UNIVERSITY OF ALBERTA

A SOFTWARE MODEL FOR TRANSPORTATION EMISSION INVENTORIES

BY

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ABSTRACT

This thesis describes an on-road vehicle emissions and fuel consumption (E&FC) inventory model named CALMOB6. It is destined for use by traffic planners who need such a tool primarily to measure the effect of any traffic control measure they take on E&FC. CALMOB6 combines data from the transportation model EMME/2 and the vehicle emissions model MOBILE6 to generate criteria and greenhouse pollutants inventories on a second-by second basis. Being *CAL*ibrated to *MOB*ILE*6*, CALMOB6 can estimate past, current and future emission levels. Similarly, it uses fuel consumption trends from Natural Resources Canada for the light-duty fleet and from Environmental Protection Agency for heavy-duty vehicles. E&FC can be estimated on any scale from an entire regional fleet down to a single road, on a defined time scale and for a particular vehicle subclass. The model is sensitive to local geographic and local meteorological parameters and accounts for the effect of cold-started, alternatively-fuelled and super-emitting vehicles.

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I wish to express my gratitude to Transport Canada for the research grant and bursary that they provided. Their financial support made this work possible.

Last in the list but first in my heart is my little loving family. In spite of the distance separating us, mum, dad and Vishwadha have always been providing emotional support and encouragement. This has been very motivating. Finally, my dear wife...a special word of thanks goes to Preety of course. She provided relentless support throughout the writing up of this thesis, as well as technical assistance, both critical for completing the project in a timely manner.

Thanks God. The thesis is done...

to my little loving family...

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NOMENCLATURE

APTA: American Public Transit Association
AQI: Air Quality Index

BER: Base Emission Rate
BSER: Basic Start Emission Rate

CAFE: Corporate Average Fuel Economy
CALMOB6: CALibrated to MOBile6
CARB: California Air Resources Board
CARB: Carbureted
CBD: Central Business District
CL: Closed Loop
CNG: Compressed Natural Gas
CO: Carbon Monoxide
CO_2: Carbon Dioxide
COM: COMmuter

DET: DETerioration
DOT: Department of Transport
DR: Deterioration Rate

E&FC: Emissions and Fuel Consumption
EMFAC: Emission Factor
EMITPP06: Emission Post Processor, version 6
EMME: Équilibre Multimodal, Multimodal Equilibrium
EMPPAFL4: EMme Post Processor, Alternative FueLs, version 4
ERE: Exhaust Running Emissions

FFV: Flexible Fuel Vehicle
FI: Fuel Injection
FTP: Federal Test Procedure

HC's: Hydrocarbons
HFET: Highway Fuel Economy Test

LEV: Low-Emission Vehicle
LPG: Liquefied Petroleum Gas

Mil: accumulated Mileage
MOVES: MOtor Vehicle Emission Simulator
mpg: Miles Per Gallon
MVEI: Motor-Vehicle Emissions Inventory

NOx: Nitrogen Oxides
NMHC: Non-Methane HydroCarbons
NREL: National Renewable Energy Laboratory
NYSERDA: New York State Energy Research and Development Authority

OL: Open Loop
PFI: Ported Fuel Injection
PM: Particulate Matter

REI: Relative Emissions Index

S/N: Serial Number

TBI: Throttle Body Injection
TIUS: Truck Inventory and Use Survey

THC: Total HydroCarbons
TMP: Transportation Master Plan

UDDS: Urban Dynamometer Driving Schedule
ULEV: Ultra-Low Emissions Vehicle
US EPA: United States Environmental Protection Agency

VOC's: Volatile Organic Compounds

WVU: West Virginia University

ZML: Zero Mile Level

CHAPTER 1

INTRODUCTION TO THE NEED AND MODELING OF CALMOB6 SOFTWARE – A TRANSPORTATION EMISSION INVENTORIES MODEL

Chapter 1 illustrates the need for continuous update in on-road vehicle emission regulations and for quantifying the amount of emissions and fuel consumption. Hence, an emissions inventory tool is required to estimate those quantities and to measure the progress of any proposed solution.

1.0 INTRODUCTION

Transport has become a significant source of air pollution in major metropolitan areas [1]. It is not news that tight emissions[1] controls have been continuously adopted. To conform to the strict standards, motor vehicle manufacturers have been forced to improve the overall vehicle performance on an on-going basis. This improvement in vehicle technology and fuel formulation mainly has led to the production of lower emitting vehicles year after year. However, with the good economy prevailing in industrialized countries and thus with prosperity in household income, motor vehicle ownership has climbed [2]. People have shifted from small car use to larger and heavier vehicles which consume more fuel and emit more. As a result, the enforcement of stringent emission regulations is being counterbalanced [3]. Health, environmental and economic problems related to on-road vehicle emissions are today a primary issue addressed by numerous countries.

The main obstacle today is the difficulty faced in accurately quantifying the emissions and fuel consumption data from motor vehicles region-wise firstly and then global-wise. There are numerous factors that affect emissions. After proper emission and fuel consumption (E&FC) quantification, while considering all the related factors, the intensity of the problem can be measured and the progress of the solution verified. In this context, an E&FC inventory tool is required to account for the level of tailpipe-released air contaminants as well as energy usage. Current models or studies fail to capture E&FC amount characterized by location, time and fleet[2]. These models do not feature all the main factors that influence

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[1] Emissions: In this thesis, emissions are referred to those as undesired pollutants that are released from the tailpipes of on-road internal-combustion-engine vehicles. Such pollutants are the criteria gases (Carbon Monoxide (CO), Nitrogen Oxides (NOx) and Non-Methane Hydrocarbons (NMHC)) and the global warming gas (Carbon Dioxide (CO_2)).

[2] Fleet: A group of all on-road motored vehicles operating within a defined region (e.g. a city). In this context, the vehicle fleet has been characterized by parameters such as age or registration distribution, mileage-accumulation rate and vehicle category.

E&FC. Likewise, they do not demonstrate E&FC magnitude and variability as a vehicle is driven under real-world conditions.

This thesis demonstrates the development of CALMOB6 – a software model for on-road transportation[3] emission inventories. It describes a model that incorporates traffic[4] flow data with the various emission factors to compute the overall E&FC. The program can deal with scenarios as large as the entire urban region to as small as a single road link between two traffic lights.

