 11898)
Incompatible US Market Vehicles *	See the Incompatible Vehicle List
* As of publication date.	

Software Requirements

Operating System	Windows 95, 98, ME, NT 4.0, 2000, XP
Disk Space	5 MB free disk space
Display	Windows-compatible VGA minimum

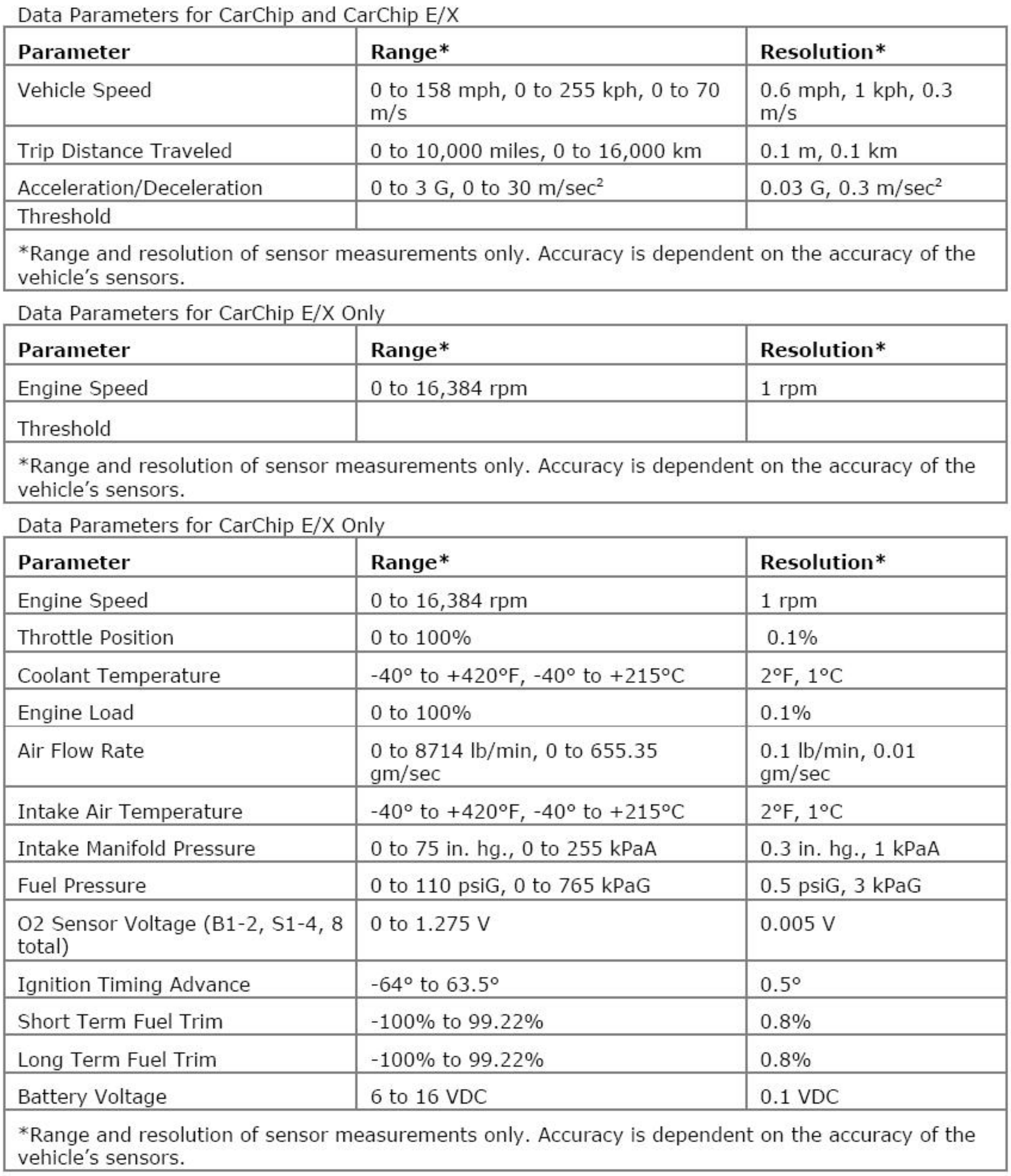


Data Display

Trip Log Summary View	Start date and time, duration, distance, max speed, time in top speed band, number of hard braking events, number of extreme braking events, number of hard acceleration events, number of extreme acceleration events, vehicle ID
Trip Log Report View	Vehicle ID, CarChip data logger ID, start time, end time, duration, time spent at idle, time spent in first speed band, time spent in second speed band, time spent in third speed band, time spent in fourth speed band, distance, average speed, maximum speed, number of hard braking events, number of extreme braking events, number of hard acceleration events, number of extreme acceleration events, list of logged parameters (speed only for CarChip, up to 5 parameters for CarChip E/X), comments
Trip Log Plot View	Line graph for vehicle speed. CarChip E/X includes line graphs for up to four additional parameters
Trip Log Table View	Elapsed time for trip and speed every 5 seconds. Up to four other parameters every 5, 10, 20, 30 or 60 seconds for CarChip E/X only
Activity Log Summary View	Date and time, CarChip ID, description
Activity Log Event View	Date and time, CarChip ID, description, comments
Accident Log Summary View (CarChip E/X only)	Date and time, CarChip ID, maximum speed in log
Accident Log Stop View (CarChip E/X only)	Date and time, CarChip ID, maximum speed in log, comments
Accident Log Plot View (CarChip E/X only	Date and time, line graph of vehicle speed for 20 seconds prior to stop.
Accident Log Table View (CarChip E/X only)	Vehicle speed for each of the 20 seconds prior to the stop.
Trouble Log Summary View	Date and time, vehicle ID, trouble code, problem description
Trouble Log Problem View	Date and time, vehicle ID, CarChip ID, trouble code, problem description, comments, OBDII freeze frame info (parameters included in freeze frame vary from car to car)

Data Options

Supported Unit Systems	U.S., Metric, S.I., custom
Vehicle Speed Sampling Interval	5 seconds
Other Parameters Sampling Intervals (E/X only)	5, 10, 20, 30, or 60 seconds
Vehicle Speed Bands	4, user configurable, use to identify typical vs atypical vehicle operation
Calculated Data	Hard and extreme braking, hard and extreme acceleration



Data Parameters for CarChip and CarChip E/X

Parameter	**Range***	**Resolution***
Vehicle Speed	0 to 158 mph, 0 to 255 kph, 0 to 70 m/s	0.6 mph, 1 kph, 0.3 m/s
Trip Distance Traveled	0 to 10,000 miles, 0 to 16,000 km	0.1 m, 0.1 km
Acceleration/Deceleration	0 to 3 G, 0 to 30 m/sec^2	0.03 G, 0.3 m/sec^2
Threshold		

*Range and resolution of sensor measurements only. Accuracy is dependent on the accuracy of the vehicle's sensors.

Data Parameters for CarChip E/X Only

Parameter	**Range***	**Resolution***
Engine Speed	0 to 16,384 rpm	1 rpm
Threshold		

*Range and resolution of sensor measurements only. Accuracy is dependent on the accuracy of the vehicle's sensors.

Data Parameters for CarChip E/X Only

Parameter	**Range***	**Resolution***
Engine Speed	0 to 16,384 rpm	1 rpm
Throttle Position	0 to 100%	0.1%
Coolant Temperature	-40° to +420°F, -40° to +215°C	2°F, 1°C
Engine Load	0 to 100%	0.1%
Air Flow Rate	0 to 8714 lb/min, 0 to 655.35 gm/sec	0.1 lb/min, 0.01 gm/sec
Intake Air Temperature	-40° to +420°F, -40° to +215°C	2°F, 1°C
Intake Manifold Pressure	0 to 75 in. hg., 0 to 255 kPaA	0.3 in. hg., 1 kPaA
Fuel Pressure	0 to 110 psiG, 0 to 765 kPaG	0.5 psiG, 3 kPaG
O2 Sensor Voltage (B1-2, S1-4, 8 total)	0 to 1.275 V	0.005 V
Ignition Timing Advance	-64° to 63.5°	0.5°
Short Term Fuel Trim	-100% to 99.22%	0.8%
Long Term Fuel Trim	-100% to 99.22%	0.8%
Battery Voltage	6 to 16 VDC	0.1 VDC

*Range and resolution of sensor measurements only. Accuracy is dependent on the accuracy of the vehicle's sensors.

APPENDIX G: Emissions simulation model table definitions

The fuel consumption and emissions simulation model uses the database tables defined in Figure G.1. The tables shown are for the specific application of the model to the collected survey data.

AverageMapsForRoadFuelClassPeriod holds the engine operating patterns from the travel survey.

BaseEngineMaps contains the definitions of the base engine-operating patterns i.e. it is the matrices of time spent in each engine speed and engine load interval for the base patterns.

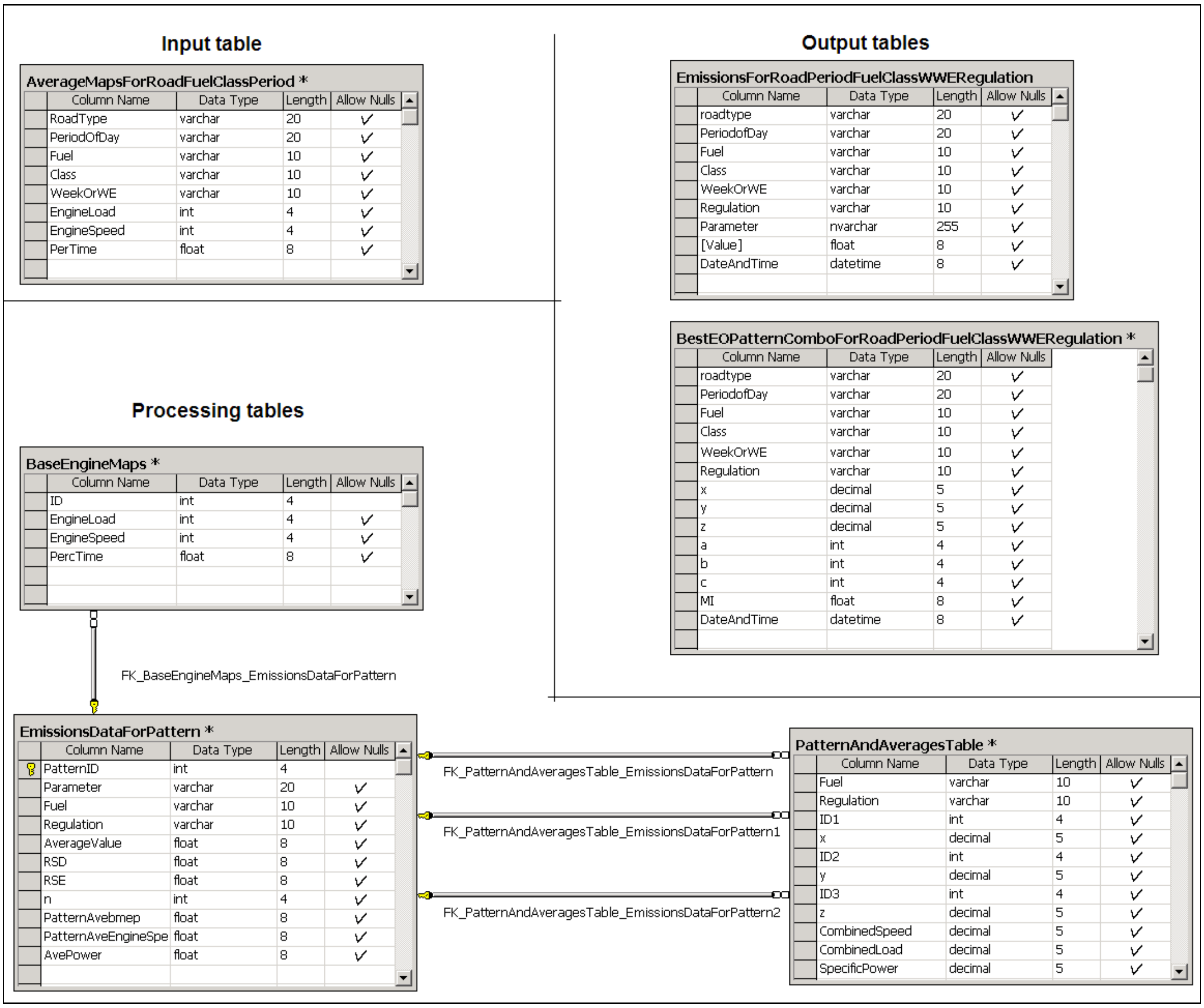
EmissionsDataForPattern contains the fuel consumption and emission factors for the base engine operating patterns.

PatternsAndAveragesTable contains the pre-calculated average engine speed, average engine load and specific power for all the possible linear combinations of base engine operating patterns for each fuel type and regulation pair.

EmissionsForRoadPeriodFuelClassWWERegulation contains the emissions factors for the given engine operating patterns.

BastEOPatternComboForRoadPeriodFuelClassWWERegulation holds the base engine operating pattern identifiers and their proportion for the simulated engine-operating patterns.

The Transact SQL code which uses these tables is given in APPENDIX H: *Transact SQL code for emissions simulation.*



Input table

AverageMapsForRoadFuelClassPeriod *

Column Name	Data Type	Length	Allow Nulls
RoadType	varchar	20	✓
PeriodOfDay	varchar	20	✓
Fuel	varchar	10	✓
Class	varchar	10	✓
WeekOrWE	varchar	10	✓
EngineLoad	int	4	✓
EngineSpeed	int	4	✓
PerTime	float	8	✓

Output tables

EmissionsForRoadPeriodFuelClassWWERegulation

Column Name	Data Type	Length	Allow Nulls
roadtype	varchar	20	✓
PeriodofDay	varchar	20	✓
Fuel	varchar	10	✓
Class	varchar	10	✓
WeekOrWE	varchar	10	✓
Regulation	varchar	10	✓
Parameter	nvarchar	255	✓
[Value]	float	8	✓
DateAndTime	datetime	8	✓

BestEOPatternComboForRoadPeriodFuelClassWWERegulation *

Column Name	Data Type	Length	Allow Nulls
roadtype	varchar	20	✓
PeriodofDay	varchar	20	✓
Fuel	varchar	10	✓
Class	varchar	10	✓
WeekOrWE	varchar	10	✓
Regulation	varchar	10	✓
x	decimal	5	✓
y	decimal	5	✓
z	decimal	5	✓
a	int	4	✓
b	int	4	✓
c	int	4	✓
MI	float	8	✓
DateAndTime	datetime	8	✓

Processing tables

BaseEngineMaps *

Column Name	Data Type	Length	Allow Nulls
ID	int	4	
EngineLoad	int	4	✓
EngineSpeed	int	4	✓
PercTime	float	8	✓

EmissionsDataForPattern *

Column Name	Data Type	Length	Allow Nulls
PatternID	int	4	
Parameter	varchar	20	✓
Fuel	varchar	10	✓
Regulation	varchar	10	✓
AverageValue	float	8	✓
RSD	float	8	✓
RSE	float	8	✓
n	int	4	✓
PatternAvebmep	float	8	✓
PatternAveEngineSpe	float	8	✓
AvePower	float	8	✓

PatternAndAveragesTable *

Column Name	Data Type	Length	Allow Nulls
Fuel	varchar	10	✓
Regulation	varchar	10	✓
ID1	int	4	✓
x	decimal	5	✓
ID2	int	4	✓
y	decimal	5	✓
ID3	int	4	✓
z	decimal	5	✓
CombinedSpeed	decimal	5	✓
CombinedLoad	decimal	5	✓
SpecificPower	decimal	5	✓

Figure G.1: Tables used during the simulation of fuel consumption and emission factors for engine operating patterns.

APPENDIX H: Transact SQL code for emissions simulation

Code for the following functions and stored procedures used in the emissions simulation is listed below:
LinearSumPatterns – calculates a aggregated engine-operating pattern from any three given base patterns and their linear combination.

MatchNewEOPatternToBasePatternsForPeriod – finds the closest linear combination of base engine-operating patterns to a new engine-operating pattern of the same fuel type and emissions regulation.

MatchBaseEOPatternToOtherBasePatterns – finds the closest linear combination of base engine-operating patterns to a specified base engine-operating pattern of the same fuel type and emissions regulation for validation.

ValidateEOPEmissionsFactors – loops through all the base patterns and calls MatchBaseEOPatternToOtherBasePatterns to validate all the base patterns.

LinearSumPatterns

```
CREATE      FUNCTION dbo.LinearSumPatterns(@x decimal(6,5), @y decimal(6,5),@z decimal(6,5),@ID1 int,@ID2 int,@ID3 int)
-- This function calculates an aggrate engine operating pattern from the linear combination of three base engine-operating patterns
RETURNS @SumBaseMaps table
(
EngineLoad  int,
EngineSpeed  int,
PercTime  decimal(6,5)
)
As
BEGIN

insert @SumBaseMaps
select SL.EngineLoad, SL.EngineSpeed,(@x*isnull(a.PercTime,0)+@y*isnull(b.PercTime,0)+@z*isnull(c.PercTime,0)) as PercTime
FROM SpeedLoadCrossJoin SL
left join [BaseEngineMaps] a on (a.id=@ID1 and SL.[EngineLoad] = a.[EngineLoad] and SL.[EngineSpeed] = a.[EngineSpeed])
left join [BaseEngineMaps] b on (b.id=@ID2 and SL.[EngineLoad] = b.[EngineLoad] and SL.[EngineSpeed] = b.[EngineSpeed])
left join [BaseEngineMaps] c on (c.id=@ID3 and SL.[EngineLoad] = c.[EngineLoad] and SL.[EngineSpeed] = c.[EngineSpeed])

RETURN

END
```

MatchNewEOPatternToBasePatternsForPeriod

```
 CREATE                 procedure MatchNewEOPatternToBasePatternsForPeriod
@RoadType varchar(20)= 'Main Road',
@PeriodofDay varchar(20) = '6:30-9:00',
@Fuel varchar(10)='Petrol',
@Class varchar(10)='<1400',
@Regulation varchar(10)='Euro-3',
@WeekOrWE varchar(10)='Weekday',
@x decimal(3,2) out,
@y decimal(3,2) out,
@z decimal(3,2) out,
@ID1 int out,
@ID2 int out,
@ID3 int out,
@MI float out
as

declare @counter int
declare @counter2 int
declare @counter3 int
declare @row int
declare @AveEngS decimal(5,3)
declare @AveEngL decimal(8,3)
declare @ClosestPatternID int

set @counter = 1
set @counter2 = 1
set @counter3 = 0

CREATE TABLE #temp(
	[x] [float] NULL ,
	[y] [float] NULL ,
	[z] [float] NULL ,
	[ID1] [int] NULL ,
	[ID2] [int] NULL ,
	[ID3] [int] NULL ,
	MI float)

-- Load the new Pattern into a temporary table (temp3)
select [EngineLoad], [EngineSpeed], Pertime as [PercTime]
into #temp3
from [AverageMapsForRoadFuelClassPeriod] a
where roadtype=@roadtype and PeriodofDay= @PeriodofDay and Fuel= @Fuel and Class= @Class and WeekOrWE = @WeekOrWE

-- find single best base pattern match
select b.id MatchingID, 1-sum(abs(a.PercTime-b.PercTime))/2 as MI
into #temp1
from
	(SELECT b.*, isnull(PercTime,0) PercTime
	FROM SpeedloadCrossJoin b
	LEFT join #temp3 a
	on (b.EngineLoad=a.engineload and b.EngineSpeed=a.EngineSpeed)) a
inner join
	(SELECT c.*, b.*, isnull(PercTime,0) PercTime
	FROM BasePatternsAverages c cross join SpeedloadCrossJoin b
	LEFT join [DrivingCycles].[dbo].[BaseEngineMaps] a
	on (a.ID =c.ID and b.EngineLoad=a.engineload and b.EngineSpeed=a.EngineSpeed)) b
on a.EngineLoad=b.engineload and a.EngineSpeed=b.EngineSpeed
where b.fuel = @Fuel and b.regulation = @Regulation
Group by b.id

select top 1 @ClosestPatternID = MatchingID from #temp1
order by MI desc

-- find the closest 1000 combination of patterns
SELECT top 1000
abs(a.CombinedSpeed*a.CombinedLoad - b.AveEngineLoad*b.AveEngineSpeed) SP,
case [x] when 0 then [ID2] else [ID1] end as ID1, [x],
case [y] when 0 then [ID3] else [ID2] end as ID2, [y],
case [z] when 0 then [ID1] else [ID3] end as ID3, [z] into #temp2
FROM [DrivingCycles].[dbo].[PatternAndAveragesTable] a
inner join AveSpeedDOWPODRoadFuelClass b on a.Fuel = b.Fuel
where a.Fuel = @fuel and a.regulation = @regulation
```

```
and ([ID1] = @ClosestPatternID or [ID2] = @ClosestPatternID or [ID3]= @ClosestPatternID)
and b.class = @Class and b.WeekOrWe = @WeekOrWe and b.RoadType = @Roadtype and b.Periodofday = @Periodofday
order by abs(a.CombinedSpeed*a.CombinedLoad - b.AveEngineLoad*b.AveEngineSpeed)

create clustered index pkid on #temp2 (ID1,ID2,ID3)

-- Loop through the combinations of basemaps that have similar averages to the considered map and calculate the MI
insert into #temp(x,y,z,ID1,ID2,ID3,MI)
select x,y,z,ID1,ID2,ID3,1-sum(abs(isnull(d.PercTime,0)-(x*isnull(a.PercTime,0)+y*isnull(b.PercTime,0)+z*isnull(c.PercTime,0))))/2
MI
FROM #temp2 cross join SpeedLoadCrossJoin SL
left join [BaseEngineMaps] a on (a.id=#temp2.ID1 and SL.[EngineLoad] = a.[EngineLoad] and SL.[EngineSpeed] = a.[EngineSpeed])
left join [BaseEngineMaps] b on (b.id=#temp2.ID2 and SL.[EngineLoad] = b.[EngineLoad] and SL.[EngineSpeed] = b.[EngineSpeed])
left join [BaseEngineMaps] c on (c.id=#temp2.ID3 and SL.[EngineLoad] = c.[EngineLoad] and SL.[EngineSpeed] = c.[EngineSpeed])
left join #temp3 d on d.[EngineLoad] = sl.[EngineLoad] and d.[EngineSpeed]=sl.[EngineSpeed]
group by x,y,z,ID1,ID2,ID3

-- Find minimum MI
Select top 1 @x=x,@y=y,@z=z,@ID1=ID1,@ID2=ID2,@ID3=ID3,@MI=MI
from #Temp
order by MI desc

drop table #Temp
drop table #Temp1
drop table #Temp2
drop table #Temp3

-- Store combination summary
-- NOTE: if no match is found previous data is written to table!!

INSERT INTO [DrivingCycles].[dbo].[BestEOPatternComboForRoadPeriodFuelClassWWERegulation]([roadtype], [PeriodofDay],
[Fuel], [Class], [WeekOrWE], [Regulation], [x], [y], [z], [a], [b], [c], [MI], [DateAndTime])
Select @roadtype , @PeriodofDay  , @Fuel  , @Class  , @WeekOrWE  , @Regulation  , @x,@y,@z,@ID1,@ID2,@ID3,@MI,
getdate()

-- store ouput combination pattern
INSERT INTO [DrivingCycles].[dbo].[BestEOPatternForRoadPeriodFuelClassWWERegulation]([roadtype], [PeriodofDay], [Fuel],
[Class], [WeekOrWE], [Regulation], [EngineLoad], [EngineSpeed], [PercTime], [DateAndTime])
select @roadtype, @PeriodofDay, @Fuel, @Class, @WeekOrWE, @Regulation, [EngineLoad], [EngineSpeed], sum([PercTime]),
getdate()
from
(SELECT [ID], [EngineLoad], [EngineSpeed],
case
when ID=@ID1 then @x*[PercTime]
when ID=@ID2 then @y*[PercTime]
when ID=@ID3 then @z*[PercTime]
end as [PercTime]
FROM [DrivingCycles].[dbo].[BaseEngineMaps]
where ID in (@ID1,@ID2,@ID3)) a
group by [EngineLoad], [EngineSpeed]

--Calculate emissions and fc for new pattern
INSERT INTO [DrivingCycles].[dbo].[EmissionsForRoadPeriodFuelClassWWERegulation]([roadtype], [PeriodofDay], [Fuel], [Class],
[WeekOrWE], [Regulation], [Parameter], [Value], [DateAndTime])
select @roadtype, @PeriodofDay, @Fuel, @Class, @WeekOrWE, @Regulation, a.Parameter, a.Value+b.Value+c.Value, getdate()
from
(Select Parameter, AverageValue*@x as Value from
EmissionsDataForPattern
where PatternID = @ID1) a
inner join
(Select Parameter, AverageValue*@y as Value from
EmissionsDataForPattern
where PatternID = @ID2) b on a.Parameter = b.Parameter
inner join
(Select Parameter, AverageValue*@z as Value from
EmissionsDataForPattern
where PatternID = @ID3) c on a.Parameter = c.Parameter
```