This research project partnership has been forged between the University of Alberta, the City of Edmonton and Alberta Transportation to enhance and validate the emissions modeling capabilities of the city's regional travel model[5]. The objectives of this project as stated in the proposal for research funding document are to [4]:

1. Enhance and upgrade the Edmonton regional travel vehicle emissions model, with an emphasis on improved estimates of criteria emissions, greenhouse gas (especially carbon dioxide) and particulate matter for past, current and future fleets.

2. Extend the application of the vehicle emissions model to use in the state-of-the-art traffic micro-simulation models.

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[3] Transportation: The act of moving goods and passengers from one place to another by means of on-road motored vehicles.

[4] Traffic: It is the movement of on-road vehicles along a public route. It includes the domestic and commercial transportation of goods and/or passengers.

[5] Travel Model: Travel models determine the amount of transportation activity occurring in a region based on an understanding of the daily activities of individuals and employers as well as the resources and transportation infrastructure available to households and individuals when making their activity and travel decisions [5]. This includes measures such as number of trips, time of day, length of trip, mode of transportation, route or location of trips, average speed of travel and age of vehicle. The number of transit trips, automobile occupancy and vehicle miles of travel (VMT) of common performance measures used to measure transportation activity [6].

3. Validate the vehicle emissions model results against observed and literature data.

4. Promote development of sustainable transportation principles by evaluating emissions impacts arising from alternative land-use scenarios, transportation investment and policies, provided by the application of regional travel forecasting and traffic micro-simulation emissions modeling.

5. Develop and support skills and capability in vehicle emissions model research and practical application.

The main purpose of the City of Edmonton's Transportation Master Plan (TMP) is to establish a framework that the City will use to address future transportation needs up to the year 2020 [7]. It establishes the policies, strategies and priorities for shorter-term decisions and actions by the City of Edmonton on behalf of Edmontonians. As part of the Master Plan, the impacts of changing traffic flows on overall emissions and fuel consumption are to be estimated [8, 9, 10].

In this perspective, an emission and fuel consumption tool to measure the effects of traffic flow and traffic management decisions on overall emissions and fuel consumption was needed. Thus, in the 1990's, Dr. M.D Checkel developed the EMITPP06 (Emission Post Processor, Version 6) vehicle emissions inventory tool [8, 9]. E&FC were estimated for the passenger car, medium- and heavy-duty trucks, and buses. Functions of E&FC were obtained by running laboratory engine dynamometers. These functions were calibrated against Environment Canada's MOBILE 5C database. In addition, adjustment factors were used to estimate emissions and fuel consumption from alternative-fuelled vehicles [10]. Traffic data was read from EMME/2 output data and a traffic motion model was thereby micro-simulated. The software was written in QuickBasic and the City of Edmonton is currently employing EMITPP06.

In 2001, Michalski [11] has translated the QuickBasic-written emission inventory software to Matlab to take advantage of the newest programming features. Simultaneously, the whole program was redesigned and improved to include Windows style user interface. The latter software was thereby renamed as EMPPAFL4 which stands for EMme Post Processor, Alternative FueLs, version 4. This inventory tool is calibrated against the MOBILE5C data.

With the eventual replacement of US EPA's emission model MOBILE5 with MOBILE6 in December 1999 [12], more vehicle standards are considered. The introduction of Tier 0, Tier 1, LEV, ULEV and Tier 2 standards has made on-road vehicles less polluting [6]. Thus, in MOBILE6, there is a better understanding of vehicle emissions. Compared with MOBILE5 estimates, MOBILE6 estimates are higher in the past and lower in the future. Further, MOBILE6 incorporates updated basic emission rates, "real world" driving patterns and emissions, separation of start and running emissions, and improved correction factors [12]. Additionally, the vehicle fleet has been sub-divided in twenty-eight vehicle classes in MOBILE6 versus the eight MOBILE5 eight vehicle classes. To take advantage of these added benefits and to make better estimates of emissions and fuel consumptions there was a need to upgrade the EMPPAFL4. The advantage with this software is that the basic program structure and E&FC functions already exist. Hence, the main reason of this study was to improve the accuracy of the emissions inventories.

In this context, Chapter 2 gives a basic literature review of the need for such an inventory tool. It includes the factors that affect emissions. With that in mind, the chapter illustrates the work of some researchers as well as the emission inventory models developed by some agencies. In the final stages of this section, the problems/limitations associated with the available emission tools are targeted and subsequently lists of features that are desired in an emissions inventory tool are pondered upon. With those criteria, all the requirements to be considered in CALMOB6 are set.

The following chapter (Chapter 3) illustrates the development of the on-road vehicle emissions inventory software. It investigates the types of information that have been retrieved from other emissions/transportation models for use in CALMOB6. Moreover, the optimum use of reliable data obtained from government agencies and private organizations is presented. Finally, other factors available from published technical literatures are built in the model to make it state-of-the-art software.

Chapter 4 is a collection of tests that have been administered to CALMOB6. The purpose of such simulations is, basically, to verify and demonstrate the appropriateness of each and every feature included in the model. Different scenarios are considered under a range of prevailing conditions to graphically observe the adequate response of the tool. Simulations over real operating conditions to measure the effectiveness of the model against real-time data are also addressed.

Similar to the previous section, Chapter 5 demonstrates use of the tool CALMOB6. This unit, however, shows applications of the tool to address some questions of interest to policy makers. Different cases are analyzed. Questions like “Is it wiser to encourage high bus rider-ship in a newly set-up community or to make provisions for high use of privately owned motor-vehicles?” are examined. All situations however are addressed by considering the environmental aspect solely.

With the above presented sections, Chapter 6 concludes on the project and determines to what extent the goals of the project have been met. The usefulness of the tool is laid out. Further, it exposes the limitations of CALMOB6. Accordingly, it suggests other specific features that should be included into the software. Finally, a brief overview of the expected future work and studies is produced. This work provides a solid foundation with a powerful vehicle emissions inventory tool at disposal. Extensive studies are still plausible to improve the software flexibility, adaptability and use in multiple circumstances by including further emissions-related features.

REFERENCES

1. Colvile, R.N.; Hutchinson, E.J.; Mindell, J.S; Warren, R.F., "The Transport Sector as a Source of Air Pollution", Atmospheric Environment 35, pp. 1537-1565, 2001.
2. Roorda, M.J.; Mohammadian, A.; Miller,E.J., "Toronto Area Car Ownership Study: A Retrospective Interview and its Applications", Transportation Research Record, issue no. 1719, p.69-76, 2000
3. Noland, R.B.; Quddus, M.A, "Flow Improvements and Vehicle Emissions: Effects of Trip Generation and Emission Control Technology", Transportation Research Part D: Transport and Environment, v11, n1m pp. 1-14, Jan 2006.
4. Checkel, M.D., "Transportation Emissions Modeling for Better Choices", Proposal for research funding to Transport Canada, May 2004.
5. Harvey, G.; Deakin, E., "A Manual of Regional Transportation Modeling Practice for Air Quality Analysis", National Association of Regional Councils, Version 1.0, 1993.
6. National Academy of Sciences, "Modeling Mobile-Source Emissions", National Academy Press, 2000.
7. City of Edmonton, "Edmonton's Transportation Master Plan", Apr 1999.
8. Checkel, M.D., "Vehicle Emissions Project – The City of Edmonton Transportation Master Plan", Mar 1996.
9. Checkel, M.D., "Truck and Bus Engine Emissions – The City of Edmonton Transportation Master Plan", Nov 1996.
10. Checkel, M.D., "Engine Emissions of Alternative Fuelled Vehicles – The City of Edmonton Transportation Master Plan", Oct 1997.
11. Michalski, M., "EMPPAFL4 – A Software Model of Engine Emissions for Cars, Trucks and Buses", University of Alberta, M.Eng/MBA Project, Apr 2001.
12. US EPA, "MOBILE6 – A Revised Model for Estimation of Highway Vehicle Emissions", EPA420-S-99-001, Dec 1998.

CHAPTER 2

REVIEW OF THE REQUIREMENTS AND USEFULNESS OF AN ON-ROAD VEHICLE EMISSIONS INVENTORY TOOL

Chapter 2 exposes the facts which will force environment and/or transport authorities to take appropriate contravening measures. For any of those measures, there needs to be a justification in terms of the resulting amount of emission and fuel consumption – hence a need for an emissions integration model. The usefulness of such a tool can be extended to measure the progress and validity of any adopted solution. How effective are the actual transport/emission models and the present inventory tools today? The aim of this section is to introduce transportation models, emission models and published literatures. This literature review determines the effectiveness of these models in addressing the numerous issues. Finally, the desirable requirements of an emissions and fuel consumption inventory model are set.

2.0 INTRODUCTION

Movements of people, goods and information are fundamental components of all human societies. This literature review highlights the need for an emission tool and outlines the potential uses of such a tool.

The next component of this chapter gathers most of the factors that affect emissions from on-road vehicles in the real world. The worthiness of those agents is directly related to the amount of resulting emissions and fuel consumption. This happens primarily through the extent of modification in the variables.

The following section examines the available models, necessary for estimating and predicting vehicle emissions. Only the parts of those models, which are of need and interest to developing an emissions inventory tool are discussed.

This chapter concludes by outlining the desirable features of an emission inventory tool.

2.1 QUANTIFY E&FC – IS IT VITAL?

Industrial revolution and urbanization contributed to increased mobility [1]. Canadian cities are not left apart. With the ever-growing economic needs, travel demand is expected to rise accordingly. More Canadians are driving sport-utility vehicles (SUV's) which consume more fuel and cause more air pollution [2].

The following are alarming facts and estimates from Environment Canada, the World Health Organization and an Italian study of motorway tollgate attendants:

- "In analyzing air-pollution and mortality data from eight Canadian cities (Québec City, Montréal, Ottawa, Toronto, Hamilton, Windsor, Calgary and Vancouver), Health Canada estimates 5,900 deaths per year in these cities can be attributed to air-pollution." [3]

- "The Ontario Medical Association has estimated that air pollution costs more than $1 billion a year in hospital admissions, emergency room visits, and absenteeism." [4]
- "The World Health Organization recently estimated that 800,000 deaths per year worldwide (1.4% of all deaths) could be attributed to urban outdoor air pollution." [5]
- "Our study demonstrates that continuous exposure to traffic pollutants impairs sperm quality in young/middle-aged men." [6]

Current thinking is that newer vehicles emit less due to technology advancement. However, the above facts will lead one to believe that tighter emissions standards have to be issued after some definite time period.

Illustrated in Figure 2-1 is the Central Edmonton Air Quality index. Measurements are made on an hourly basis. United States Environmental Protection Agency (US EPA) uses six criteria pollutants as indicators of the air quality [8] : ozone, carbon dioxide, nitrogen dioxide (/nitrogen oxides), sulphur dioxide , particulate matter and lead.

In that Central Edmonton region, there is no factory and hence industrial emissions are minimal. Hence, the major, if not only, source of emissions that deteriorates the air quality overthere is transportation. In the morning, the air-quality is stable. The effect of sunshine and increasing traffic movement leads to a deterioration of air-quality. When a graph of Air-Quality Index (AQI) versus time is plotted, a bell-shaped curve is usually obtained, as shown in Figure 2-1. The peak of the graph is reached when the optimum conditions are met, namely a combination of sunshine and vehicle population. For instance, a maximum of around 23 is reached at 20:00, on July 4th, 2005. The overall AQI of that day is satisfactory. So as to keep the AQI to a desirable level with eventual population growth, appropriate measures have to be taken. One possible measure can be use of public transit instead of car. This can oppose the resulting emission swell due to increased vehicle number,.