MatchBaseEOPatternToOtherBasePatterns

```
CREATE   procedure MatchBaseEOPatternToOtherBasePatterns
@PatternID int,
@Fuel varchar(10),
@Regulation varchar(10),
@x decimal(3,2) out,
@y decimal(3,2) out,
@z decimal(3,2) out,
@ID1 int out,
@ID2 int out,
@ID3 int out,
@MI float out
as

declare @counter int
declare @counter2 int
declare @counter3 int
declare @row int
declare @AveEngS decimal(5,3)
declare @AveEngL decimal(8,3)
declare @ClosestPatternID int

set @counter = 1
set @counter2 = 1
set @counter3 = 0

CREATE TABLE #temp(
        [x] [float] NULL ,
        [y] [float] NULL ,
        [z] [float] NULL ,
        [ID1] [int] NULL ,
        [ID2] [int] NULL ,
        [ID3] [int] NULL ,
        MI float)

-- Load the base Pattern into a temporary table (temp3)
select [EngineLoad], [EngineSpeed], Perctime as [PercTime]
into #temp3
from [BaseEngineMaps]
where ID = @PatternID

-- find single best base pattern match
select identity(int,1,1) RowID, a.id, b.id MatchingID, 1-sum(abs(a.PercTime-b.PercTime))/2 as MI into #temp1
from
        (SELECT c.ID, c.Fuel, c.Regulation, b.*, isnull(PercTime,0) PercTime
        FROM BasePatternsAverages c cross join SpeedloadCrossJoin b
        LEFT join [DrivingCycles].[dbo].[BaseEngineMaps] a
        on (a.ID =c.ID and b.EngineLoad=a.engineload and b.EngineSpeed=a.EngineSpeed)) a
inner join
        (SELECT c.ID, c.Fuel, c.Regulation, b.*, isnull(PercTime,0) PercTime
        FROM BasePatternsAverages c cross join SpeedloadCrossJoin b
        LEFT join [DrivingCycles].[dbo].[BaseEngineMaps] a
        on (a.ID =c.ID and b.EngineLoad=a.engineload and b.EngineSpeed=a.EngineSpeed)) b
on a.ID = @PatternID and a.ID!=b.ID and a.Fuel = b.Fuel and a.Regulation = b.regulation
        and a.EngineLoad=b.engineload and a.EngineSpeed=b.EngineSpeed
group by a.id, b.id

select top 1 @ClosestPatternID = MatchingID from #temp1
order by MI desc

-- find the closest 100 combination of patterns
SELECT distinct top 500
abs(a.CombinedSpeed*a.CombinedLoad - b.AveSpeed*b.AveLoad) SP,
case [x] when 0 then [ID2] else [ID1] end as ID1, [x],
case [y] when 0 then [ID3] else [ID2] end as ID2, [y],
case [z] when 0 then [ID1] else [ID3] end as ID3, [z] into #temp2
FROM [DrivingCycles].[dbo].[PatternAndAveragesTable] a
inner join BasePatternsAverages b on b.ID = @PatternID
and a.Fuel = b.Fuel and a.regulation = b.regulation
where ([ID1] = @ClosestPatternID or [ID2] = @ClosestPatternID or [ID3]= @ClosestPatternID) and
([ID1] != @PatternID and [ID2] != @PatternID and [ID3] != @PatternID)
order by abs(a.CombinedSpeed*a.CombinedLoad - b.AveSpeed*b.AveLoad)
```

```
create clustered index pkid on #temp2 (ID1,ID2,ID3)

-- Loop through the combinations of basemaps that have similar averages to the considered base map and calculate the MI
insert into #temp(x,y,z,ID1,ID2,ID3,MI)
select x,y,z,ID1,ID2,ID3,1-sum(abs(isnull(d.PercTime,0)-(x*isnull(a.PercTime,0)+y*isnull(b.PercTime,0)+z*isnull(c.PercTime,0))))/2
FROM #temp2 cross join SpeedLoadCrossJoin SL
left join [BaseEngineMaps] a on (a.id=#temp2.ID1 and SL.[EngineLoad] = a.[EngineLoad] and SL.[EngineSpeed] = a.[EngineSpeed])
left join [BaseEngineMaps] b on (b.id=#temp2.ID2 and SL.[EngineLoad] = b.[EngineLoad] and SL.[EngineSpeed] = b.[EngineSpeed])
left join [BaseEngineMaps] c on (c.id=#temp2.ID3 and SL.[EngineLoad] = c.[EngineLoad] and SL.[EngineSpeed] = c.[EngineSpeed])
left join #temp3 d on d.[EngineLoad] = sl.[EngineLoad] and d.[EngineSpeed]=sl.[EngineSpeed]
group by x,y,z,ID1,ID2,ID3

-- Find minimum MI
Select top 1 @x=x,@y=y,@z=z,@ID1=ID1,@ID2=ID2,@ID3=ID3,@MI=MI
from #Temp
order by MI desc

drop table #Temp
drop table #Temp1
drop table #Temp2
drop table #Temp3

-- Store combination summary
-- NOTE: if no match is found previous data is written to table!!

INSERT INTO [DrivingCycles].[dbo].[BestEOPatternComboForValidation](PatternID, [x], [y], [z], [a], [b], [c], [MI], [DateAndTime])
Select @PatternID, @x,@y,@z,@ID1,@ID2,@ID3,@MI, getdate()
--Select @PatternID PatternID, @x x,@y y,@z z,@ID1 a,@ID2 b,@ID3 c ,@MI MI, getdate() DateAndTime into
BestEOPatternComboForValidation

-- store ouput combination pattern
INSERT INTO [DrivingCycles].[dbo].[BestEOPatternForValidation](PatternID, [EngineLoad], [EngineSpeed], [PercTime],
[DateAndTime])
select @PatternID, [EngineLoad], [EngineSpeed], sum([PercTime]), getdate()
--select @PatternID PatternID, [EngineLoad], [EngineSpeed], sum([PercTime]) PercTime, getdate() DateAndTime into
BestEOPatternForValidation
from
(SELECT [ID], [EngineLoad], [EngineSpeed],
case
when ID=@ID1 then @x*[PercTime]
when ID=@ID2 then @y*[PercTime]
when ID=@ID3 then @z*[PercTime]
end as [PercTime]
FROM [DrivingCycles].[dbo].[BaseEngineMaps]
where ID in (@ID1,@ID2,@ID3)) a
group by [EngineLoad], [EngineSpeed]

--Calculate emissions and fc for new pattern
INSERT INTO [DrivingCycles].[dbo].[EOEmissionsForValidation](PatternID, [Parameter], [Value], [DateAndTime])
select @PatternID, a.Parameter, a.Value+b.Value+c.Value, getdate()
--select @PatternID PatternID, a.Parameter, a.Value+b.Value+c.Value value, getdate() DateAndTime into EOEmissionsForValidation
from
(Select Parameter, AverageValue*@x as Value from
EmissionsDataForPattern
where PatternID = @ID1) a
inner join
(Select Parameter, AverageValue*@y as Value from
EmissionsDataForPattern
where PatternID = @ID2) b on a.Parameter = b.Parameter
inner join
(Select Parameter, AverageValue*@z as Value from
EmissionsDataForPattern
where PatternID = @ID3) c on a.Parameter = c.Parameter
```

ValidateEOPEmissionsFactors

```
CREATE   procedure ValidateEOPEmissionsFactors
as

DECLARE @RC int
DECLARE @PatternID int
DECLARE @Fuel varchar(10)
DECLARE @Regulation varchar(10)
DECLARE @x decimal(3,2)
DECLARE @y decimal(3,2)
DECLARE @z decimal(3,2)
DECLARE @ID1 int
DECLARE @ID2 int
DECLARE @ID3 int
DECLARE @MI float

declare Combos Cursor fast_forward for
SELECT distinct [PatternID], [Fuel], [Regulation]
FROM [DrivingCycles].[dbo].[EmissionsDataForPattern]

OPEN Combos

FETCH NEXT FROM Combos
INTO @PatternID, @Fuel, @Regulation

WHILE @@FETCH_STATUS = 0
BEGIN

EXEC @RC = [DrivingCycles].[dbo].[MatchBaseEOPatternToOtherBasePatterns] @PatternID, @Fuel, @Regulation, @x OUTPUT ,
@y OUTPUT , @z OUTPUT , @ID1 OUTPUT , @ID2 OUTPUT , @ID3 OUTPUT , @MI OUTPUT

   -- Get the next map.
   FETCH NEXT FROM Combos
           INTO @PatternID, @Fuel, @Regulation

END

CLOSE Combos
DEALLOCATE Combos
```

APPENDIX I: Emissions Model Validation

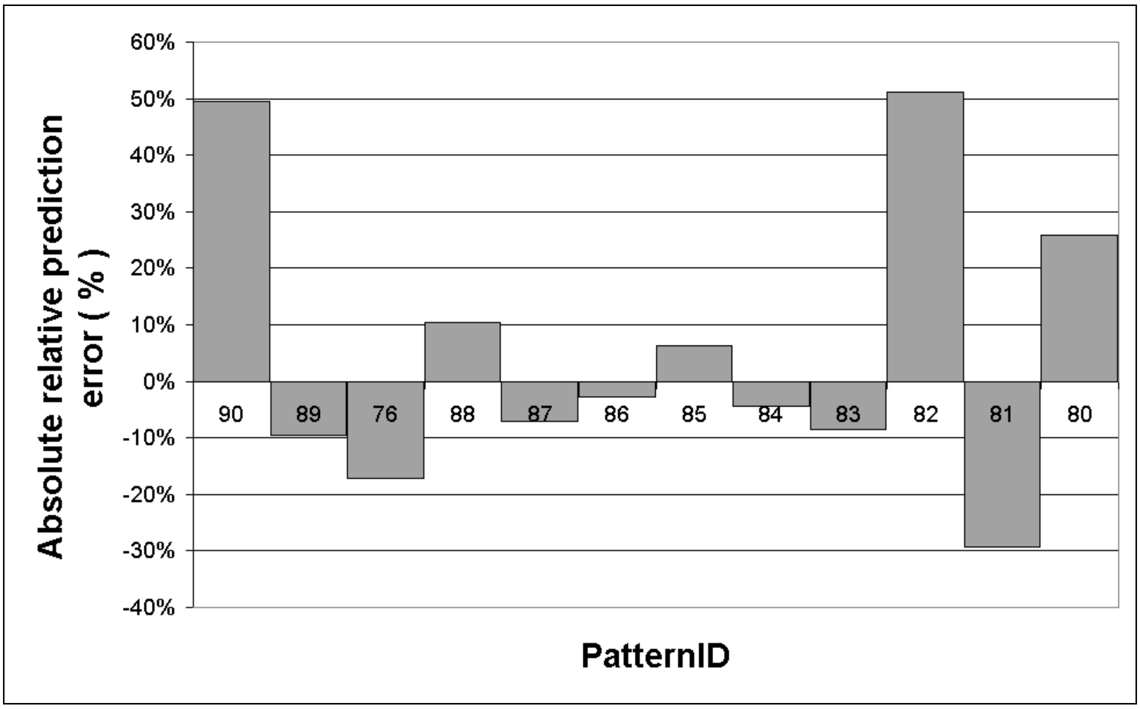


Figure I.1: Relative prediction error of CO for Euro-0 petrol vehicles.

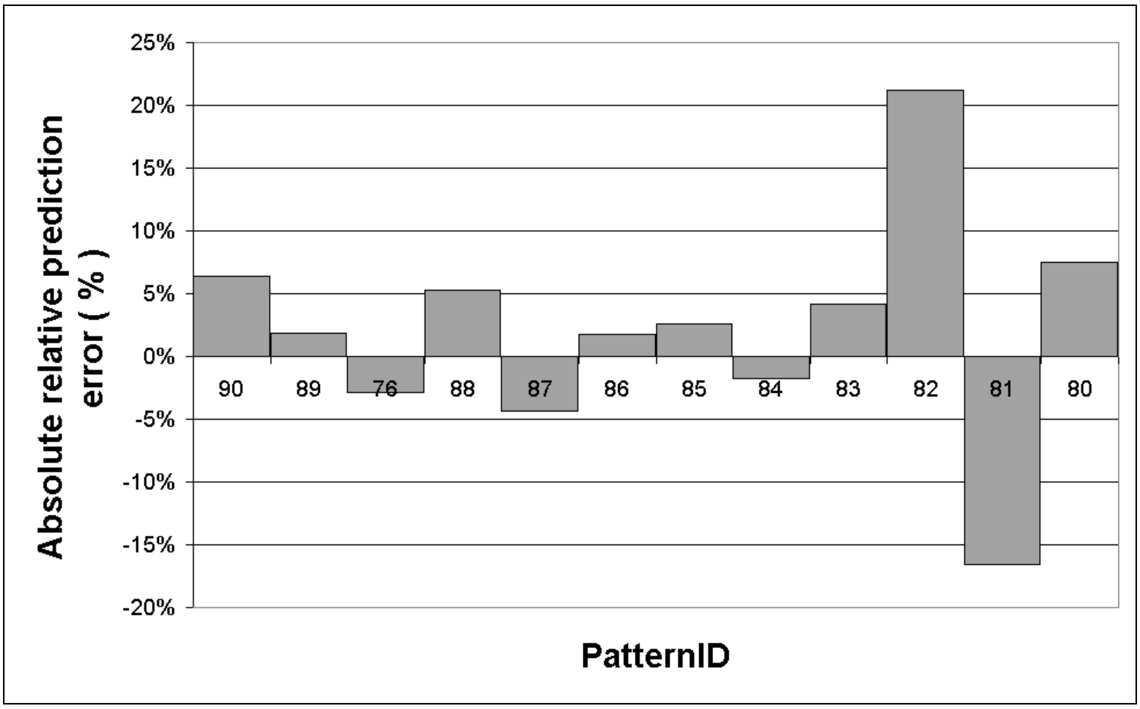


Figure I.2: Relative prediction error of CO_2 for Euro-0 petrol vehicles.

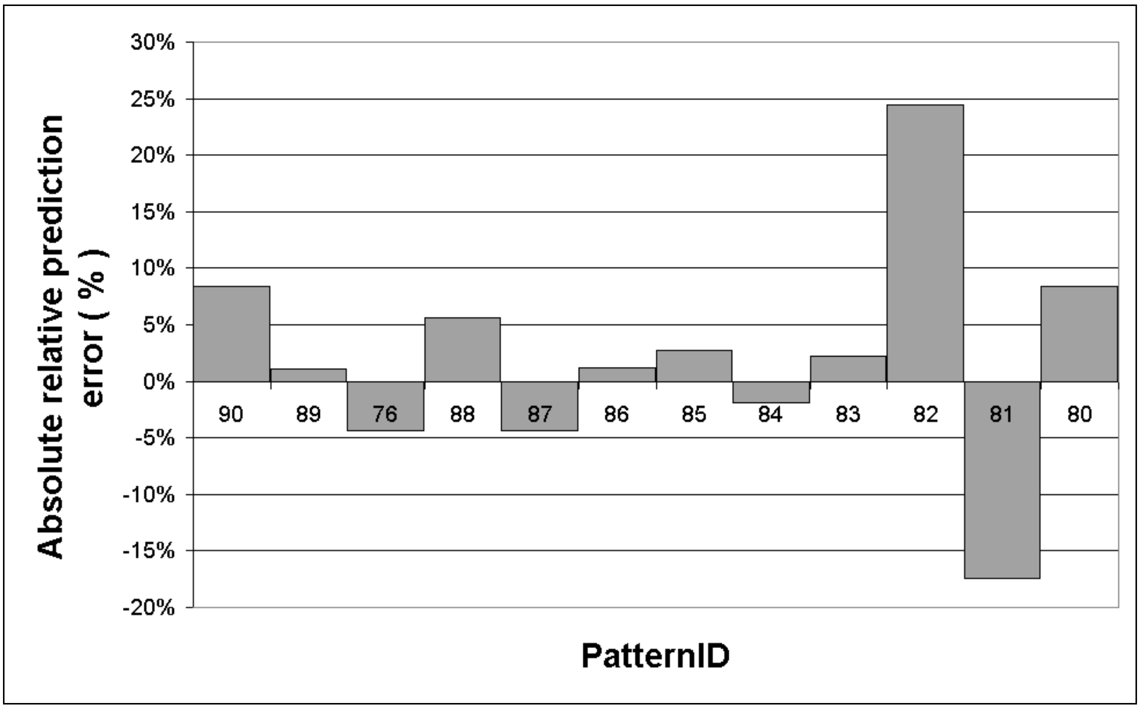


Figure I.3: **Relative prediction error of fuel consumption for Euro-0 petrol vehicles.**

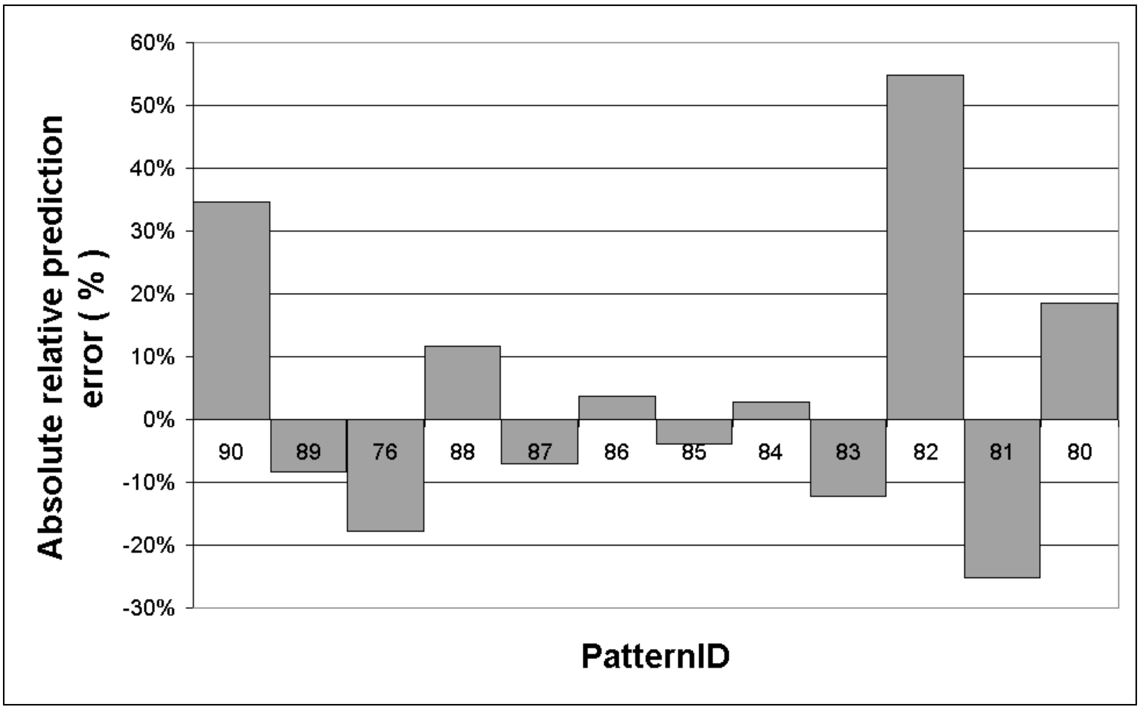


Figure I.4: **Relative prediction error of HC for Euro-0 petrol vehicles.**

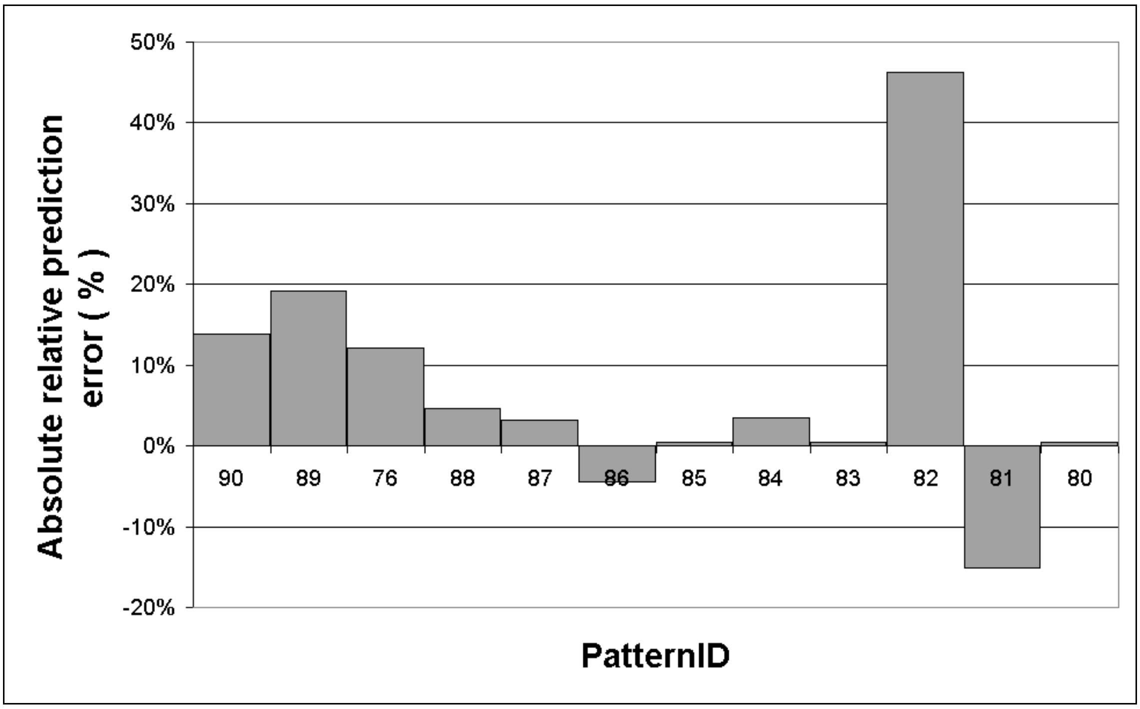


Figure I.5: Relative prediction error of NO_x for Euro-0 petrol vehicles.