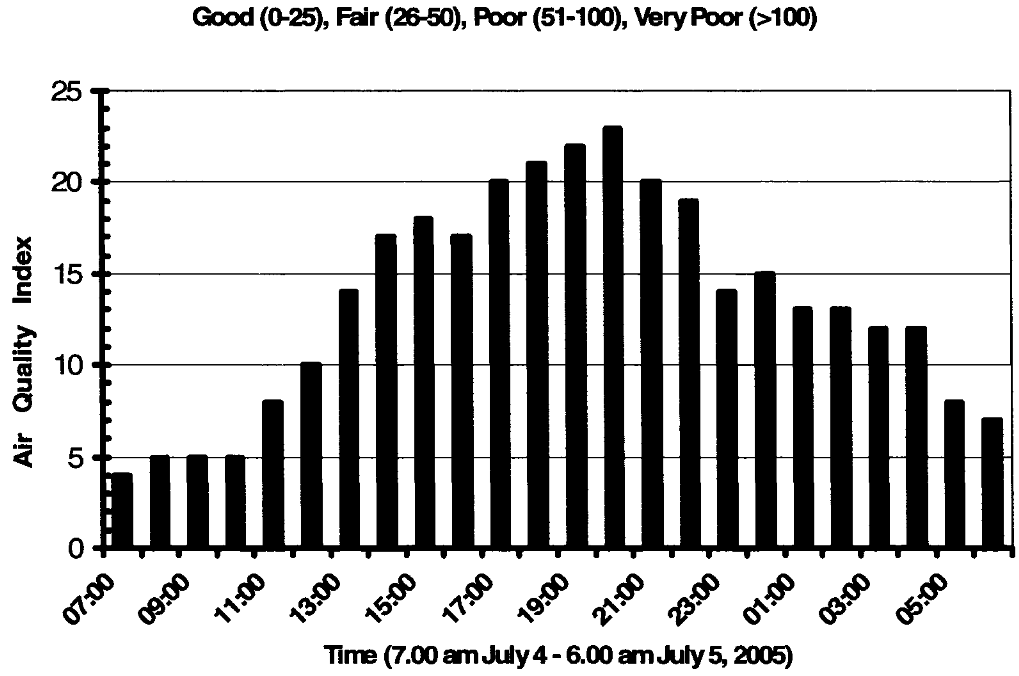

Figure 2-1: Air Quality Index (AQI) in Central Edmonton over the 24 hours of a normal weekday in July 2005. Ranges in the AQI denote the air quality as good, fair, poor and very poor. [7]

In urban areas, on-road transportation is one of the major sources of air contaminants. Motor vehicles are the major attributable sources due to their significant emissions of CO, CO_2, NOx, PM and VOC's. In order to minimize pollution due to air contaminants from car exhaust, transportation planning in urban areas is required. This will help in achieving economic, social and environmental needs of the residents and businesses. Decisions such as transportation, infrastructure, services and policies that lead towards reduced pollution are desired. These decisions can be substantially improved through the delivery of reliable and accurate quantitative vehicle emissions data. In this way, the effect on transportation pollution when altering traffic controls and/or infrastructure can be measured. Urban travel forecasting models are used to predict future travel demand. These models assist in identifying future transportation requirement. Further, they evaluate the impacts of alternative land use and transportation scenarios. In this context, traffic planners require an additional tool. The latter is needed to justify the following:

- Initiatives in the area of traffic control,
- Infrastructure development,
- Mode choice programs, and
- Regulatory actions.

The model considers the change in vehicle energy demand and the resulting alteration in emitted precursors. Besides, the transportation forecasting people can advise on the appropriate level of regulation and guide the future development [8].

2.2 FACTORS INFLUENCING EMISSIONS AND FUEL CONSUMPTION

The task of estimating emission and fuel consumption inventories is intricate; it involves several complexly interrelated parts. The vehicle fleet is composed of a broad range of vehicles which can be further differentiated according to the type, age, engine size, condition, fuel use and much more. Emissions are also affected by some geographical, meteorological conditions and traffic patterns [9]. Hence, accurate quantifying and predicting of E&FC inventories requires proper consideration of numerous factors. It is hard to obtain precise E&FC levels. On the other hand, through the availability of certain reliable sources of data and with some suitable modelling techniques, reasonable estimates can be achieved.

2.2.1 VEHICLE FLEET

The vehicle type can be simply demarcated by car, light duty truck, heavy-duty truck and buses. Each of the types can be further sub-classified and emissions for each of the subdivisions differ. Emission standards of the light-duty fleet have been improved drastically over the last decade. Tier 1 standard, with a start phase-in in 1994 and applicable up to 2003, minimized the gap between the light-duty truck and passenger car. Post year 2003, all light-duty fleet and some of the lowest in weight heavy-duty vehicles are allowed the same emission limit under the Tier 2 standard [10]. Similarly, there has been continuous improvement in heavy-duty vehicle and bus emission limit. For instance, in October 1994 and December 2000, EPA signed for more stringent emission regulations, effective as of 2004 and 2007 respectively [11].

The vehicle fleet may be composed of a variety of fuel-based propellant. Gasoline is common for the light-duty fleet while diesel is mainly burnt by heavy duty vehicles. In view of reducing emission limits, multiple fuels have been tried on various vehicles. Natural gas, propane (LPG), methanol, ethanol and electric are still secondary proponents to gasoline and diesel.

Technology employed by the vehicle is crucial. Even though the general trend is toward the ported fuel injection, there are still non-negligible amount of throttle body injection and carburetor employed. The types of fuel delivery to the engine deteriorate differently [12]. As a result, same aged vehicles employing different types of fuel delivery emit differently. During the past one or two decades, remarkable improvements in vehicle design have increased the fuel economy, hence lowered the emission rate. Some other major examples of vehicle technology improvements are: the introduction of the catalyst and the continuous upgrade in vehicle body design to minimize the coefficients of drag and of rolling resistance. Different technologies deteriorate at different paces, the consequence of which leads to different emission rates. As a result, the older the vehicles get, the more polluting they become and higher will be the probability of them being classified as high-emitters due to some malfunction.

How fast fleet renewal is cropping up will definitely change the emissions in whole as long as the traffic is left unchanged. Newer vehicles emit less. Consequently, larger be the fraction of new vehicles, lower will be the overall emission. In this context, the vehicle age distribution profile can provide the fleet renewal pace. This varies from region to region or from country to country and it depends, more likely, on the country's economy. Accordingly, the fleet age distribution is a vital component in estimating the fleet renewal and thence the total resulting emissions and fuel consumption.