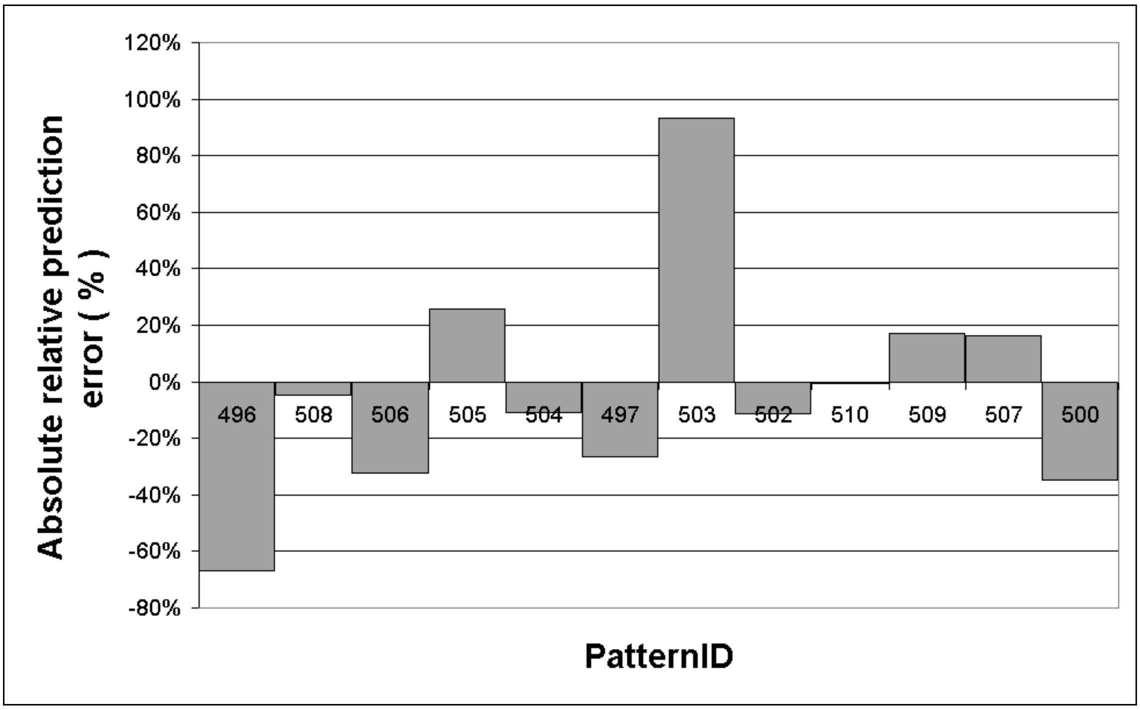


Figure I.6: Relative prediction error of CO for Euro-2 petrol vehicles.

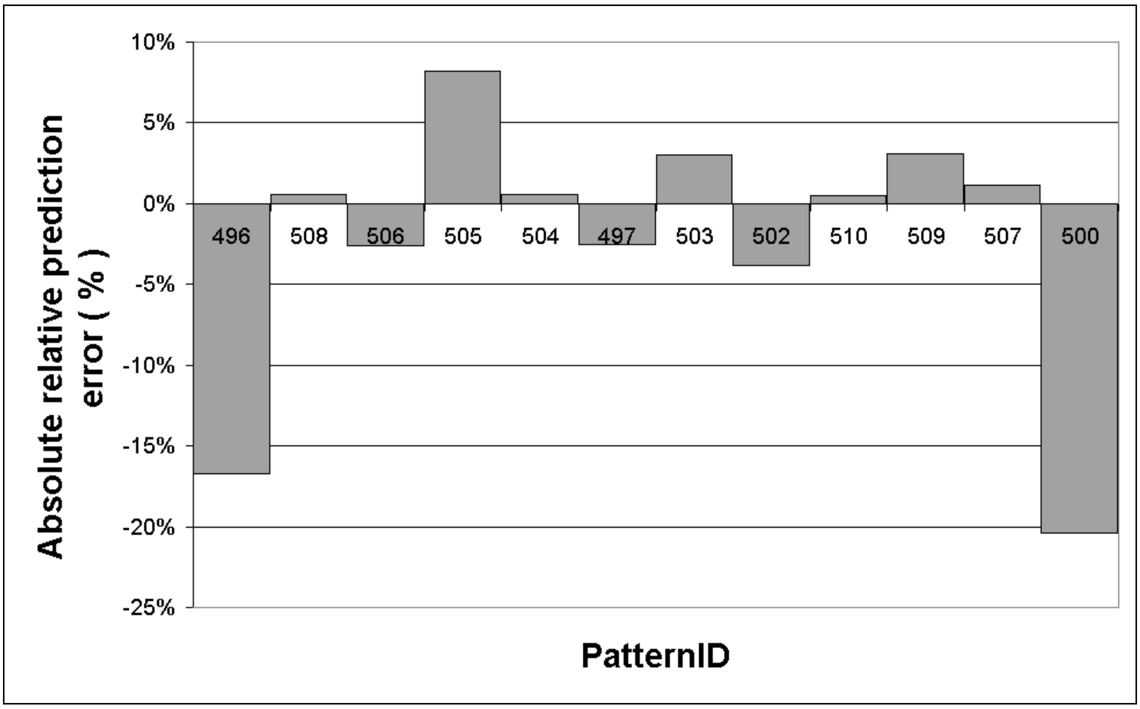


Figure I.7: Relative prediction error of CO_2 for Euro-2 petrol vehicles.

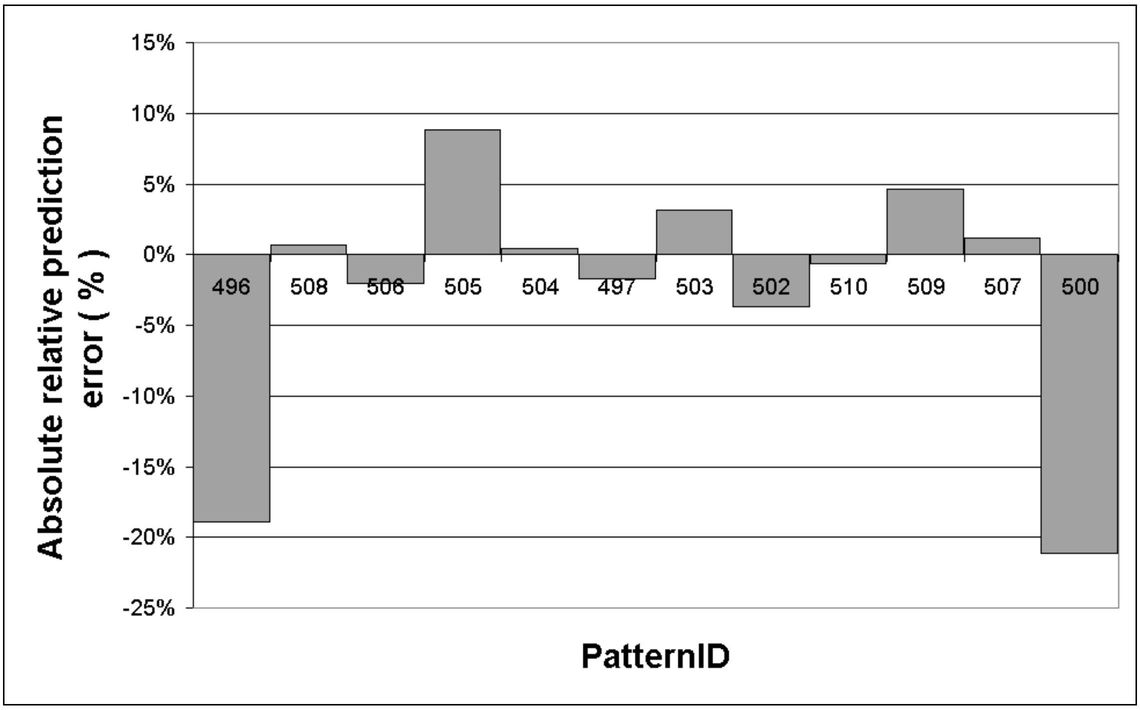


Figure I.8: Relative prediction error of fuel consumption for Euro-2 petrol vehicles.

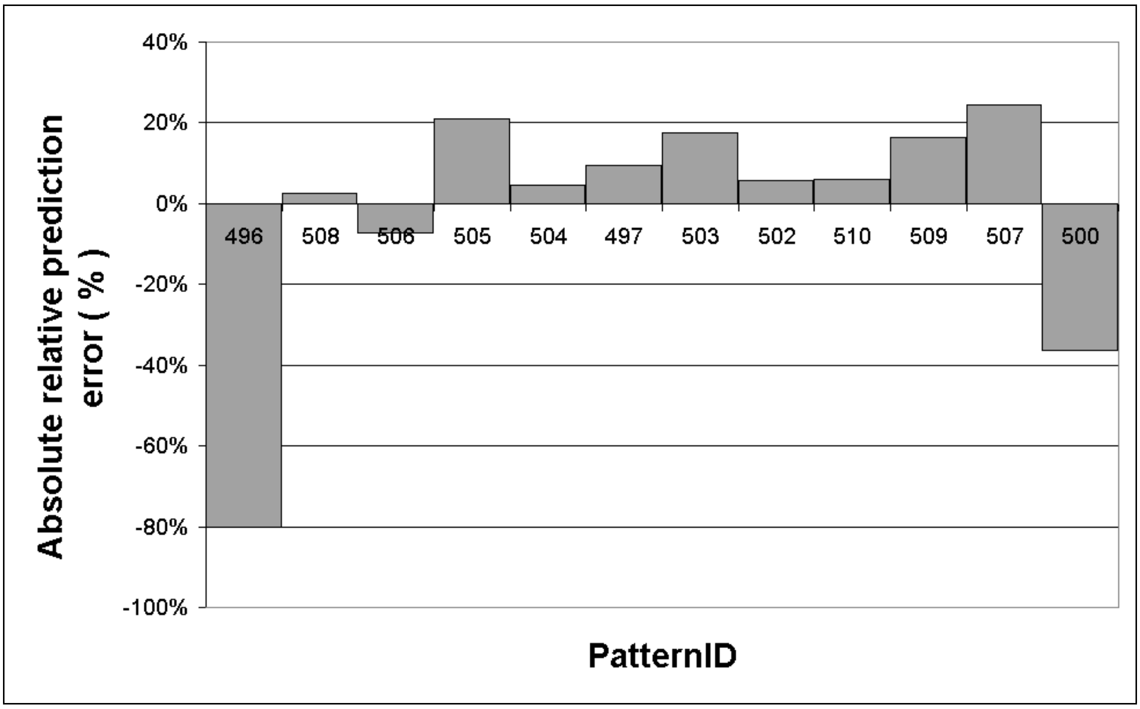


Figure I.9: Relative prediction error of HC for Euro-2 petrol vehicles.

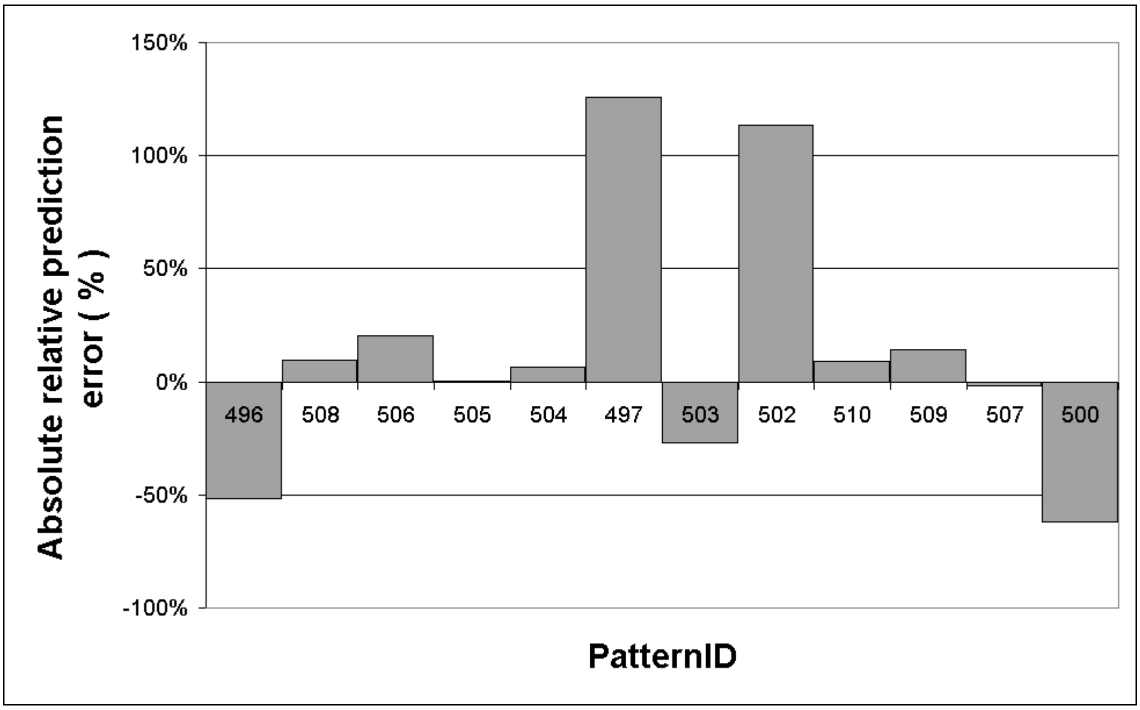


Figure I.10: Relative prediction error of NO_x for Euro-2 petrol vehicles.

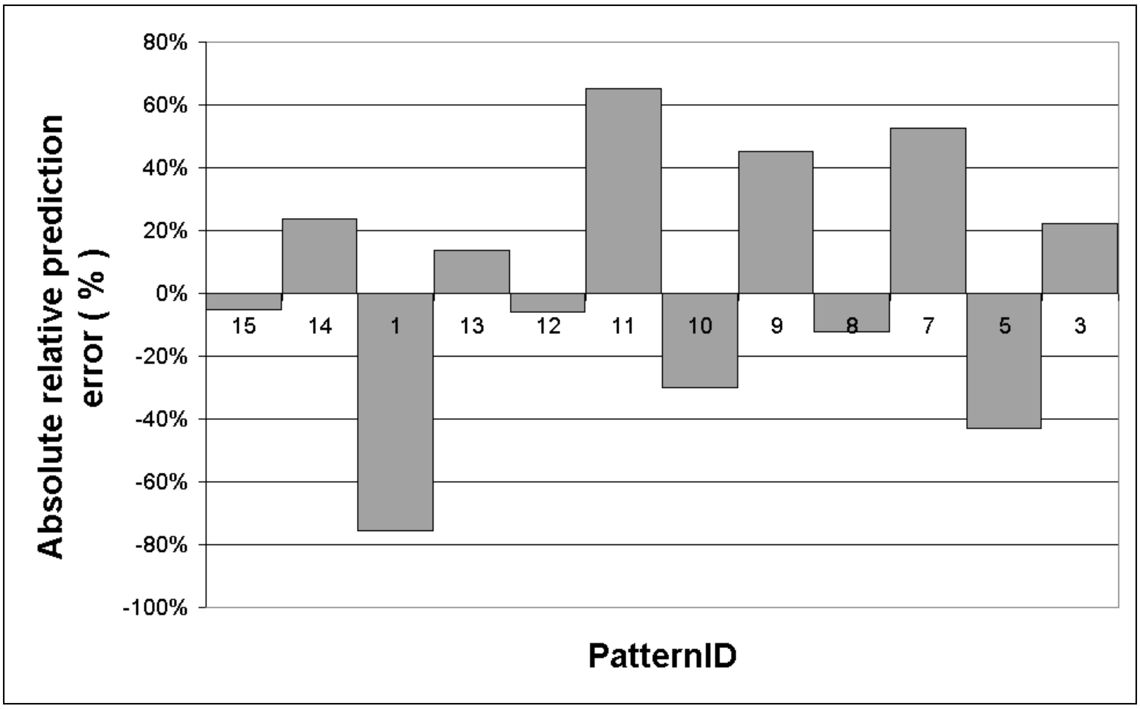


Figure I.11: Relative prediction error of CO for Euro-3 petrol vehicles.

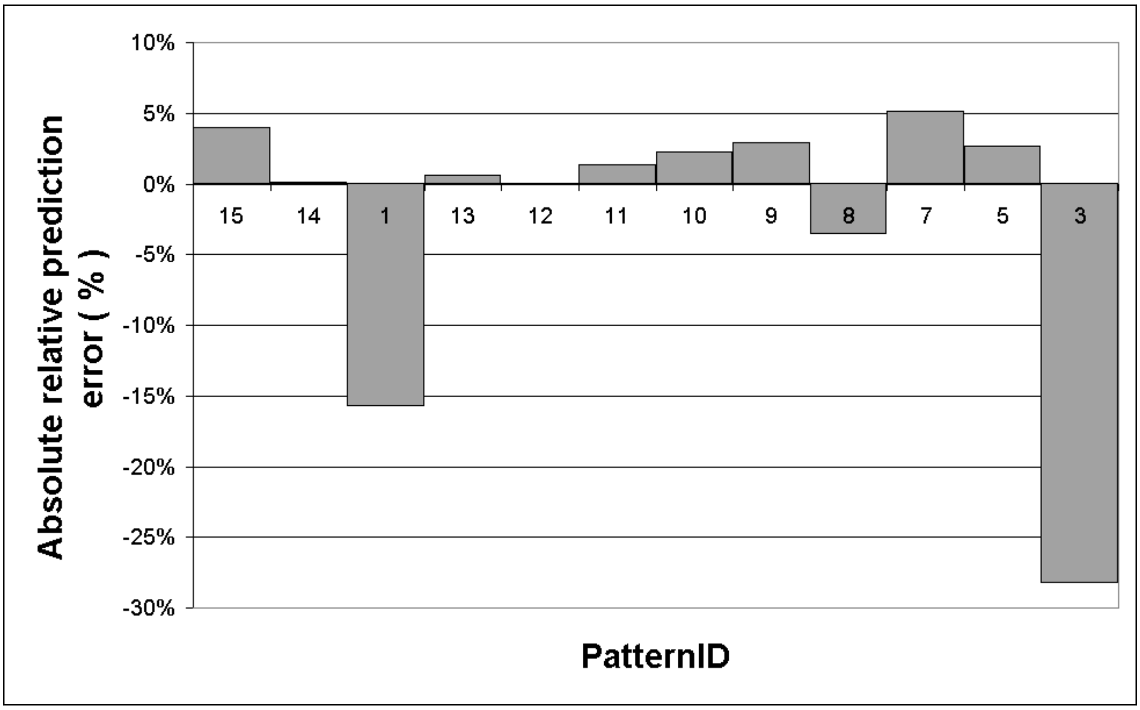


Figure I.12: Relative prediction error of CO_2 for Euro-3 petrol vehicles.

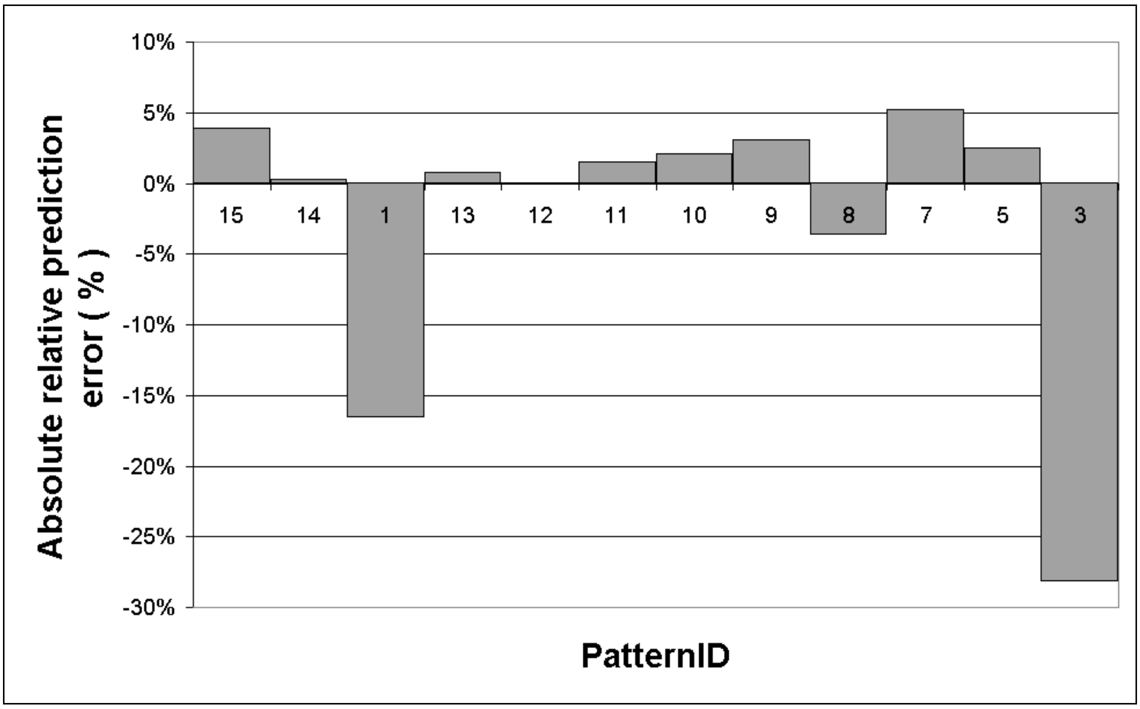


Figure I.13: Relative prediction error of fuel consumption for Euro-3 petrol vehicles.

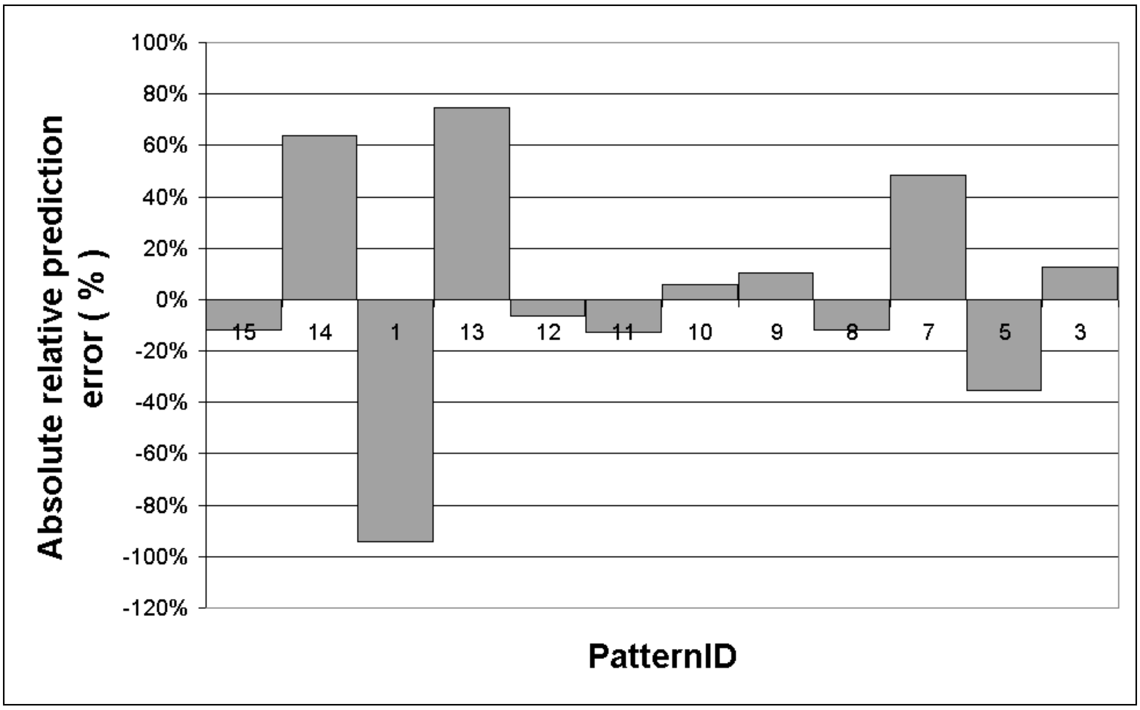


Figure I.14: Relative prediction error of HC for Euro-3 petrol vehicles.

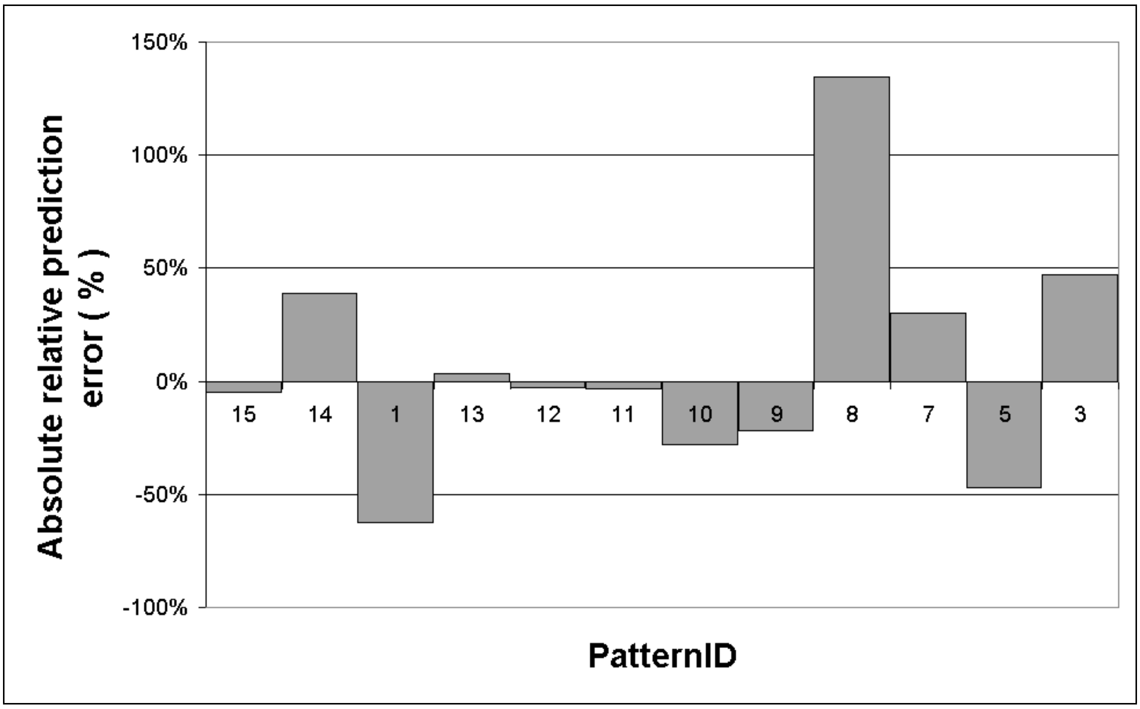


Figure I.15: Relative prediction error of NO_x for Euro-3 petrol vehicles.

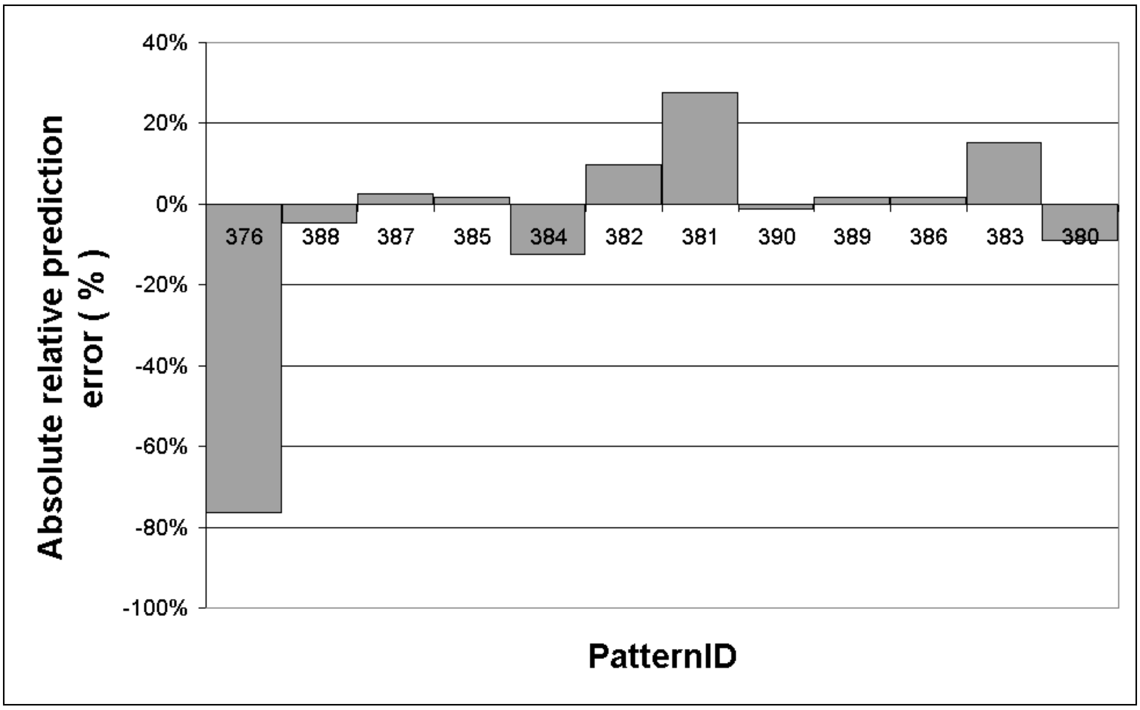


Figure I.16: Relative prediction error of CO for Euro-2 diesel vehicles.

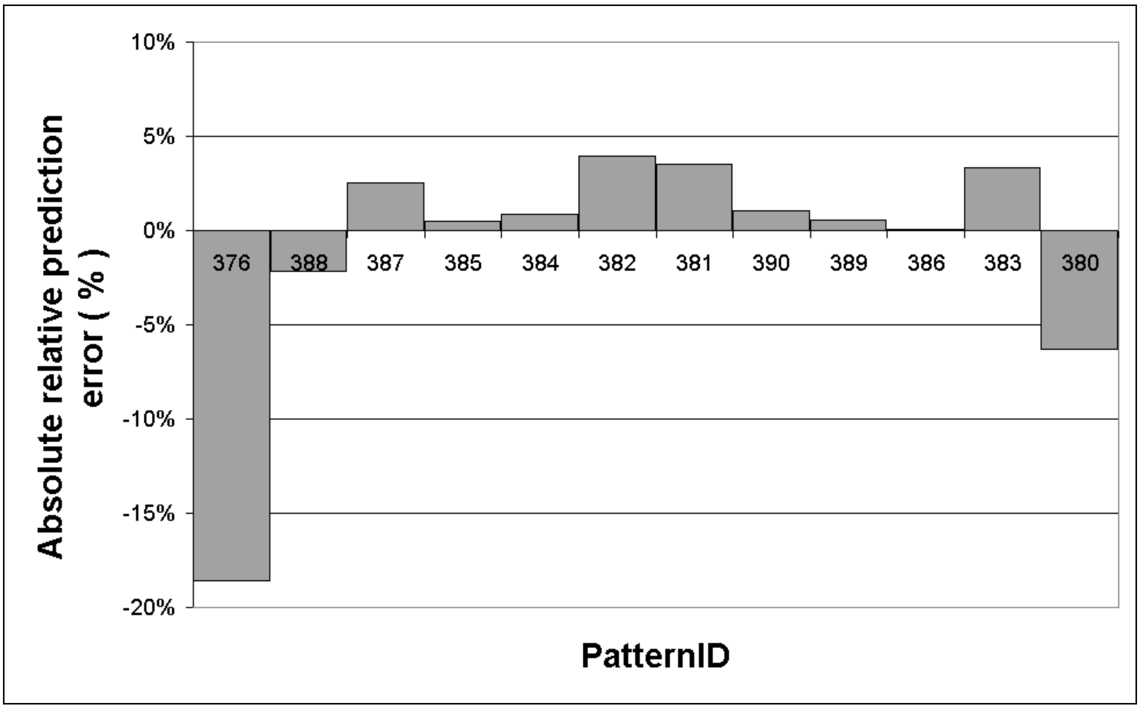


Figure I.17: Relative prediction error of CO_2 for Euro-2 diesel vehicles.

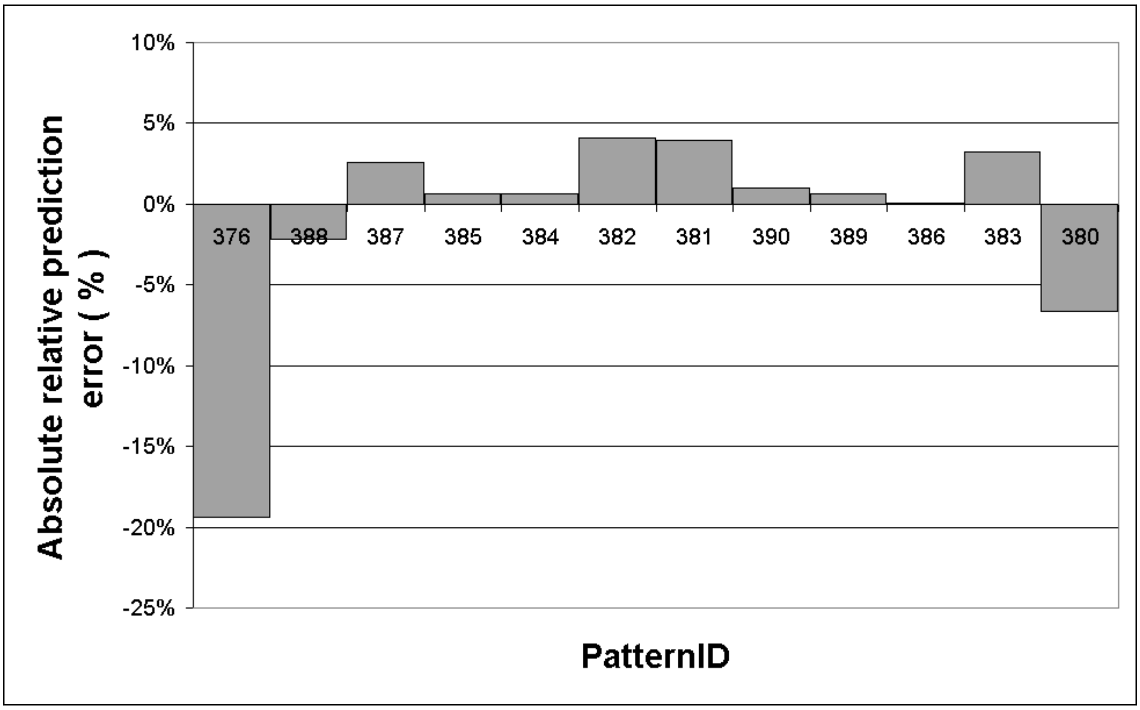


Figure I.18: Relative prediction error of fuel consumption for Euro-2 diesel vehicles.

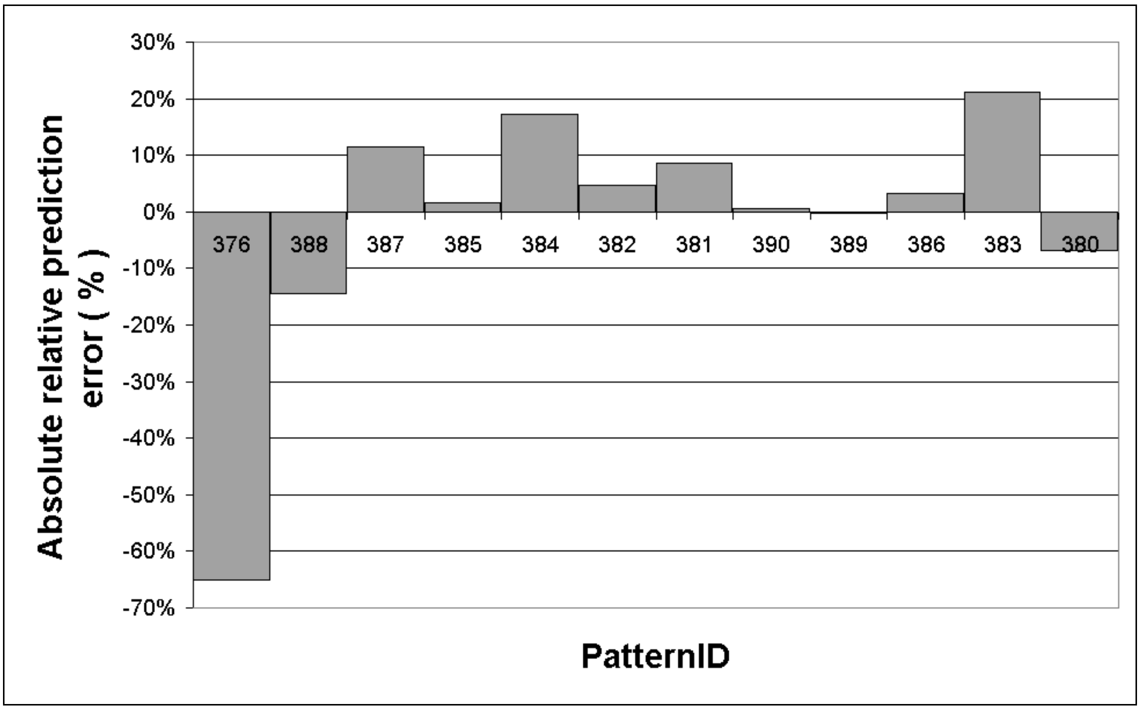


Figure I.19: Relative prediction error of HC for Euro-2 diesel vehicles.

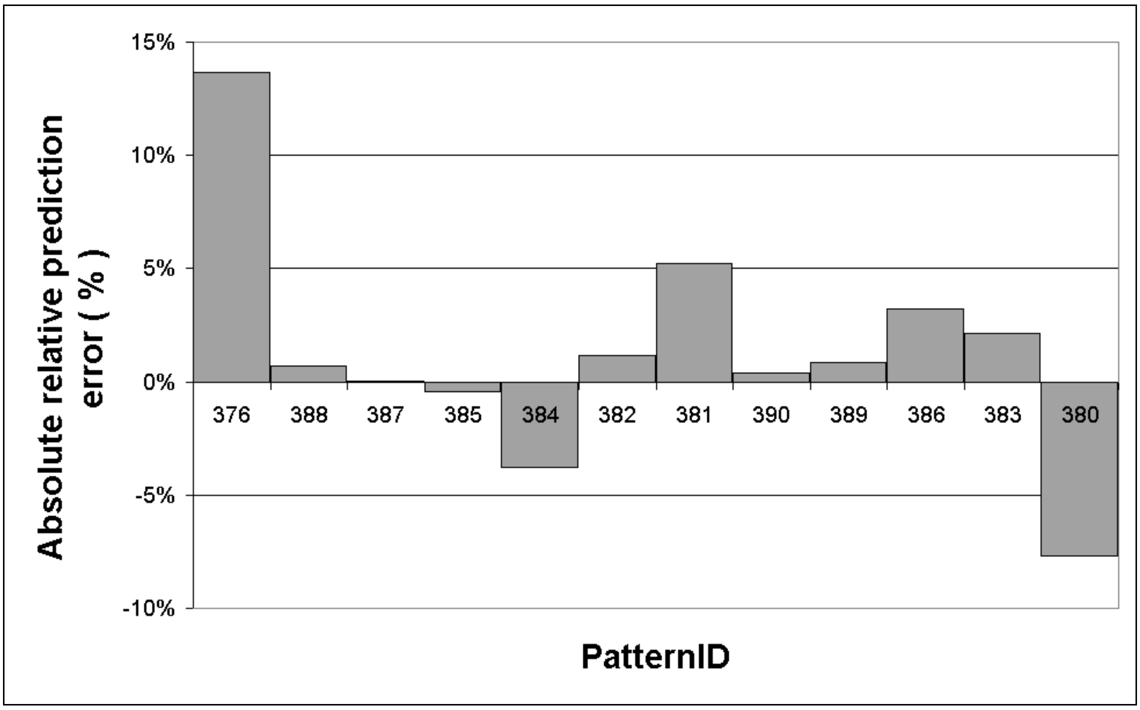


Figure I.20: Relative prediction error of NO_x for Euro-2 diesel vehicles.