2.2.2 LOCAL GEOGRAPHICAL AND ROAD CONDITIONS

The amount of E&FC is road-grade dependent. Energy demand of a vehicle at a given speed will differ from an ascending slope to a descending one and to that of a level road. The overall power developed by the engine differs in all the three cases. Road grade, as a result, is one of the main geographical parameters that impinge on the total E&FC. The road roughness is also an aspect. Higher roughness results in higher engine power demand.

The next set of geographical parameters are the geometric road design [13]. Traffic control signalization at the places of intersection forces vehicles to decelerate, stop, idle before they re-accelerate to the desired speed. On the other hand, bridges can aid in the smooth traffic flow at points of intersection. Logically, the first case demands higher power; which equally implies higher resulting E&FC [14, 15, 16]. Similarly, there may be several transportation engineering road designs that can reduce the level of congestion and render the traffic more fluid and less polluting.

2.2.3 LOCAL METEOROLOGICAL CONDITIONS

Meteorological conditions are quite hard to model. They influence the emission rate significantly. Cold ambient temperature usually retards the warming-up stage of any vehicle. Any vehicle started after a certain soak time[6] will naturally emit more. The amount of emissions will increase if the ambient temperature is lower. To account for this increase, one possibility could be the effect of catalyst which will take longer to reach its design operating temperature [15]. Moreover, the ambient temperature affects the evaporation rate of the fuel which affects evaporative emissions, (not considered in this study which concentrates on start and running emissions).

2.3 TRANSPORTATION/EMISSIONS MODELING FRAMEWORK [9]

To estimate the on-road vehicle emissions inventory, it is essential to have a vehicle-activity component and an emission-factor component. The rest of this chapter will introduce the various models from which such elements can be retrieved. However, the integration of the vehicle-activity and the emission-factor models can be classified according to different scale levels of consideration. The left hand side of Figure 2-2 gives the transportation models and the sets of data that they can provide. It is only when combined with specific information from the emissions model (illustrated in the right hand side of Figure 2-2), that the scale of use of the transportation/emission model can be defined.

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[6] Soak Time: This is the period of time the engine remains off in a particular ambient environment after running.

At the microscopic level, driving cycles are used to obtain the second-by-second vehicle operation data. Power based E&FC functions are used for estimation At the macroscopic level, raw data such as average speed, travel distance and traffic volume are plugged into a basic formula. The inventory in this case will give a basic idea when comparing some control strategies. At the mesoscale level, the model is mainly based on statistical data. For example, statistically obtained modal emission rates are used in the latter case.

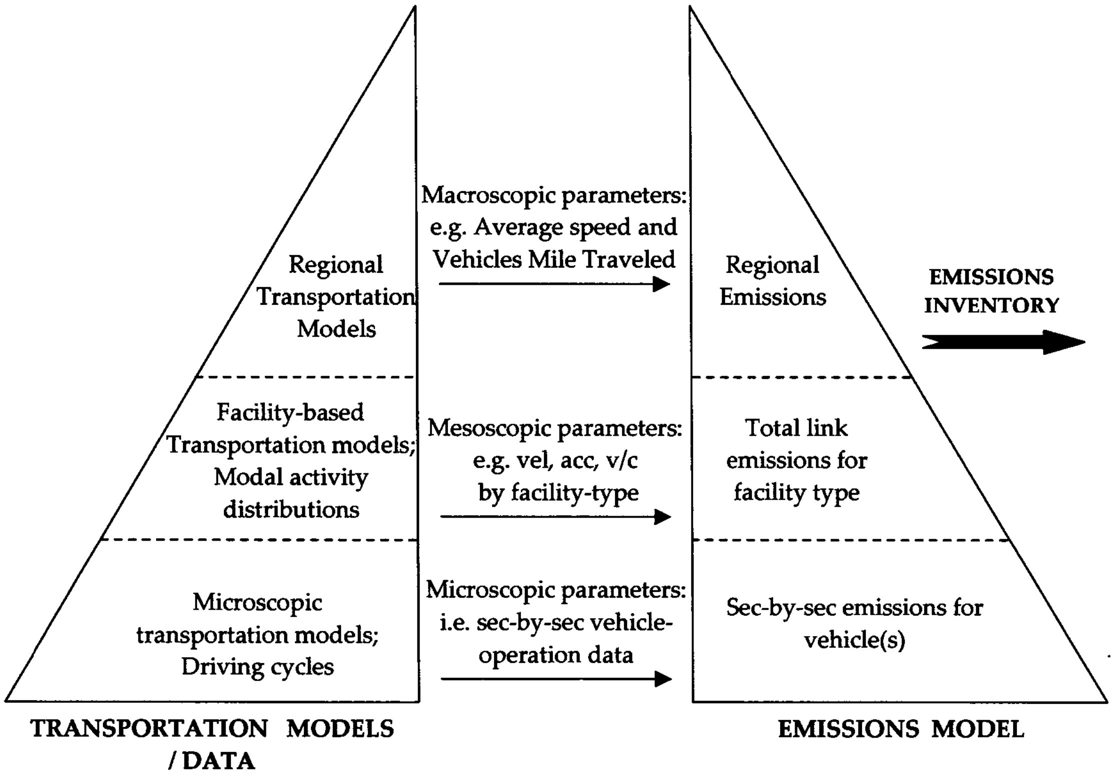

Figure 2-2: Transport/Emissions Modeling Framework [9]

2.4 VEHICLE EMISSION MODEL

There are several vehicle emission models being developed worldwide. This section will concentrate on the most widely used emission models in the North American continent and Europe. Little emphasis will be laid on other emission models, developed by numerous researchers in view of aiding in the quantification of emissions and fuel consumption. The latter emission models, presented in section 2.6, integrate the transportation forecasting models

2.4.1 US EPA's MOBILE6 Model

In the United States, the Environmental Protection Agency (EPA) developed the MOBILE model in 1978. The latter is used in all its states except California. MOBILE6.0, released in Jan 2002, is the most up to date software for estimating and predicting the gram per mile amount of the following: hydrocarbons, carbon monoxide and oxides of nitrogen. Further updates to report on particulate matter (PM10 and PM2.5) and air-toxic compounds from on-road vehicles were brought up in MOBILE6.1 and MOBILE6.2 respectively. Fuel consumption and the emissions of greenhouse gases will be considered in MOBILE6.3 [17].