APPENDIX J: Sensitivity Analysis of Emissions Simulation Model

Curve fits

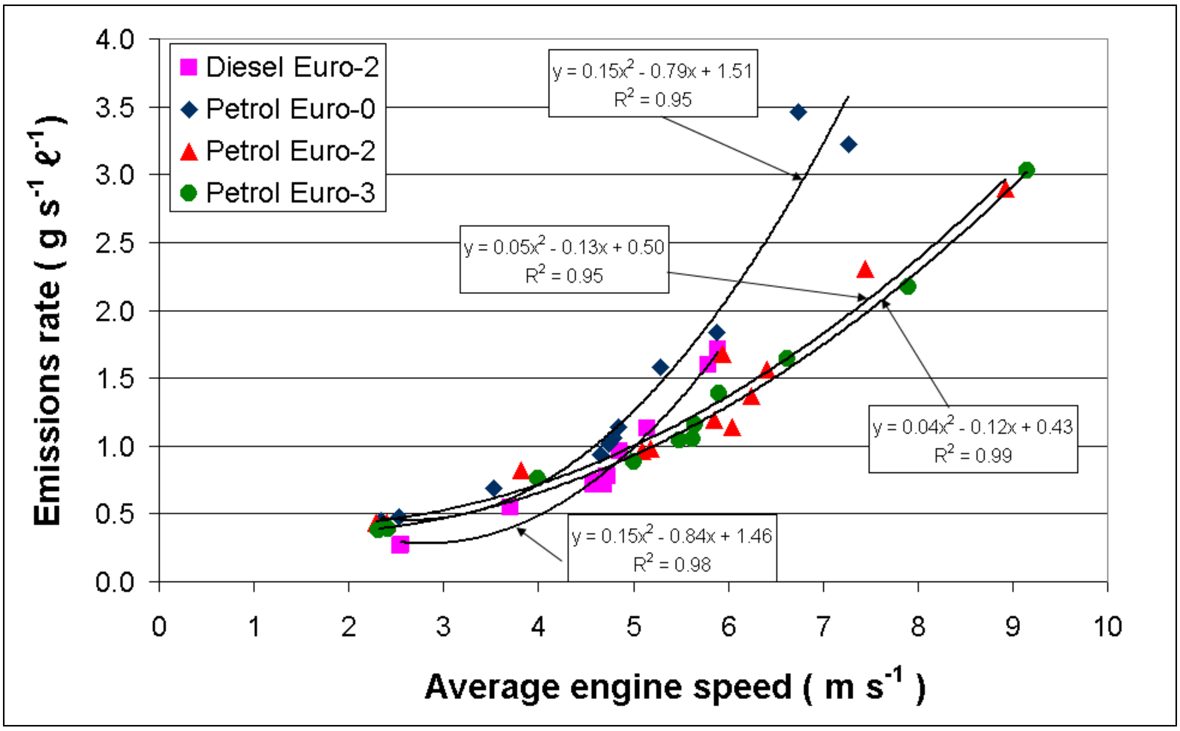


Figure J.1: **CO_2 emissions per litre engine capacity vs. engine speed for different fuels and emissions regulations.**

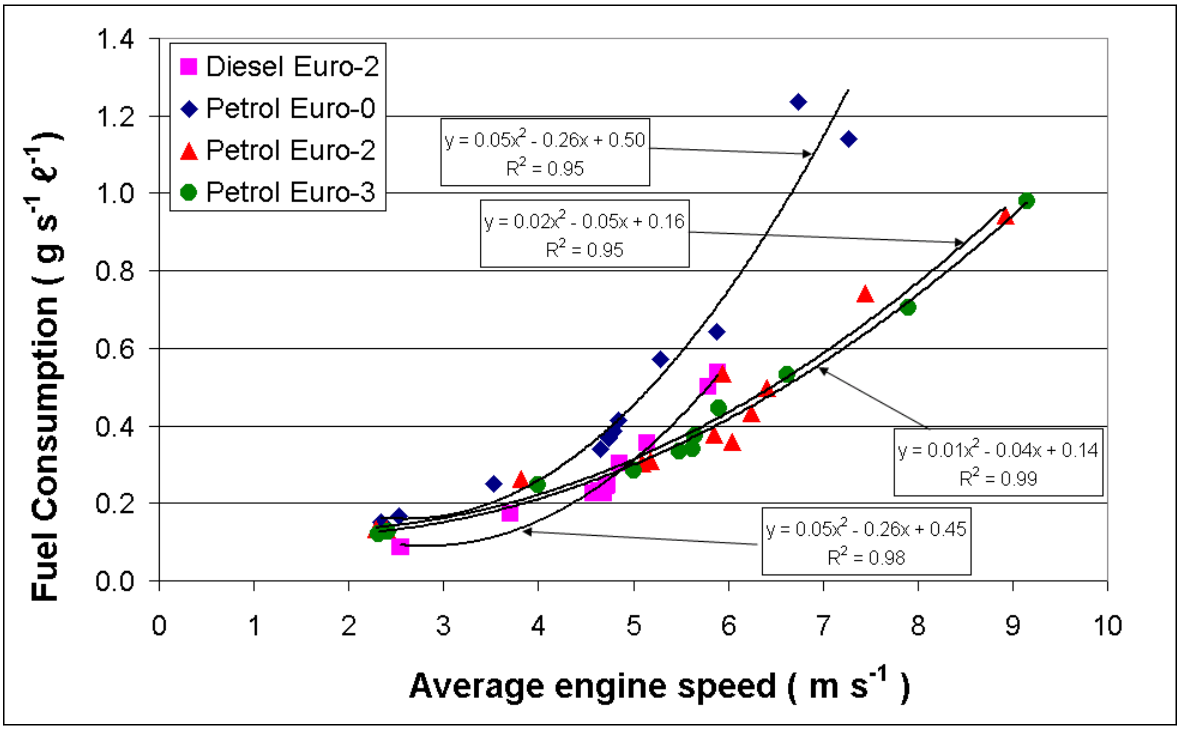


Figure J.2: **Fuel consumption per litre engine capacity vs. engine speed for different fuels and emissions regulations.**

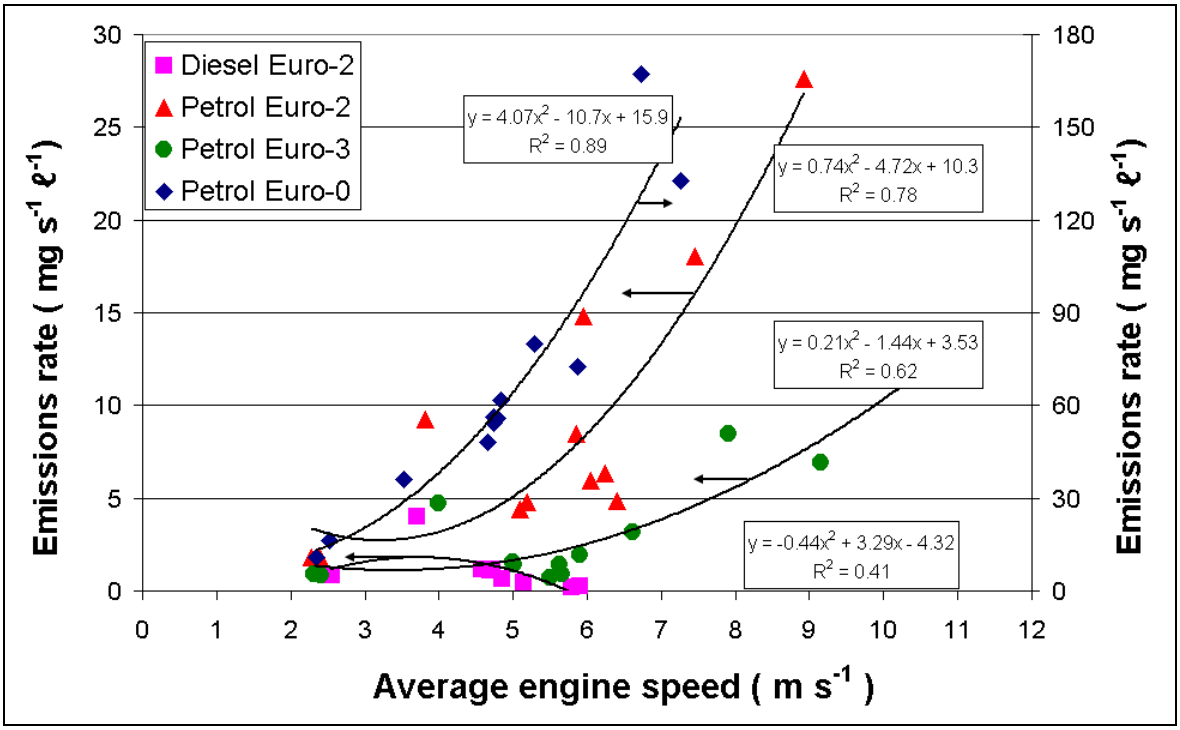


Figure J.3: **CO emissions per litre engine capacity vs. engine speed for different fuels and emissions regulations.**

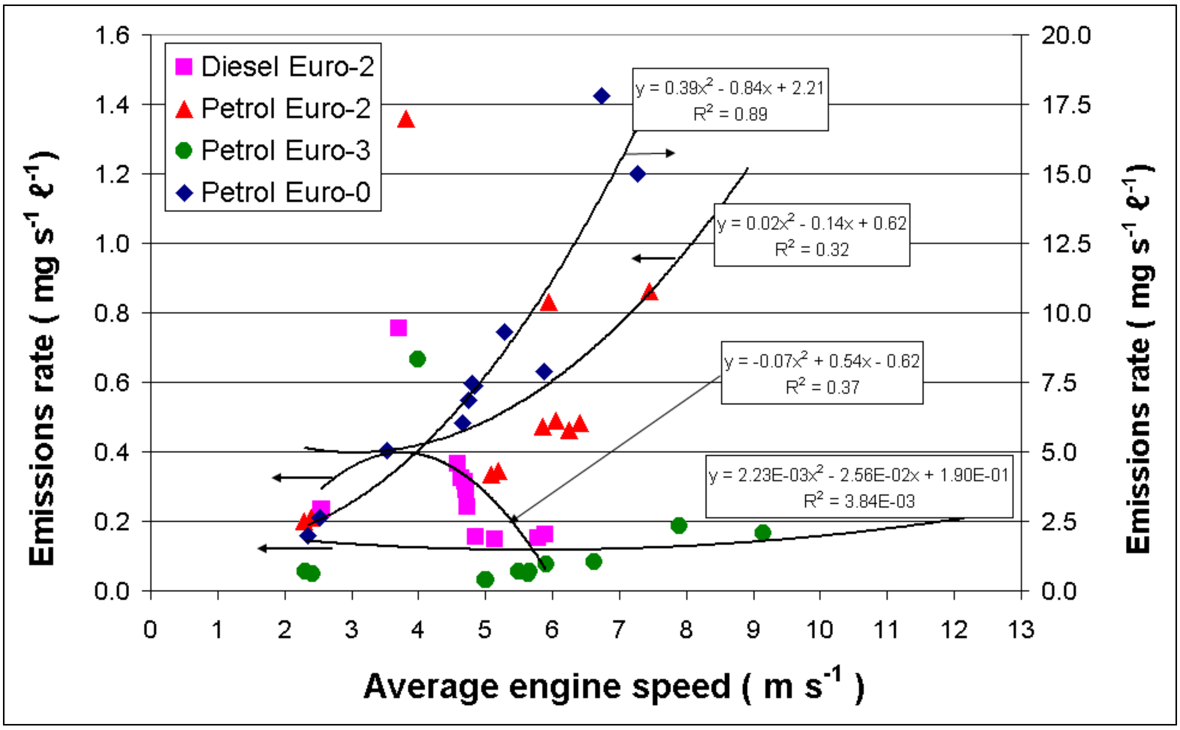


Figure J.4: **HC emissions per litre engine capacity vs. engine speed for different fuels and emissions regulations.**

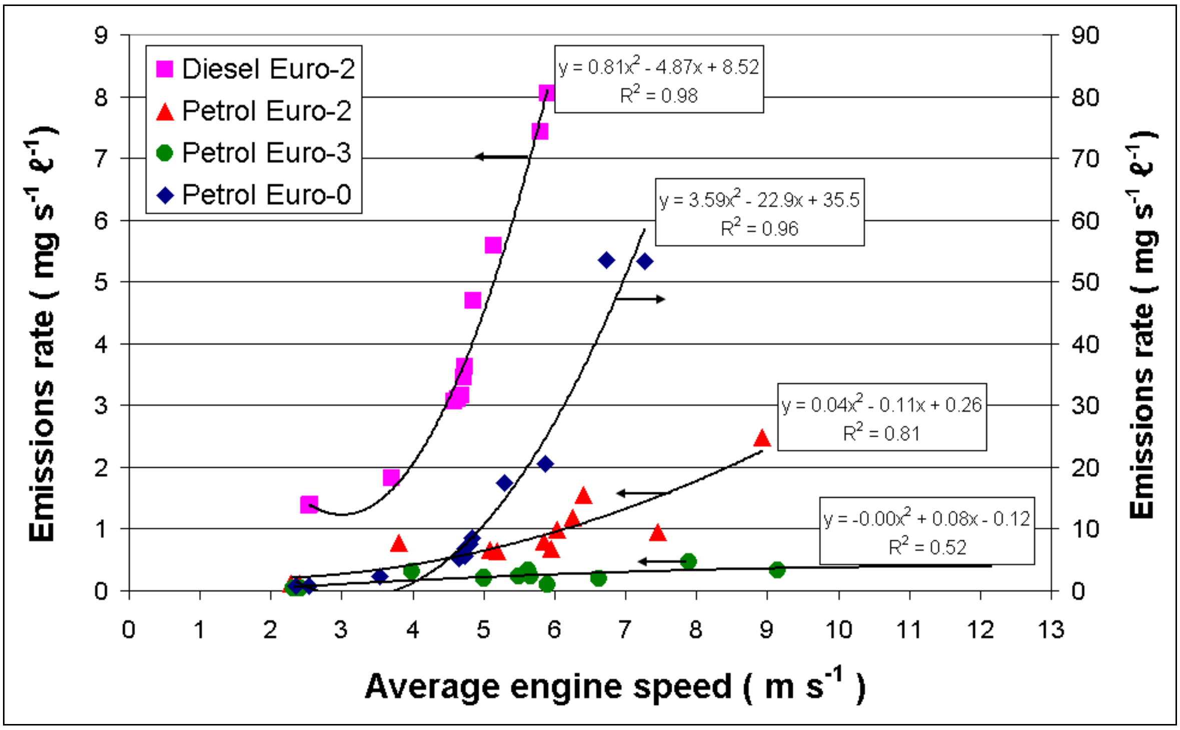


Figure J.5: NO_x emissions per litre engine capacity vs. engine speed for different fuels and emissions regulations.

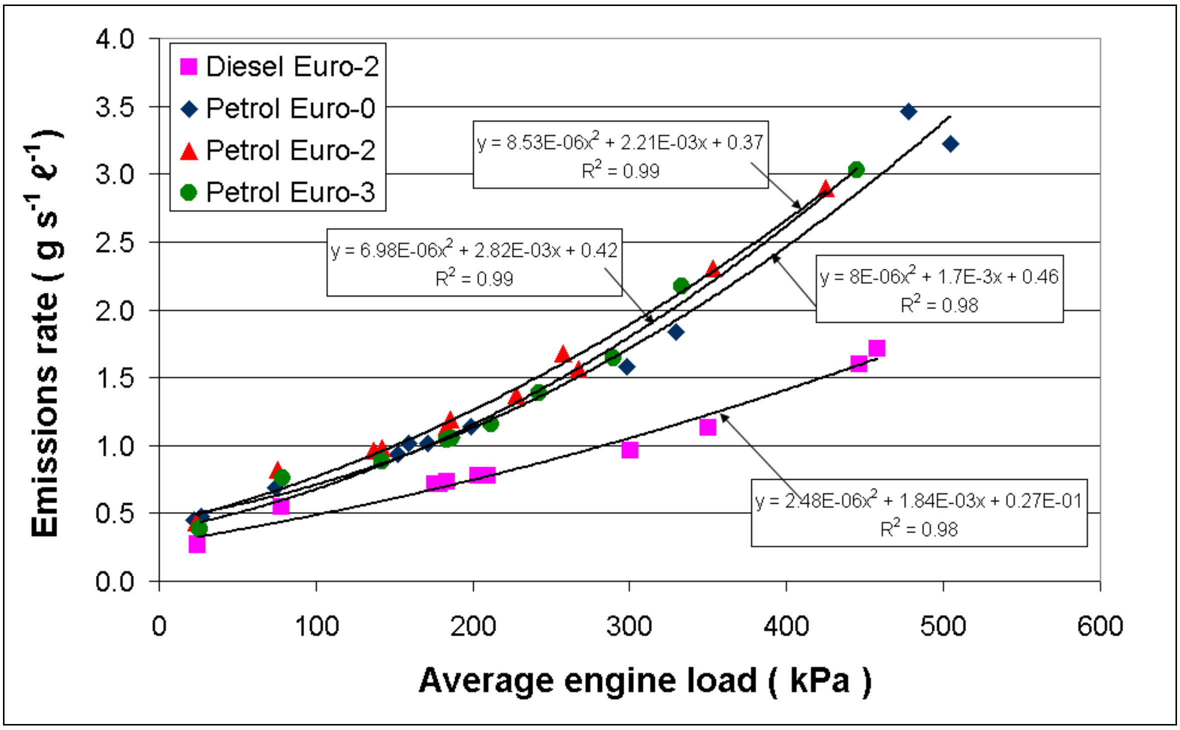


Figure J.6: CO_2 emissions per litre engine capacity vs. engine load for different fuels and emissions regulations.

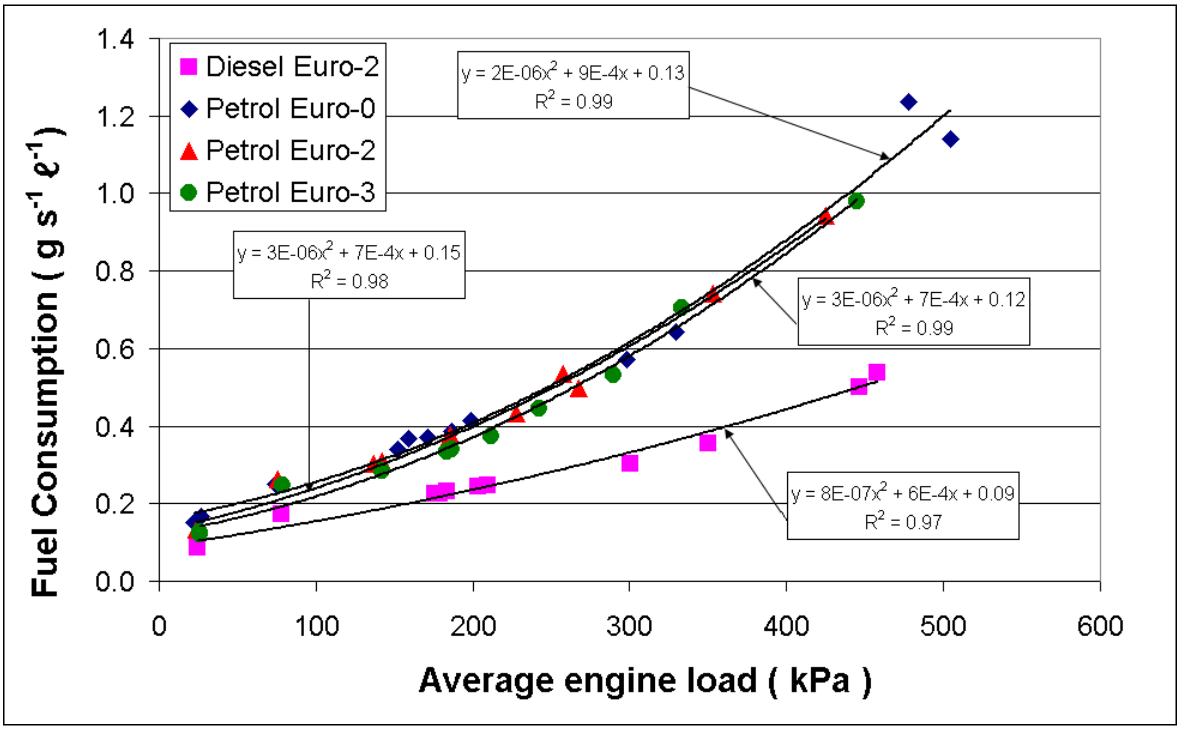


Figure J.7: Fuel consumption per litre engine capacity vs. engine load for different fuels and emissions regulations.

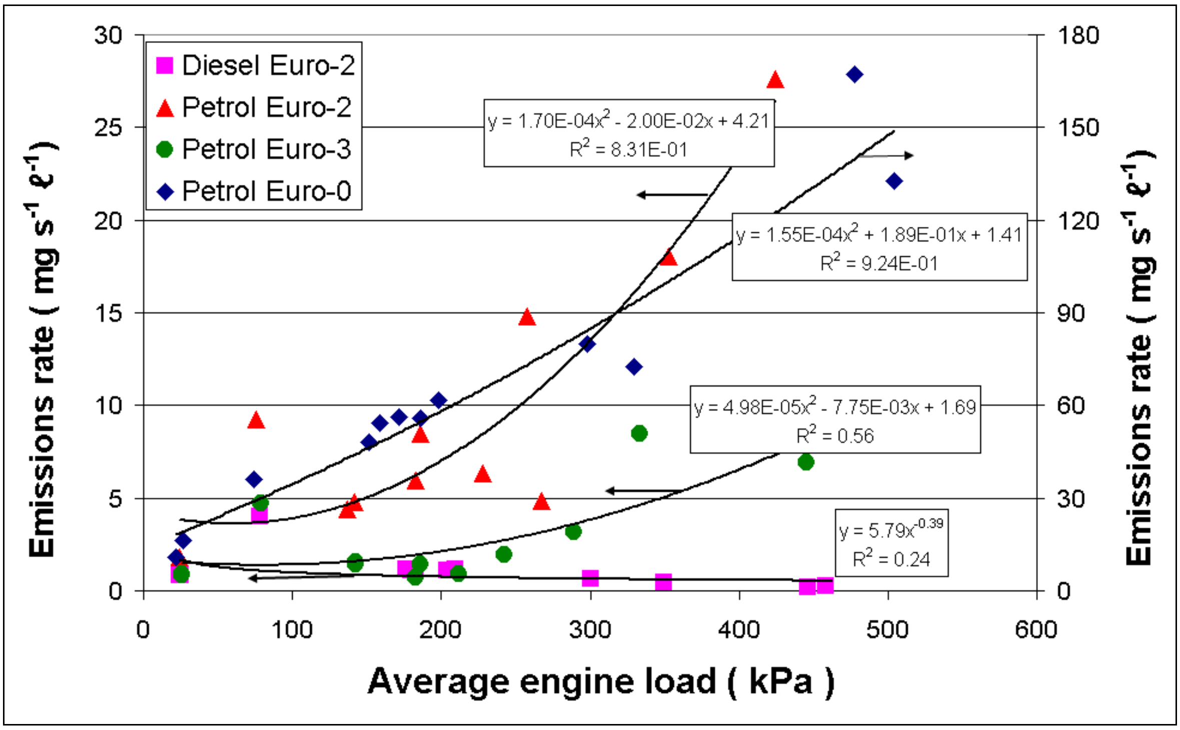


Figure J.8: CO emissions per litre engine capacity vs. engine load for different fuels and emissions regulations.

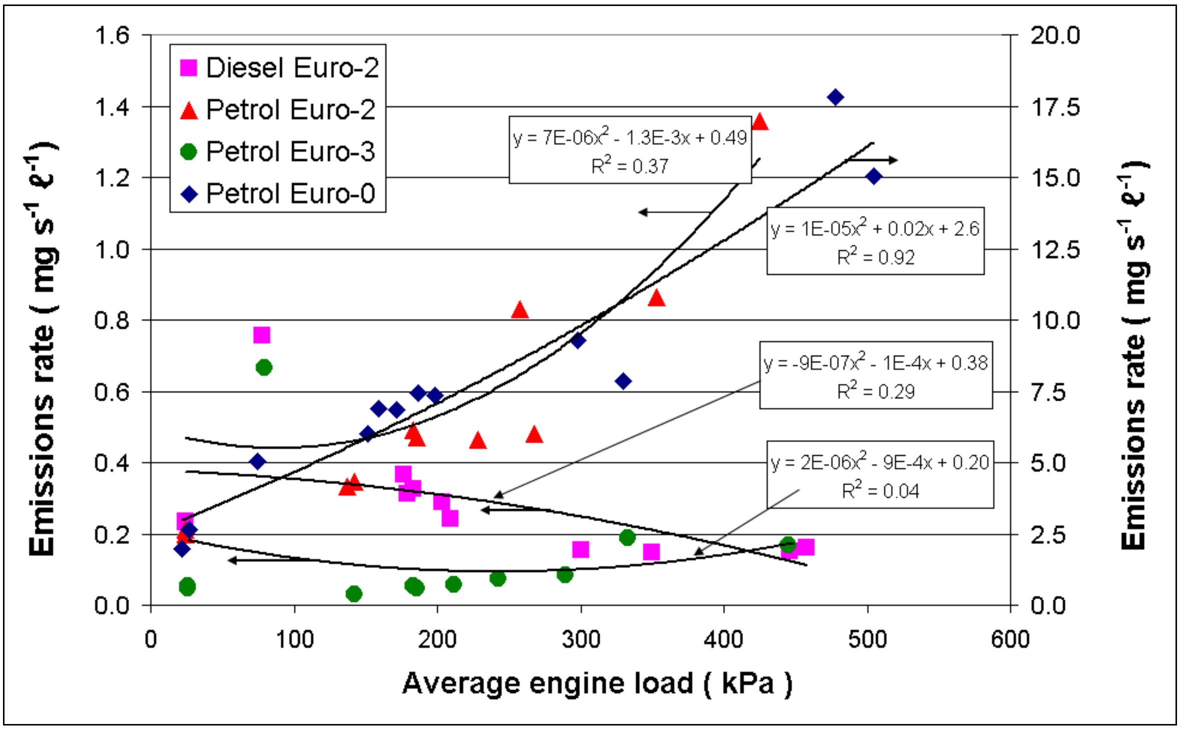


Figure J.9: HC emissions per litre engine capacity vs. engine load for different fuels and emissions regulations.

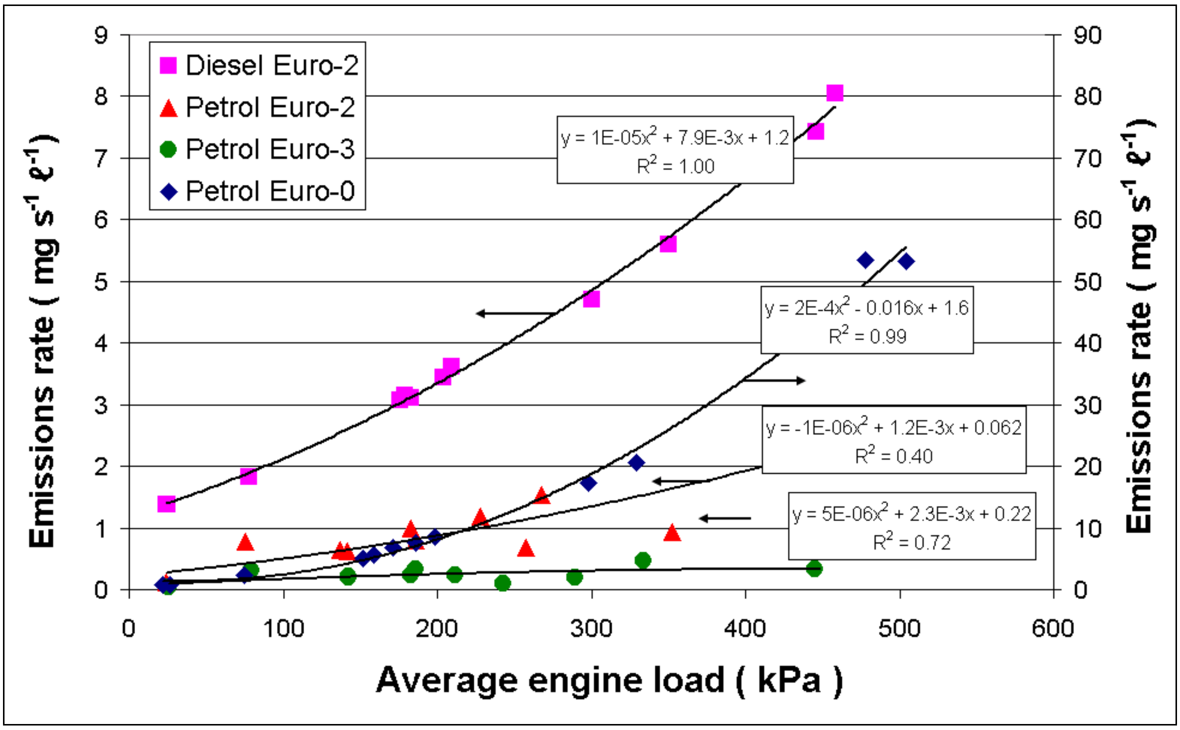


Figure J.10: NO_x emissions per litre engine capacity vs. engine load for different fuels and emissions regulations.

SUMMARY OUTPUT: Fuel consumption

Regression Statistics	
Multiple R	0.99
R Square	0.98
Adjusted R Square	0.97
Standard Error	0.04
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	3.11	3.89E-01	196	5.05E-29
Residual	39	0.08	1.99E-03		
Total	47	3.19			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	-7.32E-01	1.16E-01	-6.30	**1.96E-07**	-9.67E-01	-4.97E-01
Fuel	1.08E-01	2.40E-02	4.51	**5.78E-05**	5.97E-02	1.57E-01
Regulation a	**6.69E-02**	**2.25E-02**	**2.98**	**4.94E-03**	**2.15E-02**	**1.12E-01**
Regulation b	2.45E-02	1.83E-02	1.34	1.88E-01	-1.25E-02	6.14E-02
Average load	**-5.88E-03**	**8.97E-04**	**-6.56**	**8.74E-08**	**-7.70E-03**	**-4.07E-03**
Average load squared	**-4.46E-06**	**1.54E-06**	**-2.90**	**6.12E-03**	**-7.57E-06**	**-1.35E-06**
Average speed	**5.16E-01**	**7.88E-02**	**6.55**	**8.90E-08**	**3.57E-01**	**6.76E-01**
Average speed squared	**-7.81E-02**	**1.30E-02**	**-6.01**	**5.05E-07**	**-1.04E-01**	**-5.18E-02**
Average specific power	**1.71E-03**	**2.81E-04**	**6.07**	**4.15E-07**	**1.14E-03**	**2.27E-03**

SUMMARY OUTPUT: CO_2 emissions

Regression Statistics	
Multiple R	0.99
R Square	0.98
Adjusted R Square	0.98
Standard Error	0.11
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	26.66	3.33E+00	261	2.07E-31
Residual	39	0.50	1.27E-02		
Total	47	27.16			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	-1.79E+00	2.94E-01	-6.08	**3.99E-07**	-2.39E+00	-1.19E+00
Fuel	3.23E-01	6.08E-02	5.32	**4.60E-06**	2.00E-01	4.46E-01
Regulation a	**9.66E-02**	**5.69E-02**	**1.70**	**9.76E-02**	**-1.85E-02**	**2.12E-01**
Regulation b	9.00E-02	4.63E-02	1.94	5.90E-02	-3.60E-03	1.84E-01
Average load	**-1.46E-02**	**2.27E-03**	**-6.42**	**1.34E-07**	**-1.92E-02**	**-1.00E-02**
Average load squared	**-1.05E-05**	**3.90E-06**	**-2.69**	**1.04E-02**	**-1.84E-05**	**-2.61E-06**
Average speed	**1.28E+00**	**2.00E-01**	**6.39**	**1.49E-07**	**8.72E-01**	**1.68E+00**
Average speed squared	**-1.90E-01**	**3.29E-02**	**-5.77**	**1.08E-06**	**-2.57E-01**	**-1.23E-01**
Average specific power	**4.26E-03**	**7.12E-04**	**5.99**	**5.36E-07**	**2.82E-03**	**5.70E-03**

SUMMARY OUTPUT: CO emissions

Regression Statistics	
Multiple R	0.93
R Square	0.87
Adjusted R Square	0.84
Standard Error	0.01
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	0.05	6.23E-03	32	7.14E-15
Residual	39	0.01	1.93E-04		
Total	47	0.06			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	-1.99E-01	3.62E-02	-5.50	**2.59E-06**	-2.72E-01	-1.26E-01
Fuel	1.37E-02	7.49E-03	1.83	7.49E-02	-1.45E-03	2.89E-02
Regulation a	**4.56E-02**	**7.01E-03**	**6.51**	**1.02E-07**	**3.14E-02**	**5.98E-02**
Regulation b	7.31E-03	5.70E-03	1.28	2.07E-01	-4.21E-03	1.88E-02
Average load	**-1.38E-03**	**2.80E-04**	**-4.91**	**1.65E-05**	**-1.94E-03**	**-8.09E-04**
Average load squared	**-1.16E-06**	**4.80E-07**	**-2.42**	**2.02E-02**	**-2.13E-06**	**-1.92E-07**
Average speed	**1.27E-01**	**2.46E-02**	**5.15**	**7.77E-06**	**7.69E-02**	**1.76E-01**
Average speed squared	**-2.00E-02**	**4.05E-03**	**-4.94**	**1.53E-05**	**-2.82E-02**	**-1.18E-02**
Average specific power	**3.84E-04**	**8.77E-05**	**4.38**	**8.68E-05**	**2.07E-04**	**5.61E-04**

SUMMARY OUTPUT: HC emissions

Regression Statistics	
Multiple R	0.95
R Square	0.89
Adjusted R Square	0.87
Standard Error	0.00
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	0.00	8.25E-05	41	1.36E-16
Residual	39	0.00	2.02E-06		
Total	47	0.00			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	-2.13E-02	3.71E-03	-5.76	**1.13E-06**	-2.88E-02	-1.38E-02
Fuel	1.05E-03	7.67E-04	1.37	1.79E-01	-5.01E-04	2.60E-03
Regulation a	**5.78E-03**	**7.17E-04**	**8.07**	**7.73E-10**	**4.33E-03**	**7.23E-03**
Regulation b	5.92E-04	5.83E-04	1.02	3.16E-01	-5.87E-04	1.77E-03
Average load	**-1.48E-04**	**2.86E-05**	**-5.16**	**7.64E-06**	**-2.06E-04**	**-8.98E-05**
Average load squared	**-1.14E-07**	**4.91E-08**	**-2.33**	**2.51E-02**	**-2.14E-07**	**-1.51E-08**
Average speed	**1.38E-02**	**2.52E-03**	**5.48**	**2.69E-06**	**8.71E-03**	**1.89E-02**
Average speed squared	**-2.14E-03**	**4.15E-04**	**-5.17**	**7.38E-06**	**-2.98E-03**	**-1.30E-03**
Average specific power	**4.00E-05**	**8.97E-06**	**4.46**	**6.83E-05**	**2.18E-05**	**5.81E-05**

SUMMARY OUTPUT: No$_x$ emissions

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.82
Standard Error	0.00
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	0.00	6.04E-04	27	9.71E-14
Residual	39	0.00	2.20E-05		
Total	47	0.01			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	-7.52E-02	1.22E-02	-6.15	**3.20E-07**	-9.99E-02	-5.04E-02
Fuel	1.60E-03	2.53E-03	0.63	5.30E-01	-3.51E-03	6.71E-03
Regulation a	**6.08E-03**	**2.36E-03**	**2.57**	**1.41E-02**	**1.29E-03**	**1.09E-02**
Regulation b	1.07E-03	1.92E-03	0.56	5.82E-01	-2.82E-03	4.95E-03
Average load	**-5.56E-04**	**9.44E-05**	**-5.89**	**7.35E-07**	**-7.47E-04**	**-3.65E-04**
Average load squared	**-3.21E-07**	**1.62E-07**	**-1.98**	**5.45E-02**	**-6.48E-07**	**6.54E-09**
Average speed	**5.10E-02**	**8.29E-03**	**6.15**	**3.19E-07**	**3.42E-02**	**6.78E-02**
Average speed squared	**-7.92E-03**	**1.37E-03**	**-5.79**	**1.01E-06**	**-1.07E-02**	**-5.15E-03**
Average specific power	**1.44E-04**	**2.96E-05**	**4.86**	**1.94E-05**	**8.39E-05**	**2.03E-04**

APPENDIX K: Comparison of Petrol and Diesel Vehicles

Table K.1: Comparison of petrol and diesel vehicle purchase prices and fuel consumption.

			Purchase price ('000 R)			Fuel economy (ℓ/100 km)			Fuel cost Diff (R/km)	Break even distance for period (km)		
Make	**Diesel model**	**Petrol model**	**Diesel**	**Petrol**	**Diff**	**Diesel**	**Petrol**	**Diff**		**lifetime**	**10 years**	**5 years**
Citroën	C3 1.4 HDI	C2 1.4i VTR	138	127	11	5.50	7.63	2.13	0.15	74	7	15
Ford	Focus 2.0 TDCi Si 5dr	Focus 2.0 Si 5dr	203	191	11	6.90	8.70	1.80	0.13	90	9	18
Audi	A3 2.0 TDI Ambition	A3 2.0 FS Attraction	252	227	25	6.21	9.60	3.39	0.24	103	10	21
Renault	Mégane CC 1.9 dCi Privilege	Mégane CC 2.0 Privilege	205	195	10	8.80	10.09	1.29	0.09	111	11	22
VW	Passat 2.0 TDI Highline	Passat 2.0 FSI Highline	267	240	27	7.00	10.09	3.09	0.22	125	12	25
BMW	120d	120i	266	244	22	7.01	9.10	2.09	0.15	150	15	30
Mercedes	C220 CDI Classic	C180K Classic	290	260	30	7.26	9.60	2.34	0.16	183	18	37
Opel	Corsa Classic 1.7 CDTI Elegance	Corsa Classic 1.4 Comfrt	155	115	40	6.90	9.90	3.00	0.21	189	19	38
Peugeot	407 2.0 HDI ST Comfort	407 2.0 ST Comfort	254	220	34	7.26	9.50	2.24	0.16	217	22	43
Citroën	C4 1.6 Hdi	C3 1.6i	189	138	51	5.80	8.65	2.85	0.20	254	25	51
Peugeot	206 HDI 5dr	206 XLine 1.4 16V 5dr	170	139	31	6.70	8.40	1.70	0.12	261	26	52
Kia	Cerato 2.0 CRDi	Cerato 1.6	179	136	43	7.13	9.47	2.34	0.16	263	26	53
Fiat	Stilo 1.9 JTD Dynamic 5dr	Stilo 1.6 Active 3dr	204	166	38	7.00	8.95	1.95	0.14	277	28	55
Audi	A4 2.0 TDI	A4 2.0	284	245	39	7.20	8.80	1.60	0.11	344	34	69
Average			218	189	29	6.91	9.18	2.27	0.16	189	19	38

Diff: difference between petrol and diesel

Data were sourced from Car Magazine for December 2006. The petrol and diesel models were matched on similar performance characteristics. The fuel price of R7 for both petrol and diesel was used. The higher the fuel price the greater the benefit of purchasing a diesel vehicle instead of a petrol vehicle. There is only a benefit of owning a diesel vehicle if the break-even annual mileage for the period of ownership is exceeded.

APPENDIX L: Driving conditions from travel survey by vehicle type

Proportions of time spent by each fuel type and capacity class in the combinations of driving conditions are shown in Table L.1. The corresponding average vehicle speeds for the combinations of driving conditions and vehicle types in Table L.1 are presented in Table L.2. The empty cells in the tables indicate that the combination of driving conditions and vehicle types did not occur during the survey. The missing data are primarily for diesel vehicles and weekends due to the limited size of the sample.

Table L.1: Proportion of time spent in different driving conditions by different vehicle types.

Proportion of time in driving condition (%)			**Petrol**			**Diesel**		
			Capacity class (ℓ)			**Capacity class (ℓ)**		
Day of week	**Period of day**	**Road type**	**< 1.4**	**1.4 - 2.0**	**> 2.0**	**< 1.4**	**1.4 - 2.0**	**> 2.0**
Weekday	06:30-09:00	Freeway	3.2	7.9	14.0	20.1	0.4	1.8
		Main Road	17.1	18.1	13.6	9.4	18.6	8.7
		Street	7.8	1.9	2.1	2.0	3.8	0.8
	06:30-09:00 Total		28.1	27.9	29.7	31.5	22.7	11.2
	09:00-12:00	Freeway	0.3	2.2	5.3	0.4	5.7	7.9
		Main Road	3.1	2.9	4.8	0.4	3.2	5.4
		Street	1.8	0.8	0.8	0.4	0.9	2.3
	09:00-12:00 Total		5.2	5.9	10.9	1.1	9.8	15.6
	12:00-14:00	Freeway	1.8	0.9	2.6			2.0
		Main Road	2.0	2.9	1.6		0.9	5.4
		Street	0.8	0.7	0.4		0.4	0.6
	12:00-14:00 Total		4.5	4.5	4.5		1.3	8.1
	14:00-16:00	Freeway	0.8	2.8	1.5	3.2	1.3	9.7
		Main Road	4.1	5.4	2.7	11.5	3.5	7.8
		Street	1.6	0.6	0.5	0.6	2.2	0.2
	14:00-16:00 Total		6.6	8.8	4.6	15.3	7.0	17.7
	16:00-18:30	Freeway	4.3	11.7	11.9	14.6	0.1	14.2
		Main Road	9.8	13.2	10.7	12.3	28.8	4.2
		Street	5.1	2.4	2.2	1.8	4.4	0.8
	16:00-18:30 Total		19.3	27.3	24.9	28.7	33.3	19.1
	Other	Freeway	3.9	4.0	11.7	1.5		13.7
		Main Road	6.2	7.2	3.6	6.3	2.9	5.8
		Street	2.7	1.7	1.3	2.9	0.7	0.5
	Other Total		12.8	12.9	16.6	10.7	3.6	20.0
Weekday Total			**76.5**	**87.4**	**91.3**	**87.4**	**77.8**	**91.7**
Weekend	06:30-09:00	Freeway	0.3	0.2	0.4			
		Main Road	1.3	0.6	0.8		4.3	
		Street	1.0	0.2	0.3		0.5	
	06:30-09:00 Total		2.6	1.0	1.6		4.9	
	09:00-12:00	Freeway	0.8	0.4	0.4		0.0	1.3
		Main Road	4.4	1.7	3.1		1.8	1.3
		Street	1.6	0.5	1.1		0.5	0.2
	09:00-12:00 Total		6.8	2.6	4.5		2.3	2.8
	12:00-14:00	Freeway	0.3	0.1	0.2		0.1	
		Main Road	4.6	1.3	0.4		0.5	
		Street	1.1	1.0	0.1		1.1	
	12:00-14:00 Total		5.9	2.4	0.7		1.7	
	14:00-16:00	Freeway	0.1	0.2	0.0		0.0	0.8
		Main Road	2.0	1.0	0.5		4.6	0.8
		Street	0.3	0.4	0.2		0.2	0.2
	14:00-16:00 Total		2.5	1.7	0.7		4.8	1.8
	16:00-18:30	Freeway	1.9	0.3	0.1	2.5		1.9
		Main Road	1.3	1.5	0.3	6.1		1.5
		Street	0.8	0.4	0.2	1.1		0.3
	16:00-18:30 Total		4.0	2.2	0.6	9.8		3.7
	Other	Freeway	0.0	0.8	0.0	1.4	1.9	
		Main Road	1.3	1.5	0.4	1.1	5.4	
		Street	0.4	0.4	0.2	0.3	1.1	
	Other Total		1.7	2.7	0.6	2.8	8.4	
Weekend Total			**23.5**	**12.6**	**8.7**	**12.6**	**22.2**	**8.3**
Grand Total			**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table L.2: Average vehicle speed (km h^{-1}) for different driving conditions and vehicle types.

Average vehicle speed (km h^{-1})			Petrol			Diesel		
			Engine capacity (ℓ)			Engine capacity (ℓ)		
Day of week	**Period Of Day**	**Road type**	**< 1.4**	**1.4 - 2.0**	**> 2.0**	**< 1.4**	**1.4 - 2.0**	**> 2.0**
Weekday	06:30-09:00	Freeway	59	47	49	64	9	47
		Main Road	32	31	30	32	30	41
		Street	31	38	35	22	19	52
	09:00-12:00	Freeway	61	58	76	88	98	68
		Main Road	37	45	47	33	44	47
		Street	45	43	54	40	57	44
	12:00-14:00	Freeway	72	61	65			61
		Main Road	42	27	50		27	53
		Street	40	26	41		23	62
	14:00-16:00	Freeway	51	57	67	88	72	78
		Main Road	31	36	46	35	46	37
		Street	35	34	42	46	24	30
	16:00-18:30	Freeway	67	54	62	55	51	61
		Main Road	32	33	35	29	32	28
		Street	34	37	34	38	31	64
	Other	Freeway	86	70	67	84		70
		Main Road	42	48	52	50	54	48
		Street	50	48	41	28	23	57
Weekend	06:30-09:00	Freeway	61	96	79			
		Main Road	45	60	47		49	
		Street	42	63	35		38	
	09:00-12:00	Freeway	63	94	66		98	122
		Main Road	45	40	42		41	65
		Street	35	36	33		8	61
	12:00-14:00	Freeway	69	40	106		81	
		Main Road	43	27	35		28	
		Street	38	29	33		29	
	14:00-16:00	Freeway	54	66	84			107
		Main Road	44	44	44		54	66
		Street	44	32	33		73	72
	16:00-18:30	Freeway	67	89	87	100		114
		Main Road	44	52	44	54		68
		Street	37	36	24	27		73
	Other	Freeway	45	73		114	76	
		Main Road	55	49	41	64	50	
		Street	42	33	37	74	36	

APPENDIX M: Variation of Measured Engine-operating Patterns

Table L.1: Variation of measured engine-operating patterns for weekdays.