An extensive number of vehicles were made to follow the standard FTP driving cycles in order to obtain the gram/mile emission factor. MOBILE6 emission rates date back from the 1960's and extends to 2050, by considering the applicable emission standards for each vehicle type. MOBILE6 has a significantly larger breakdown of vehicle classes (twenty-eight) over its predecessor MOBILE5.

The MOBILE model uses components like annual vehicle miles traveled (VMT) accruals, average speed, vehicle age and ambient temperature and vehicle type to generate its emission factors [9]. A base emission rate for each vehicle type is set-up at reference quantities of the above components. The BER (Base Emission Rate) is estimated using the cumulative annual accrued VMT and the evolution of vehicle technologies. More important, the zero-mile level and the deterioration rate for both start and running pollutant emissions from every MOBILE6 vehicle class are necessary to calculate the BER. Correction factors are used to adjust the BER to reflect emissions at different average speed and temperature other than the referenced ones. MOBILE6 uses vehicle registration data to obtain vehicle age which is employed to generate a fleet distribution-by-age profile, specific to each vehicle type. For each calendar year, MOBILE6 assumes that twenty-five of the most recent model-year vehicles to be in operation [18]. The 25-year age profile of each vehicle class, when combined with the respective BER for each calendar year, develops a composite base emission rate. This output is given on a gram per mile basis and is representative of a vehicle category from the whole fleet. To estimate emissions inventory, MOBILE6 multiplies the average travel distance with the composite BER and the number of vehicles.

MOBILE uses average speed to describe the "approximate" vehicle motion. This is a major drawback of the on-road vehicle emission model as several traffic patterns can be represented by a single average speed. Vehicle dynamics such as acceleration, deceleration, idling and cruising are not considered. Consequently, MOBILE6 estimates are not responsive to the actual travel and the actual driving conditions. As a result, emissions cannot be localized. Hence, MOBILE is classified as a macro-scale model.

Samaras *et al* [19] conclude that MOBILE is appropriate for use in countries where the vehicle fleet characteristics are similar to the North American ones. As for the off-road vehicles, US EPA proposes the NONROAD model. It is noteworthy that these two US EPA models will be replaced by the "New Generation model", MOVES - MOtor Vehicle Emission Simulator. This is planned for release in 2006 [20]. In addition to accounting for both on-road and off-road vehicles and to covering the wide range of pollutants as well as the greenhouse gases, this modeling tool will permit the emission estimation from a defined small scale to the national level [21]. Fuel consumption is also considered. Contrary to MOBILE6, MOVES relies on second-by-second data through a "modal" emission rate approach. As a result, MOVES will be able to develop the emission and fuel consumption quantities on a finer scale. This approach is unlikely with MOBILE because its emission factor is on a gram per mile basis. Recent vehicle technologies, such as the hybrids and advances internal combustion (gas and diesel) are also considered in MOVES.

2.4.2 CARB's MVEI7G Model

The State of California employs the MVEI7G model. This model has been adapted to account for the more strict emission standards that are enforced in that state. There are four distinguishable sub-models which make up MVEI7G – CALIMFAC, WEIGHT, EMFAC and BURDEN. Similar to MOBILE, it generates exhaust and evaporative emission estimates for the same criteria pollutants. In addition, fuel consumption and greenhouse gases quantities are also estimated [22].

The core of the MVEI model, EMFAC, is similar to MOBILE6. The composite base emission rates of each vehicle type generated for each calendar year are functions of the average speed and temperature. EMFAC2002 is the most recent version. CALIMFAC provides the base emission rates by considering California's stringent emission standards. WEIGHT assumes the VMT by vehicle age, vehicle category, the distribution of vehicles and vehicle technology fractions [9]. So, CALIMFAC and WEIGHT provide the required input variables to EMFAC. The latter calculates the composite BER. Subsequently, BURDEN uses correction factors to adjust EMFAC-obtained emission rates to applicable non-standard average speed and temperature. Finally, BURDEN couples the VMT, number of vehicles to generate an on-road vehicle emissions inventory.

The overall approach by the Californian model is comparable to the US EPA MOBILE6 model. However, while MOBILE still employs the standard FTP cycles to measure the gram/mile factor, EMFAC uses a test cycle, which is more representative to the real-world driving conditions – the unified cycle.

2.4.3 COPERT Model

In Europe, the CORINAIR (CO-oRdinated INformation on the Environment in the European Community – AIR) working group developed a methodology using appropriate emission factors. The results of their work have been translated, in 1989, into a software name COPERT (COmputer Programme to calculate Emissions from Road Transport) to ease the application of that methodology [19]. Actually, COPERT III, financed by the European Environment Agency, is employed by European Union (EU) countries to produce a national emission dataset from road transport. The emissions considered in this most recent emissions calculator are CO, NOx, VOC, PM, N_2O, NH_3 and NMVOC [23]. Fuel consumption is also computed. FOREMOVE model is a post processor to COPERT. It predicts vehicle emissions and fuel consumption inventories. Likewise, it accounts for future vehicle-technology improvement and evolution in fuel characteristics. [24].

What properties make the COPERT different? While the two American vehicle emission models, described above, use annual mileage accumulation to estimate the base emission rate, COPERT bases its assumption on the fuel sale statistical data. Moreover, MOBILE relies on the standard FTP cycles to obtain the gram/mile emission rate. COPERT, instead, tries to mimic the real life situation by testing vehicles over several driving patterns in various locations. Finally, MOBILE obtains an excess amount of resulting emissions due to cold start. This amount is the difference between the Bag 1 and Bag 3 emissions of the FTP cycle. MOBILE assumes a cold-start after a 12-hr soak time [25]. On the other hand, COPERT model assumes a cold start when the coolant temperature is below 70^0C [19].

2.5 TRANSPORTATION SIMULATION AND FORECASTING MODELS

To develop the E&FC inventory, it is vital to combine the vehicle emission model with the traffic/travel model. Hence, it is important to know the type of information the models can provide. In this literature survey, two transportation models namely VISSIM and EMME/2 will be highlighted.