				Petrol			Diesel		
				Capacity class (ℓ)			Capacity class (ℓ)		
Period of day	**Road type**	**Value**	**Unit**	**< 1.4**	**1.4-2.0**	**> 2.0**	**< 1.4**	**1.4-2.0**	**> 2.0**
06:30-09:00	**Freeways**	Ave engine speed	$m\ s^{-1}$	5.91	5.29	4.76	5.05	3.78	5.78
		Stdev engine speed	$m\ s^{-1}$	2.50	1.43	0.84			
		Ave engine load	kPa	342	320	298	399	285	451
		Stdev engine load	kPa	103	113	148			
		Average MI		0.34	0.50	0.54	1.00	1.00	1.00
		Number of vehicles		5	12	6	1	1	1
	Main Road	Ave engine speed	$m\ s^{-1}$	4.55	4.33	4.08	4.23	4.43	5.33
		Stdev engine speed	$m\ s^{-1}$	1.40	0.64	0.69		0.02	
		Ave engine load	kPa	250	272	266	368	569	419
		Stdev engine load	kPa	144	114	132		232	
		Average MI		0.45	0.50	0.51	1.00	0.66	1.00
		Number of vehicles		5	13	7	1	2	1
	Street	Ave engine speed	$m\ s^{-1}$	4.56	4.76	4.31	3.52	4.04	5.28
		Stdev engine speed	$m\ s^{-1}$	0.98	0.78	0.83		0.00	
		Ave engine load	kPa	233	315	275	348	504	350
		Stdev engine load	kPa	142	119	174		161	
		Average MI		0.49	0.40	0.46	1.00	0.67	1.00
		Number of vehicles		5	13	7	1	2	1
09:00-12:00	**Freeways**	Ave engine speed	$m\ s^{-1}$	6.48	5.66	5.96	5.51	7.07	6.72
		Stdev engine speed	$m\ s^{-1}$	0.24	1.51	0.16			0.61
		Ave engine load	kPa	172	348	308	280	774	556
		Stdev engine load	kPa	14	92	142			2
		Average MI		0.65	0.45	0.61	1.00	1.00	0.66
		Number of vehicles		2	6	5	1	1	2
	Main Road	Ave engine speed	$m\ s^{-1}$	4.82	4.96	5.21	4.37	4.55	5.52
		Stdev engine speed	$m\ s^{-1}$	1.26	0.89	0.86			0.31
		Ave engine load	kPa	256	347	290	390	582	509
		Stdev engine load	kPa	168	165	132			97
		Average MI		0.46	0.45	0.47	1.00	1.00	0.64
		Number of vehicles		4	8	5	1	1	2
	Street	Ave engine speed	$m\ s^{-1}$	5.10	4.92	5.42	5.12	5.16	5.45
		Stdev engine speed	$m\ s^{-1}$	1.19	1.41	2.27			0.34
		Ave engine load	kPa	206	266	315	520	600	610
		Stdev engine load	kPa	72	92	184			64
		Average MI		0.50	0.36	0.44	1.00	1.00	0.59
		Number of vehicles		4	8	4	1	1	2
12:00-14:00	**Freeways**	Ave engine speed	$m\ s^{-1}$	6.68	6.02	5.36			5.79
		Stdev engine speed	$m\ s^{-1}$	0.58	1.50	0.43			
		Ave engine load	kPa	225	337	229			419
		Stdev engine load	kPa	72	58	180			
		Average MI		0.75	0.42	0.51			1.00
		Number of vehicles		2	6	4			1
	Main Road	Ave engine speed	$m\ s^{-1}$	5.24	4.20	4.99		4.12	5.63
		Stdev engine speed	$m\ s^{-1}$	1.11	0.73	0.30		0.16	
		Ave engine load	kPa	325	276	210		622	518
		Stdev engine load	kPa	245	90	123		25	
		Average MI		0.48	0.49	0.55		0.53	1.00
		Number of vehicles		3	8	4		2	1
	Street	Ave engine speed	$m\ s^{-1}$	4.92	4.39	4.75		4.13	5.91
		Stdev engine speed	$m\ s^{-1}$	1.36	0.99	0.86		0.04	
		Ave engine load	kPa	297	282	181		596	514
		Stdev engine load	kPa	205	130	125		95	
		Average MI		0.49	0.36	0.38		0.63	1.00
		Number of vehicles		3	9	4		2	1

				Petrol			Diesel		
				Capacity class (ℓ)			Capacity class (ℓ)		
Period of day	**Road type**	**Value**	**Unit**	**< 1.4**	**1.4-2.0**	**< 1.4**	**1.4-2.0**	**1.4-2.0**	**> 2.0**
14:00-16:00	**Freeways**	Ave engine speed	m s^{-1}	5.19	5.73	5.60	5.65	5.41	6.72
		Stdev engine speed	m s^{-1}	1.54	1.32	1.11			0.78
		Ave engine load	kPa	309	309	284	393	569	534
		Stdev engine load	kPa	188	81	146			87
		Average MI		0.38	0.47	0.43	1.00	1.00	0.74
		Number of vehicles		4	10	5	1	1	2
	Main Road	Ave engine speed	m s^{-1}	4.29	4.81	4.61	4.14	5.30	5.43
		Stdev engine speed	m s^{-1}	0.80	0.73	0.47		1.34	0.00
		Ave engine load	kPa	247	287	232	345	493	546
		Stdev engine load	kPa	195	126	141		96	20
		Average MI		0.44	0.54	0.49	1.00	0.68	0.69
		Number of vehicles		5	11	5	1	2	2
	Street	Ave engine speed	m s^{-1}	4.82	4.64	4.31	4.48	4.26	5.13
		Stdev engine speed	m s^{-1}	0.99	0.86	0.34		0.55	1.07
		Ave engine load	kPa	285	266	243	370	511	360
		Stdev engine load	kPa	184	112	174		60	7
		Average MI		0.46	0.42	0.38	1.00	0.65	0.52
		Number of vehicles		5	11	5	1	2	2
16:00-18:30	**Freeways**	Ave engine speed	m s^{-1}	5.88	5.71	5.28	4.41	6.04	6.07
		Stdev engine speed	m s^{-1}	2.25	1.70	0.81			1.63
		Ave engine load	kPa	341	300	282	304	747	572
		Stdev engine load	kPa	155	101	142			188
		Average MI		0.40	0.51	0.59	1.00	1.00	0.61
		Number of vehicles		4	12	6	1	1	2
	Main Road	Ave engine speed	m s^{-1}	4.63	4.51	4.26	3.58	4.76	4.20
		Stdev engine speed	m s^{-1}	0.68	0.75	0.68		0.04	2.12
		Ave engine load	kPa	250	272	266	281	516	397
		Stdev engine load	kPa	176	105	141		64	148
		Average MI		0.50	0.54	0.49	1.00	0.79	0.52
		Number of vehicles		5	13	7	1	2	2
	Street	Ave engine speed	m s^{-1}	4.68	4.70	4.28	3.93	4.53	6.64
		Stdev engine speed	m s^{-1}	1.05	1.55	0.94		0.46	1.54
		Ave engine load	kPa	253	289	265	262	556	421
		Stdev engine load	kPa	164	100	157		56	133
		Average MI		0.49	0.44	0.44	1.00	0.72	0.50
		Number of vehicles		5	13	6	1	2	2
Other	**Freeways**	Ave engine speed	m s^{-1}	6.70	6.70	6.10	5.78		6.54
		Stdev engine speed	m s^{-1}	1.84	1.65	1.87			1.73
		Ave engine load	kPa	422	392	383	390		563
		Stdev engine load	kPa	180	88	165			155
		Average MI		0.43	0.40	0.53	1.00		0.65
		Number of vehicles		4	10	5	1		2
	Main Road	Ave engine speed	m s^{-1}	5.11	5.33	4.99	4.72	5.56	5.38
		Stdev engine speed	m s^{-1}	0.88	1.54	0.71		0.97	0.62
		Ave engine load	kPa	324	304	278	352	541	576
		Stdev engine load	kPa	187	116	130		40	72
		Average MI		0.50	0.44	0.45	1.00	0.61	0.62
		Number of vehicles		4	11	7	1	2	2
	Street	Ave engine speed	m s^{-1}	5.14	5.31	4.55	3.47	4.25	5.87
		Stdev engine speed	m s^{-1}	1.63	2.10	0.63		0.56	0.30
		Ave engine load	kPa	303	309	259	311	395	434
		Stdev engine load	kPa	161	153	108		11	299
		Average MI		0.39	0.37	0.41	1.00	0.63	0.50
		Number of vehicles		4	11	7	1	2	2

Ave – average, Stdev – standard deviation, MI matching index

Table L.2: Variation of measured engine-operating patterns for weekends.

				Petrol			Diesel		
				Capacity class (ℓ)			Capacity class (ℓ)		
Period of day	**Road type**	**Value**	**Unit**	**< 1.4**	**1.4-2.0**	**< 1.4**	**1.4-2.0**	**1.4-2.0**	**> 2.0**
06:30-09:00	**Freeways**	Ave engine speed	m s^{-1}	6.11	8.18	6.13			
		Stdev engine speed	m s^{-1}	1.61	2.12				
		Ave engine load	kPa	328	431	293			
		Stdev engine load	kPa	324	109				
		Average MI		0.46	0.58	1.00			
		Number of vehicles		3	3	1			
	Main Road	Ave engine speed	m s^{-1}	5.33	6.12	4.56		5.75	
		Stdev engine speed	m s^{-1}	1.45	2.45	0.25		1.12	
		Ave engine load	kPa	302	377	271		548	
		Stdev engine load	kPa	159	152	185		147	
		Average MI		0.39	0.32	0.51		0.61	
		Number of vehicles		5	7	3		2	
	Street	Ave engine speed	m s^{-1}	5.29	6.31	4.09		5.37	
		Stdev engine speed	m s^{-1}	1.11	2.68	0.87		1.12	
		Ave engine load	kPa	289	418	264		520	
		Stdev engine load	kPa	153	159	160		103	
		Average MI		0.43	0.26	0.47		0.56	
		Number of vehicles		5	7	3		2	
09:00-12:00	**Freeways**	Ave engine speed	m s^{-1}	5.72	8.16	5.49		7.61	8.99
		Stdev engine speed	m s^{-1}	1.47	1.32	0.39			
		Ave engine load	kPa	336	379	355		1006	771
		Stdev engine load	kPa	191	112	224			
		Average MI		0.36	0.33	0.53		1.00	1.00
		Number of vehicles		4	6	3		1	1
	Main Road	Ave engine speed	m s^{-1}	5.29	4.98	4.57		5.22	6.01
		Stdev engine speed	m s^{-1}	1.28	1.06	0.59		0.38	
		Ave engine load	kPa	304	297	261		479	609
		Stdev engine load	kPa	181	78	168		113	
		Average MI		0.46	0.50	0.54		0.71	1.00
		Number of vehicles		5	9	4		2	1
	Street	Ave engine speed	m s^{-1}	4.75	4.67	4.02		3.34	5.73
		Stdev engine speed	m s^{-1}	1.13	1.93	0.99		0.03	
		Ave engine load	kPa	253	273	230		523	615
		Stdev engine load	kPa	170	119	117		44	
		Average MI		0.45	0.41	0.47		0.74	1.00
		Number of vehicles		5	9	4		2	1
12:00-14:00	**Freeways**	Ave engine speed	m s^{-1}	5.11	4.92	7.75		5.62	
		Stdev engine speed	m s^{-1}	2.16	2.68				
		Ave engine load	kPa	193	381	308		679	
		Stdev engine load	kPa	18	202				
		Average MI		0.50	0.26	1.00		1.00	
		Number of vehicles		2	4	1		1	
	Main Road	Ave engine speed	m s^{-1}	5.07	4.09	4.09		3.72	
		Stdev engine speed	m s^{-1}	0.98	0.97	0.84			
		Ave engine load	kPa	286	259	268		435	
		Stdev engine load	kPa	164	96	183			
		Average MI		0.43	0.46	0.44		1.00	
		Number of vehicles		5	9	3		1	
	Street	Ave engine speed	m s^{-1}	5.08	4.19	4.65		4.86	
		Stdev engine speed	m s^{-1}	1.37	0.99	0.79			
		Ave engine load	kPa	290	277	389		590	
		Stdev engine load	kPa	156	97	319			
		Average MI		0.39	0.45	0.39		1.00	
		Number of vehicles		5	9	3		1	

				Petrol			Diesel		
				Capacity class (ℓ)			Capacity class (ℓ)		
Period of day	**Road type**	**Value**	**Unit**	**< 1.4**	**1.4-2.0**	**< 1.4**	**1.4-2.0**	**1.4-2.0**	**> 2.0**
14:00-16:00	**Freeways**	Ave engine speed	m s^{-1}	6.51	6.22	7.29		2.88	8.18
		Stdev engine speed	m s^{-1}	0.85	2.15				
		Ave engine load	kPa	199	369	226		303	746
		Stdev engine load	kPa	53	153				
		Average MI		0.40	0.35	1.00		1.00	1.00
		Number of vehicles		3	4	1		1	1
	Main Road	Ave engine speed	m s^{-1}	5.36	5.00	4.86		5.76	6.10
		Stdev engine speed	m s^{-1}	1.08	0.76	0.32			
		Ave engine load	kPa	237	331	312		637	578
		Stdev engine load	kPa	131	133	159			
		Average MI		0.55	0.42	0.41		1.00	1.00
		Number of vehicles		4	8	4		1	1
	Street	Ave engine speed	m s^{-1}	5.57	4.35	4.28		7.17	6.55
		Stdev engine speed	m s^{-1}	1.07	0.70	0.62			
		Ave engine load	kPa	226	297	253		512	608
		Stdev engine load	kPa	130	141	143			
		Average MI		0.50	0.40	0.36		1.00	1.00
		Number of vehicles		4	8	4		1	1
16:00-18:30	**Freeways**	Ave engine speed	m s^{-1}	5.57	7.52	6.17	6.35		8.51
		Stdev engine speed	m s^{-1}	3.59	1.09				
		Ave engine load	kPa	288	552	175	464		734
		Stdev engine load	kPa	18	156				
		Average MI		0.50	0.43	1.00	1.00		1.00
		Number of vehicles		2	4	1	1		1
	Main Road	Ave engine speed	m s^{-1}	5.34	5.33	4.39	4.77		6.03
		Stdev engine speed	m s^{-1}	1.12	0.86	0.66			
		Ave engine load	kPa	347	331	294	394		514
		Stdev engine load	kPa	168	134	208			
		Average MI		0.46	0.47	0.44	1.00		1.00
		Number of vehicles		4	9	3	1		1
	Street	Ave engine speed	m s^{-1}	4.89	4.63	3.96	3.69		5.97
		Stdev engine speed	m s^{-1}	1.51	1.11	1.51			
		Ave engine load	kPa	303	282	262	231		580
		Stdev engine load	kPa	154	104	172			
		Average MI		0.43	0.39	0.37	1.00		1.00
		Number of vehicles		4	9	3	1		1
Other	**Freeways**	Ave engine speed	m s^{-1}	6.09	6.27	2.24	7.19	5.74	
		Stdev engine speed	m s^{-1}	2.04	1.31				
		Ave engine load	kPa	418	372	321	487	748	
		Stdev engine load	kPa	92	91				
		Average MI		0.50	0.45	1.00	1.00	1.00	
		Number of vehicles		2	4	1	1	1	
	Main Road	Ave engine speed	m s^{-1}	5.75	5.00	4.08	4.98	5.69	
		Stdev engine speed	m s^{-1}	2.01	0.47	0.98		1.02	
		Ave engine load	kPa	338	325	305	456	571	
		Stdev engine load	kPa	113	84	236		150	
		Average MI		0.55	0.54	0.51	1.00	0.64	
		Number of vehicles		2	7	2	1	2	
	Street	Ave engine speed	m s^{-1}	4.82	4.22	4.12	5.24	4.46	
		Stdev engine speed	m s^{-1}	1.43	0.85	0.22		0.01	
		Ave engine load	kPa	327	304	311	460	509	
		Stdev engine load	kPa	103	93	285		15	
		Average MI		0.44	0.38	0.52	1.00	0.68	
		Number of vehicles		3	7	2	1	2	

Ave – average, Stdev – standard deviation, MI matching index

APPENDIX N: Emission Factors for Local Driving Conditions and Vehicles

Table N.1: Fuel consumption factors.

Table N.2: CO2 emission factors.

Table N.3: CO emission factors.

Table N.4: HC emission factors.

Table N.5: NOx emission factors.

Table N.1: Fuel consumption factors.

Fuel consumption factors (ℓ/100km) by fuel, capacity class (ℓ) and regulation			Petrol									Diesel		
			< 1.4			1.4-2.0			> 2.0			< 1.4	1.4-2.0	> 2.0
Day of week	**Period of day**	**Road type**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-2**	**Euro-2**	**Euro-2**
Weekday	06:30-09:00	Freeway	8.3	7.1	6.7	12.2	10.1	9.9	16.1	13.9	13.1	3.4	24.6	13.0
		Main Road	11.0	9.6	8.3	16.4	12.2	11.8	25.2	19.4	18.5	6.2	13.6	12.9
		Street	10.5	8.7	7.9	15.6	11.5	11.4	21.1	18.3	17.3	8.2	17.9	9.6
	09:00-12:00	Freeway	5.0	4.4	4.4	10.6	8.7	8.4	12.1	10.5	9.6	2.1	4.4	9.0
		Main Road	9.0	7.8	7.4	14.6	10.7	10.4	21.1	15.1	14.4	6.1	9.5	13.1
		Street	7.1	5.8	5.4	10.0	9.2	8.9	18.1	14.9	14.6	6.9	7.5	14.1
	12:00-14:00	Freeway	5.5	4.6	4.3	12.2	7.9	8.3	12.3	9.7	9.1			9.3
		Main Road	10.7	8.4	8.0	17.9	14.3	13.4	12.2	11.2	10.6		15.5	11.5
		Street	9.6	8.1	7.8	19.5	15.5	14.0	16.1	12.0	10.9		17.3	10.1
	14:00-16:00	Freeway	8.2	6.9	6.6	11.6	8.0	7.7	12.7	11.0	10.3	2.8	6.0	7.9
		Main Road	10.3	9.2	9.0	16.0	11.4	11.2	13.2	12.1	11.5	5.2	9.3	16.9
		Street	11.6	8.7	8.5	13.7	11.3	10.7	16.1	13.1	12.3	4.3	14.8	15.9
	16:00-18:30	Freeway	7.0	5.8	5.7	10.4	8.3	8.1	13.2	11.0	10.3	2.9	8.5	10.2
		Main Road	10.6	9.1	8.1	13.5	11.5	11.1	20.3	17.3	16.4	5.0	12.6	16.6
		Street	9.7	8.5	8.0	15.0	11.5	10.8	21.2	18.5	17.2	4.2	13.0	9.6
	Other	Freeway	6.9	5.7	5.4	10.8	8.8	8.4	18.2	13.8	13.5	3.1		8.9
		Main Road	9.6	8.1	7.7	13.4	9.7	9.6	17.5	13.4	12.3	4.0	8.0	12.9
		Street	8.0	6.9	6.4	11.8	10.1	9.7	17.6	14.6	13.9	5.2	14.5	10.1
Weekend	06:30-09:00	Freeway	7.9	6.4	6.2	9.6	7.8	7.7	14.6	9.7	9.3			
		Main Road	9.1	7.7	7.2	11.5	9.3	9.0	16.0	13.5	12.9		8.7	
		Street	10.0	7.7	7.3	11.9	9.8	9.7	19.3	15.5	14.7		11.2	
	09:00-12:00	Freeway	7.4	6.0	5.7	8.8	7.2	7.1	15.3	12.5	12.0		4.4	5.1
		Main Road	9.0	7.4	7.2	12.9	10.7	10.5	18.0	14.7	13.6		9.7	9.3
		Street	9.6	8.3	7.8	13.1	11.5	11.0	19.2	16.4	14.5		41.9	9.8
	12:00-14:00	Freeway	4.5	3.9	3.5	13.6	12.4	11.4	11.9	9.3	8.7		5.3	
		Main Road	9.0	7.4	7.0	17.4	12.9	12.7	19.7	16.5	15.2		11.4	
		Street	10.4	8.8	8.0	15.8	13.3	13.0	29.9	23.9	23.0		14.2	
	14:00-16:00	Freeway	6.0	4.7	4.9	10.3	8.4	8.0	9.8	8.0	8.1			5.9
		Main Road	7.1	6.2	6.0	14.4	10.3	10.5	19.8	16.3	15.4		7.9	9.4
		Street	7.0	5.9	5.8	16.0	12.0	12.0	21.9	17.4	16.9		5.7	8.7
	16:00-18:30	Freeway	6.6	5.6	5.1	10.4	8.6	8.7	7.0	5.8	5.8	2.8		5.4
		Main Road	10.2	8.4	8.0	11.0	9.2	8.4	20.0	14.8	13.8	4.0		9.1
		Street	10.6	8.6	8.2	15.4	11.2	10.7	26.0	24.8	21.2	5.1		8.3
	Other	Freeway	11.9	10.2	9.8	10.4	7.4	7.2				2.5	5.8	
		Main Road	8.1	6.9	6.6	10.7	8.6	8.5	17.6	15.4	13.8	3.7	8.6	
		Street	9.9	7.8	7.4	15.8	12.2	10.6	20.1	17.8	17.0	3.5	10.7	

Table N.2: CO$_2$ emission factors.