2.5.1 VISSIM MICRO-SIMULATION MODEL

Based primarily on the traffic flow theory, this traffic micro-simulation model uses computerized methods. It is capable of tracking vehicle movements along every street and of simulating visual displays of real-time traffic and conditions. Thus, the speed and location of individual vehicles can be calculated and/or predicted [31]. Nowadays, such models account for the driver behavior and the vehicle performance [30]. Examples of such micro-simulation models are VISSIM, PARAMICS, CORSIM, INTEGRATION, etc.

In addition to the main traffic flow, VISSIM has the ability to integrate light rail and bus rapid transit. Moreover, the human behavioral parameters can be modified. Likewise, VISSIM is not restricted by the number of vehicles, nodes and links for a particular simulation purpose [26].

2.5.2 EMME/2 TRAVEL FORECASTING MODEL

EMME/2 is a regional travel-forecasting model that helps in computation task solely. It is also referred to as a macro-analytical model. Unlike micro-simulation models, EMME/2 does not have the capability to track individual vehicle motion. Examples for other travel forecasting models are TRAFFIX, TRIPS, TransCAD and TP Plus. Such models are unable to estimate the immediate traffic flow impacts of some minute measures. For example, when increasing limit speed by a small amount, from 50km/hr to 52km/hr, there is a possibility that the increase in traffic volume may not be captured by the macro-analytical model. Micro-simulation models are reputed for observing such immediate effect [27].

Modeling with EMME/2 involves two parts: the supply part and the demand part. The supply side requires the transportation infrastructure information as input. The demand side accounts for the travel demand. Model traffic flow is achieved when equilibrium between the supply side and demand side is reached [28]. This model is based on the travel demand model involving, trip generation, trip distribution, time of day allocation, mode split and assignment [29].

EMME/2 has the ability to deliver specific results for post-processing purposes. To generate an emission inventory, for instance, the traffic volume and the average speed on each link can be obtained. As for cold start, the number of vehicles within a certain distance from the point of origin can be auto-assigned. The product of MOBILE composite BER (in gram/mile), the traffic volume and the length of the link gives total emissions. EMME/2 can store several scenarios. As a result, it can be used to study other options. Such option could be flow on an alternative infrastructure [28].

Unfortunately, the time step data of the individual vehicle motion cannot be provided by EMME/2.

2.6 TRANSPORTATION – EMISSIONS MODELS [9]

Numerous researcher and agencies are trying to develop a transport emission model. Some examples are the TREM, MEASURE, UC Riverside, GIT and TRANSIMS. These models have a resulting continuous vehicle motion trace.

TRANSIMS, for instance, uses a set of three different acceleration types to develop such a trace. These are hard acceleration, insignificant acceleration and hard deceleration. The acceleration rate is however, chosen based on a cumulative probability distribution [9].

For estimating emissions, TRANSIMS develops a trajectory that is fed to its modal emissions model. Vehicle emission are estimated and predicted through this modal emissions model. This means that emission rates are adjusted according to the mode of operation of the vehicle: idle, start, hot stabilized, etc. These modal emission rates were obtained through laboratory tests at the various operation modes.

2.7 EMITPP06 – the emission micro-simulation post-processor

EMITPP06 was developed by Dr. M. David Checkel in 1995 [32]. Being a post-processor, the model uses data from the EMME/2 travel-demand tool. It is a micro-simulation model where inputs such as the traffic average speed and the permissible speed are required to model driving cycle. Further information such as the vehicle and link type is needed. Using different model acceleration rates for different vehicle types, specific speed traces can be generated with a number of stops, idling time and cruise time.

Laboratory-dynamometer obtained emission and fuel consumption are applied to the model. These mathematical functions relate to the E&FC rates as a function of the developed engine power. Finally, the model is calibrated against MOBILE5C data to estimate and predict emission. As for fuel consumption function calibration, fuel economy trends for the vehicle types are considered.

2.8 CONCLUSION

To estimate emissions and fuel consumption a model is required. This model will use output data from the travel-demand model and the mobile-source emission model to generate E&FC inventory.

MOBILE and EMFAC are those which are applicable for the countries where the vehicle fleet has similar characteristics to the American one. These main US vehicle emission models are macro-scale; they use average speed to obtain the emission factors. As a result, the real-time driving condition is not reflected in the emission inventory model. Consequently, they cannot be employed to correctly evaluate the emission effect on any traffic control measures.

The other Transport-Emission models are meso-scale; they are able to generate the individual vehicle path. However, the emission rates are adjusted to represent the different vehicle operation modes emissions. These modal emissions were characterized according to the speed and acceleration of the vehicle. These models are more refined than the macro-scale models.

For a micro-scale vehicle emission model, the speed-time trace of the driving cycle is essential. Ideally, this can be obtained though the traffic micro-simulation models. However, to a less accurate extent, the speed traces can be modeled using the following estimates: the average speed, road length and limit speed on the link. Rather than relating emission rates to vehicle operation modes (as with the meso-scale transport-emission models), power-based emissions will be more accurate. These functions relate the E&FC rate with the developed tractive power of the vehicle. Hence, the second-by-second E&FC quantities obtained from the power-based E&FC functions are more reliable when estimating total E&FC.

Several inter-related factors influence the level of E&FC. E&FC quantities can be related to the real world by accounting for the local geographic parameters, the evolution of the fleet and the local meteorological factors. Examples of geographical conditions are road grade and altitude. Further, temperature effect, high-emitters, cold-start effect, alternative fuel vehicles are some of those components that need to be considered for reliable estimates.