CO$_2$ emission factors (g km^{-1}) by fuel, capacity class (ℓ) and regulation			Petrol									Diesel		
			< 1.4			1.4-2.0			> 2.0			< 1.4	1.4-2.0	> 2.0
Day of week	**Period of day**	**Road type**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-2**	**Euro-2**	**Euro-2**
Weekday	06:30-09:00	Freeway	177	166	158	261	238	233	343	332	309	91	648	344
		Main Road	234	226	195	347	289	278	533	461	436	163	359	339
		Street	224	206	186	331	271	268	449	434	406	216	471	252
	09:00-12:00	Freeway	107	105	104	226	204	198	261	250	227	55	116	239
		Main Road	194	186	175	311	252	244	448	360	338	162	252	347
		Street	152	138	127	217	219	210	386	352	344	181	198	371
	12:00-14:00	Freeway	119	110	102	259	186	194	260	231	215			245
		Main Road	229	199	187	380	340	315	262	267	249		409	305
		Street	204	192	184	413	366	330	339	287	257		457	265
	14:00-16:00	Freeway	175	164	154	247	189	181	272	261	242	75	159	210
		Main Road	221	218	212	339	271	263	283	289	270	138	244	445
		Street	246	207	199	291	268	251	341	312	288	114	390	420
	16:00-18:30	Freeway	150	137	134	221	196	191	281	261	243	78	224	269
		Main Road	226	214	191	288	273	261	432	411	385	130	331	437
		Street	206	201	188	318	271	253	456	440	404	111	343	253
	Other	Freeway	147	133	128	232	206	197	389	325	319	80		234
		Main Road	205	192	182	284	229	225	371	318	288	105	212	341
		Street	171	162	150	252	236	229	375	349	328	136	382	267
Weekend	06:30-09:00	Freeway	169	151	146	205	181	182	310	231	218			
		Main Road	195	183	169	246	219	211	341	321	303		231	
		Street	213	183	170	256	230	228	416	371	347		296	
	09:00-12:00	Freeway	157	141	133	190	169	167	330	297	283		117	135
		Main Road	192	174	169	275	253	247	383	350	320		257	246
		Street	203	198	184	279	272	258	407	392	341		1105	258
	12:00-14:00	Freeway	95	93	83	288	294	269	255	220	204		141	
		Main Road	192	176	165	369	308	297	420	395	357		300	
		Street	221	207	187	335	314	304	638	568	543		374	
	14:00-16:00	Freeway	130	112	115	220	197	189	213	191	191			155
		Main Road	154	148	142	305	244	247	423	387	363		210	249
		Street	150	141	135	339	285	283	470	415	399		151	229
	16:00-18:30	Freeway	141	131	120	224	200	203	150	140	137	75		143
		Main Road	219	199	188	237	218	199	424	352	324	106		240
		Street	227	202	193	325	267	251	560	590	500	135		220
	Other	Freeway	254	240	230	222	175	169				66	152	
		Main Road	173	162	155	232	204	199	371	367	324	99	226	
		Street	212	185	174	336	290	249	424	425	400	94	283	

Table N.3: CO emission factors.

CO emission factors (mg km^{-1}) by fuel, capacity class (ℓ) and regulation			Petrol									Diesel		
			< 1.4			1.4-2.0			> 2.0			< 1.4	1.4-2.0	> 2.0
Day of week	Period of day	Road type	Euro-0	Euro-2	Euro-3	Euro-0	Euro-2	Euro-3	Euro-0	Euro-2	Euro-3	Euro-2	Euro-2	Euro-2
Weekday	06:30-09:00	Freeway	7476	1562	347	11162	1979	496	15626	2347	615	31	1361	58
		Main Road	10508	2047	691	17268	1942	565	26401	3274	952	201	67	90
		Street	10187	1497	501	15954	2163	673	20481	3374	802	400	168	221
	09:00-12:00	Freeway	4483	687	385	9877	1600	538	11007	1804	588	35	17	36
		Main Road	8259	1280	568	14968	2071	516	21938	2584	668	108	41	51
		Street	6889	1018	357	8987	1494	422	16778	2929	732	29	29	61
	12:00-14:00	Freeway	5033	850	368	12667	1154	474	12825	1588	655			50
		Main Road	9830	1453	657	18427	2590	1171	11692	1774	460		74	46
		Street	9086	1577	412	20318	3003	658	17379	1689	444		91	37
	14:00-16:00	Freeway	7652	1334	628	12162	1186	536	12095	1986	730	34	23	31
		Main Road	9560	1810	710	16682	2127	546	13088	1966	492	195	44	67
		Street	12112	1420	402	13092	1818	785	15737	1918	544	110	110	192
	16:00-18:30	Freeway	6612	1145	300	9697	1366	387	12684	1657	593	64	31	40
		Main Road	10339	1803	572	12703	2022	525	19796	2970	802	303	65	493
		Street	9426	1571	410	15606	2318	520	19545	3357	798	285	63	37
	Other	Freeway	6289	1209	343	9845	1785	561	17359	2508	672	39		35
		Main Road	9264	1432	374	13663	1878	477	18242	2364	561	95	32	51
		Street	7526	1391	565	11116	2107	666	17137	2299	623	274	427	43
Weekend	06:30-09:00	Freeway	7352	1163	395	8457	1723	410	14690	1284	542			
		Main Road	8596	1411	578	10600	1808	654	15912	2244	647		35	
		Street	9354	1258	507	10770	2087	516	17653	1652	564		44	
	09:00-12:00	Freeway	7012	1090	476	7782	1535	379	13646	2110	575		16	19
		Main Road	8462	1327	400	11977	2006	513	17244	2382	625		52	33
		Street	9266	1556	362	12874	2413	710	19103	2581	598		579	41
	12:00-14:00	Freeway	4346	818	250	13731	2648	536	10367	1790	774		21	
		Main Road	8513	1352	429	18440	2134	1070	19424	2557	785		331	
		Street	9760	1619	612	15371	2330	977	28189	4334	975		63	
	14:00-16:00	Freeway	5359	490	163	9380	1717	538	8357	601	365			21
		Main Road	6473	854	267	14727	2017	611	18747	2775	719		31	34
		Street	6713	498	242	16434	2213	687	20441	2639	771		43	31
	16:00-18:30	Freeway	6059	1115	467	9207	1903	485	6948	872	224	10		23
		Main Road	9522	1512	387	9939	1615	398	20850	2388	621	70		39
		Street	9995	1518	494	16132	1858	833	24469	5032	728	376		30
	Other	Freeway	11241	2222	448	9862	1180	337				9	21	
		Main Road	7499	1289	319	9601	1085	390	18194	2772	602	23	34	
		Street	9351	1305	573	16522	2217	467	20703	3480	816	21	79	

Table N.4: HC emission factors.

HC emission factors (mg km^{-1}) by fuel, capacity class (ℓ) and regulation			Petrol									Diesel		
			< 1.4			1.4-2.0			> 2.0			< 1.4	1.4-2.0	> 2.0
Day of week	**Period of day**	**Road type**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-2**	**Euro-2**	**Euro-2**
Weekday	06:30-09:00	Freeway	867	98	8	1308	105	12	1850	130	14	11	285	34
		Main Road	1278	173	33	1994	107	14	3068	218	37	47	36	37
		Street	1241	104	11	1780	117	35	2469	230	19	88	67	57
	09:00-12:00	Freeway	522	39	28	1145	82	12	1256	93	16	12	11	23
		Main Road	971	69	13	1653	111	12	2462	139	16	34	25	33
		Street	840	72	8	1027	81	10	1976	156	18	18	19	37
	12:00-14:00	Freeway	589	55	13	1391	74	23	1474	100	19			25
		Main Road	1160	74	15	2113	192	61	1385	109	10		41	29
		Street	1079	98	15	2323	266	15	2062	124	10		47	25
	14:00-16:00	Freeway	904	89	28	1355	73	12	1416	107	17	11	15	21
		Main Road	1146	174	67	1888	117	13	1560	119	12	44	25	43
		Street	1373	77	9	1575	99	18	1917	117	12	27	44	72
	16:00-18:30	Freeway	774	60	7	1139	79	9	1496	102	16	19	21	26
		Main Road	1257	135	13	1520	115	13	2395	195	25	61	34	118
		Street	1136	108	16	1768	160	12	2320	252	19	59	34	24
	Other	Freeway	717	61	8	1133	90	14	1959	138	16	13		23
		Main Road	1094	77	9	1513	101	12	2067	151	13	23	20	33
		Street	890	89	22	1312	157	46	2067	135	14	56	104	26
Weekend	06:30-09:00	Freeway	859	59	9	958	85	10	1642	80	14			
		Main Road	1014	87	13	1229	91	15	1927	145	21		22	
		Street	1113	67	11	1235	110	14	2078	130	15		28	
	09:00-12:00	Freeway	807	56	15	878	78	11	1558	109	14		11	13
		Main Road	998	72	9	1416	110	12	2081	153	14		26	23
		Street	1115	106	8	1536	178	45	2350	196	15		207	25
	12:00-14:00	Freeway	532	68	6	1590	143	16	1191	87	17		14	
		Main Road	1012	79	10	2151	205	83	2353	154	18		84	
		Street	1159	107	14	1867	224	85	3297	244	30		37	
	14:00-16:00	Freeway	613	43	6	1081	92	13	922	60	10			15
		Main Road	744	55	6	1632	110	29	2220	150	17		20	24
		Street	785	45	6	1866	128	35	2458	170	18		18	22
	16:00-18:30	Freeway	718	57	14	1043	94	12	825	57	6	7		14
		Main Road	1113	78	9	1149	82	10	2376	144	15	19		24
		Street	1187	85	11	1830	100	19	2880	417	28	79		21
	Other	Freeway	1287	115	12	1113	70	9				6	14	
		Main Road	867	67	8	1100	74	10	2157	162	15	11	22	
		Street	1110	70	13	1884	155	13	2468	207	20	11	38	

Table N.5: NO$_x$ emission factors.

NO$_x$ emission factors (mg km^{-1}) by fuel, capacity class (ℓ) and regulation			Petrol									Diesel		
			< 1.4			1.4-2.0			> 2.0			< 1.4	1.4-2.0	> 2.0
Day of week	**Period of day**	**Road type**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-0**	**Euro-2**	**Euro-3**	**Euro-2**	**Euro-2**	**Euro-2**
Weekday	06:30-09:00	Freeway	2617	142	20	3664	189	31	3829	161	48	433	2944	1620
		Main Road	2918	140	48	4110	139	43	5918	356	82	742	1700	1613
		Street	2580	160	41	4334	211	44	5177	346	66	946	2221	1160
	09:00-12:00	Freeway	1029	53	23	3181	126	34	3286	117	45	252	547	1123
		Main Road	2199	86	37	4229	203	33	5788	170	51	739	1190	1633
		Street	1774	108	28	2174	105	33	5393	280	46	855	936	1749
	12:00-14:00	Freeway	1543	54	24	3664	170	27	2928	122	49			1159
		Main Road	3295	88	40	4391	187	79	2233	176	45		1933	1436
		Street	2611	153	29	4965	334	52	3479	177	52		2163	1251
	14:00-16:00	Freeway	2381	80	38	3284	163	35	3223	118	48	348	747	986
		Main Road	2441	200	42	4373	208	38	2312	178	46	631	1149	2099
		Street	3036	100	31	3559	128	55	3718	174	53	534	1859	1950
	16:00-18:30	Freeway	2082	111	19	3002	163	27	3222	214	52	359	1057	1266
		Main Road	2678	176	41	3465	210	41	4845	319	70	579	1567	1987
		Street	2345	161	33	4009	224	37	5073	244	66	469	1620	1191
	Other	Freeway	2290	111	20	3563	151	29	5724	281	39	374		1101
		Main Road	2594	124	27	3845	181	30	4572	161	45	489	998	1609
		Street	2252	134	35	3503	211	38	4263	235	56	620	1730	1240
Weekend	06:30-09:00	Freeway	2430	86	25	3369	155	19	4428	156	33			
		Main Road	2594	88	37	3636	144	38	3875	171	53		1087	
		Street	2920	89	35	3950	193	28	4121	289	53		1396	
	09:00-12:00	Freeway	2186	86	30	2992	140	19	4475	146	37		551	638
		Main Road	2554	124	28	3629	197	35	4628	189	55		1216	1151
		Street	2342	158	30	3433	228	47	4061	235	62		5119	1217
	12:00-14:00	Freeway	1046	77	18	3634	156	45	4039	111	43		663	
		Main Road	2476	139	31	4205	235	65	4505	213	71		1356	
		Street	2900	104	41	3975	293	61	9012	282	47		1769	
	14:00-16:00	Freeway	1297	102	8	3237	152	29	2338	188	24			729
		Main Road	1495	119	23	4098	160	39	5500	185	54		988	1172
		Street	1352	126	21	4092	160	49	5435	232	67		708	1078
	16:00-18:30	Freeway	2007	86	26	3686	171	23	1267	104	25	352		674
		Main Road	3040	116	26	3208	94	27	5140	184	52	496		1131
		Street	3001	156	36	4109	123	54	5123	349	45	563		1030
	Other	Freeway	3753	165	30	3377	159	18				310	717	
		Main Road	2287	110	21	2860	180	28	4088	216	53	472	1065	
		Street	2867	98	39	4073	154	35	4760	192	67	439	1322	

APPENDIX O: Breakdown of Total Vehicle Activity

Table O.1: Fraction of total vehicle kilometres by vehicle type and driving condition.

Fraction of total vehicle kilometres (%)			Petrol				Diesel				Grand Total
			Capacity class (ℓ)			Total	Capacity class (ℓ)			Total	
Day of Week	Period of day	Road type	< 1.4	1.4-2.0	> 2.0		< 1.4	1.4-2.0	> 2.0		
Weekday	06:30-09:00	Freeway	0.7	3.6	3.5	7.8	0.3	0.0	0.2	0.5	8.3
		Main Road	2.1	5.4	2.1	9.6	0.1	0.4	0.8	1.3	10.8
		Street	0.9	0.7	0.4	2.0	0.0	0.1	0.1	0.1	2.2
	06:30-09:00 Total		3.7	9.6	6.0	19.4	0.4	0.5	1.1	1.9	21.3
	09:00-12:00	Freeway	0.1	1.2	2.1	3.4	0.0	0.4	1.2	1.6	5.0
		Main Road	0.5	1.3	1.2	2.9	0.0	0.1	0.6	0.7	3.5
		Street	0.3	0.3	0.2	0.8	0.0	0.0	0.2	0.3	1.1
	09:00-12:00 Total		0.8	2.8	3.4	7.1	0.0	0.5	2.0	2.5	9.6
	12:00-14:00	Freeway	0.5	0.5	0.9	1.9	0.0	0.0	0.3	0.3	2.2
		Main Road	0.3	0.7	0.4	1.4	0.0	0.0	0.6	0.7	2.1
		Street	0.1	0.2	0.1	0.4	0.0	0.0	0.1	0.1	0.5
	12:00-14:00 Total		0.9	1.5	1.3	3.7	0.0	0.0	1.0	1.0	4.7
	14:00-16:00	Freeway	0.2	1.5	0.5	2.2	0.1	0.1	1.7	1.8	4.0
		Main Road	0.5	1.9	0.6	3.0	0.1	0.1	0.6	0.8	3.8
		Street	0.2	0.2	0.1	0.5	0.0	0.0	0.0	0.1	0.6
	14:00-16:00 Total		0.9	3.6	1.2	5.7	0.2	0.2	2.3	2.7	8.4
	16:00-18:30	Freeway	1.1	6.1	3.8	11.0	0.2	0.0	1.9	2.1	13.1
		Main Road	1.2	4.2	1.9	7.4	0.1	0.7	0.3	1.0	8.4
		Street	0.7	0.8	0.4	1.9	0.0	0.1	0.1	0.2	2.1
	16:00-18:30 Total		3.0	11.2	6.1	20.3	0.3	0.8	2.2	3.3	23.6
	Other	Freeway	1.3	2.7	4.0	8.0	0.0	0.0	2.1	2.1	10.1
		Main Road	1.0	3.3	1.0	5.3	0.1	0.1	0.6	0.8	6.1
		Street	0.5	0.8	0.3	1.6	0.0	0.0	0.1	0.1	1.7
	Other Total		2.8	6.8	5.2	14.8	0.1	0.1	2.8	3.0	17.8
Weekday Total			12.1	35.4	23.4	70.9	1.0	2.2	11.3	14.5	85.4
Weekend	06:30-09:00	Freeway	0.1	0.2	0.2	0.5	0.0	0.0	0.0	0.0	0.5
		Main Road	0.2	0.3	0.2	0.7	0.0	0.2	0.0	0.2	0.9
		Street	0.2	0.1	0.1	0.3	0.0	0.0	0.0	0.0	0.4
	06:30-09:00 Total		0.5	0.6	0.4	1.5	0.0	0.2	0.0	0.2	1.7
	09:00-12:00	Freeway	0.2	0.3	0.1	0.7	0.0	0.0	0.3	0.3	1.0
		Main Road	0.8	0.7	0.7	2.1	0.0	0.1	0.2	0.2	2.3
		Street	0.2	0.2	0.2	0.6	0.0	0.0	0.0	0.0	0.6
	09:00-12:00 Total		1.2	1.2	1.0	3.3	0.0	0.1	0.6	0.6	4.0
	12:00-14:00	Freeway	0.1	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.2
		Main Road	0.7	0.3	0.1	1.2	0.0	0.0	0.0	0.0	1.2
		Street	0.2	0.3	0.0	0.5	0.0	0.0	0.0	0.0	0.5
	12:00-14:00 Total		1.0	0.7	0.2	1.8	0.0	0.0	0.0	0.0	1.9
	14:00-16:00	Freeway	0.0	0.1	0.0	0.2	0.0	0.0	0.2	0.2	0.4
		Main Road	0.3	0.4	0.1	0.9	0.0	0.2	0.1	0.3	1.2
		Street	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.3
	14:00-16:00 Total		0.4	0.7	0.2	1.3	0.0	0.2	0.3	0.5	1.8
	16:00-18:30	Freeway	0.5	0.3	0.1	0.8	0.1	0.0	0.5	0.5	1.3
		Main Road	0.2	0.8	0.1	1.0	0.1	0.0	0.2	0.3	1.4
		Street	0.1	0.1	0.0	0.3	0.0	0.0	0.1	0.1	0.3
	16:00-18:30 Total		0.8	1.2	0.1	2.1	0.2	0.0	0.8	0.9	3.0
	Other	Freeway	0.0	0.6	0.0	0.6	0.0	0.1	0.0	0.1	0.7
		Main Road	0.3	0.7	0.1	1.1	0.0	0.2	0.0	0.2	1.3
		Street	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.2
	Other Total		0.3	1.4	0.1	1.8	0.1	0.3	0.0	0.4	2.2
Weekend Total			4.2	5.7	2.0	12.0	0.2	0.8	1.6	2.7	14.6
Grand Total			16.3	41.2	25.4	82.9	1.2	3.0	12.9	17.1	100.0

Table O.2: Total vehicle kilometres travelled by vehicle type and driving conditions.

Million vehicle kilometres		Petrol				Diesel				Grand Total
		Capacity Class (ℓ)			Total	Capacity Class (ℓ)			Total	
Period of day	Road type	< 1.4	1.4 – 2.0	> 2.0		< 1.4	1.4 – 2.0	> 2.0		
Weekday										
06:30-09:00	Freeway	106	531	525	1 162	47		27	74	1 236
	Main Road	311	798	313	1 423	11	60	117	189	1 612
	Street	136	105	57	298	2	8	13	22	321
06:30-09:00 Total		554	1 435	895	2 883	59	69	157	285	3 168
09:00-12:00	Freeway	11	182	306	500	1	61	176	238	738
	Main Road	67	186	173	426		15	83	99	525
	Street	46	49	32	126	1	5	33	39	165
09:00-12:00 Total		124	417	511	1 052	2	82	292	375	1 428
12:00-14:00	Freeway	73	80	127	280			41	41	320
	Main Road	47	109	59	216		3	95	98	313
	Street	19	27	12	58		1	12	13	71
12:00-14:00 Total		139	216	199	554		4	147	151	705
14:00-16:00	Freeway	23	226	76	326	10	10	246	267	593
	Main Road	73	279	94	446	15	17	93	125	571
	Street	33	30	16	79	1	6	2	9	88
14:00-16:00 Total		129	536	186	850	26	34	341	401	1 251
16:00-18:30	Freeway	166	907	564	1 637	29	1	280	309	1 947
	Main Road	181	631	285	1 097	13	100	38	152	1 249
	Street	99	125	58	282	2	15	16	34	315
16:00-18:30 Total		445	1 664	908	3 016	45	116	334	495	3 511
Other	Freeway	192	401	594	1 186	5		310	315	1 501
	Main Road	149	489	144	783	11	17	90	119	902
	Street	76	116	40	233	3	2	10	15	248
Other Total		418	1 006	778	2 202	19	19	411	449	2 650
Weekday Total		1 808	5 274	3 476	10 558	151	322	1 682	2 155	12 713
Weekend										
06:30-09:00	Freeway	10	31	27	68					68
	Main Road	33	48	30	111		23		23	134
	Street	25	17	8	51		2		2	53
06:30-09:00 Total		68	96	65	229		25		25	255
09:00-12:00	Freeway	28	49	20	97		1	51	52	149
	Main Road	116	100	99	314		8	28	36	350
	Street	31	28	27	86			4	4	90
09:00-12:00 Total		175	176	146	497		9	83	92	589
12:00-14:00	Freeway	10	6	14	29		1		1	30
	Main Road	112	51	11	174		2		2	175
	Street	24	42	3	68		4		4	71
12:00-14:00 Total		145	99	27	271		6		6	277
14:00-16:00	Freeway	4	20		24			30	30	53
	Main Road	52	65	18	135		27	17	44	178
	Street	9	21	4	34		2	4	6	39
14:00-16:00 Total		64	105	23	192		29	50	79	271
16:00-18:30	Freeway	74	38	8	120	9		70	79	199
	Main Road	31	114	10	156	12		34	46	202
	Street	17	20	3	41	1		8	9	50
16:00-18:30 Total		122	172	22	316	22		112	134	450
Other	Freeway		86		87	6	15		21	108
	Main Road	40	104	14	158	2	30		32	190
	Street	10	17	4	31	1	4		5	36
Other Total		50	207	18	275	9	49		59	334
Weekend Total		625	855	301	1 780	32	118	245	395	2 175
Grand Total		2 432	6 129	3 777	12 338	182	441	1 927	2 550	14 888