REFERENCES

1. Rodrigue, J.P.; Comtois, C.; Slack, B., "The Geography of Transport Systems", Hofstra University, Department of Economics & Geography, 2006 (http://people.hofstra.edu/geotrans)
2. Health Canada, http://www.hc-sc.gc.ca/iyh-vsv/environ/traf_e.html , 2004 (site accessed on May 24, 2006)
3. Environment Canada, http://www.ec.gc.ca/cleanair-airpur/Health_Concerns-WSC8A1FE65-1_En.htm, Aug 2005 (site accessed on May 17, 2006)
4. Environment Canada , http://www.ec.gc.ca/cleanair-airpur/Health,_Environment_and_the_Economy/Economic_Issues-WS2EE1026A-1_En.htm , June 2005 (site accessed on May 25, 2006)
5. Environment Canada, http://www.ec.gc.ca.cleanair-airpur/ Revised Mortality Estimates Dues to Air Pollution, (site accessed on July 25, 2005)
6. De Rosa M.; Zarrilli, S.; Paesano, L.; Carbone, U.; Boggia, B.; Peretta, M.; Maisto, A; Cimmino, F.; Puca, G.; Colao, A.; Lombardi, G., "Traffic Pollutants Affect Fertility in Men", Oxford Journals – Medicine - Human Reproduction Vol. 18, No.5 pp.1055-1061, 2003.
7. http://www.telusgeomatics.com/tgpub/ag_air/default.asp (site accessed on July 25, 2005)
8. Busawon, R.; Checkel, M.D., "Predicting On-Road Vehicle Emissions Inventories", Association Québécoise du Transport et des Routes (AQTR), Québec, April 2006.
9. National Academy of Sciences, "Modeling Mobile-Source Emissions", National Academy Press, 2000
10. DieselNet, http://www.dieselnet.com/standards/us/light.html, (site accessed on May 25, 2006)

11. DieselNet, http://www.dieselnet.com/standards/us/hd.html, (site accessed on May 25, 2006)

12. US EPA, "Determination of Start Emissions as a Function of Mileage and Soak time for the 1981-1993 Model-Year Light-Duty Vehicles", EPA420-R-01-058, M6.STE.003, Nov 2001.

13. Abo-Qudais, S.; Abu Qdais, H., "Performance Evaluation of Vehicle Emissions Prediction Models", Clean Technologies and Environmental Policy, vol. 7, No. 4, pp.279-284, Dec 2005.

14. Tong, H.Y.; Hung, W.T.; Cheung, C.S., "On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions", Journal of the Air & Waste Management Association, vol. 50, April 2000.

15. Joumard, R.; Jost, P.; Hickman, J., "Influence of Instantaneous Speed and Acceleration on Hot Passenger Car Emissions and Fuel Consumption", SAE 950928, Feb 1995.

16. Rakha, H.; Ding, Y., "Impact of Stops on Vehicle Fuel Consumption and Emissions", Journal of Transportation Engineering, vol. 129, no. 1, Feb 2003.

17. US EPA, "Updating Fuel Economy Estimates in MOBILE6.3 - DRAFT", EPA420-P-02-005, M6.GHG.001, Aug 2002.

18. Yu, L., "Effects of High Emitter Vehicles on the On-Road Vehicle Emission Modeling", Center for Transportation Training and Research, No. 167600-1, Oct 2000.

19. Samaras, Z.; Zachariadis, T., "Modelling the Emissions of Road Vehicles at Macroscale and Microscale", Air Pollution Emissions Inventory, Vol. 3, Chapter 3, pp. 71, 1998.

20. US EPA, "A Roadmap to MOVES2004", EPA420-S-05-002, Mar 2005.

21. US EPA, http://www.epa.gov/otaq/ngm.htm (site accessed on May 18, 2006)

22. CARB, "EMFAC2001 Version 2.08 / EMFAC2002 Version 2.2 – User's Guide"

23. Kouridis, C.; Ntziachristos, L.; Samras, Z., "COPERT III – Computer Programme to Calculate Emissions from Road Transport – User manual (Version 2.1), European Environment Agency, Nov. 2000.

24. Tsilingidis, G.; Zachariadis, T.; Samaras, Z.; Chantzaridou, A, "An Emissions Inventory for the City of Thessaloniki", 7th International Conference on Environmental Science and Technology, Greece, Sept. 2001.

25. US EPA, "Basic Exhaust Emission Rates of Open Loop Vehicles for MOBILE6: Exhaust Emissions at High and Low Altitudes and Running Emissions for Motorcycles, Light-Duty Diesel Vehicles and Trucks and Pre-

1981 Model Year Light-Duty Gasoline Vehicles and Trucks", EPA420-R-01-027, M6.EXH.005, Apr 2001.

26. Institute of Transportation Engineers – California Border Section, "A Report on the Use of Traffic Simulation Models in the San Diego Region", Mar 2004.
27. Liu, R.; Van Vliet, D.; Watling, D., "Microsimulation Models Incorporating both demand and Supply dynamics", Transportation Research Part A: Policy and Practice, vol. 40, Issue 2, pp. 1225-150, Feb 2006.
28. INRO, "The EMME/2 Transportation Planning Software: Modelling and Analysis Features", www.inro.ca
29. Hunt, J.D.; "The Role of Modelling in the Transportation Master Plan", City of Edmonton, Mar 1997.
30. PTV Planung Transport Verkehr AG, "VISSIM 4.00 – User Manual", Jun 2004.
31. Chu, L.; Liu, H.X.; Recker, W., "Development of the Capability-Enhanced PARAMICS Simulation Environment", Institute of Transportation Studies, UCI-ITS-WP-02-8, Aug 2002.
32. Checkel, M.D, "Vehicle Emissions Project – The City of Edmonton Transportation Master Plan", Mar 1996.
33. US EPA, "Automobile Emissions: An Overview", EPA400-F-92-007, Fact Sheet OMS-5, Aug 1994.

CHAPTER 3

METHODOLOGY ADOPTED IN THE DEVELOPMENT OF CALMOB6 – THE ON-ROAD VEHICLE EMISSIONS INVENTORY SOFTWARE

As was discussed in Chapter 2 there is a need for a micro-simulation traffic tool. With this tool, power-based emission and fuel consumption (E&FC) functions are required to develop a reliable micro-scale vehicle emission model. This refined model is essentially sensitive to the vehicle driving conditions – acceleration, cruise, idle, stops, etc. E&FC are directly related to the engine power demand rather than using statistical means to obtain E&FC at modal vehicle operation. CALMOB6 can be used to evaluate traffic control strategies and hence, aid in policy decision making. This tool has been designed for use by city-traffic planners.

3.0 INTRODUCTION

Traffic planners require a tool to evaluate the resulting emission and fuel consumption (E&FC) when any minute traffic control measure is applied. The goal of this project is to provide transportation engineers with an on-road E&FC calculator. City of Edmonton data is used for the sake of illustration in this thesis. The tool is named CALMOB6 for CALibrated to MOBile6.

Figure 3-1 illustrates the main components that are required in the modeling of CALMOB6. Emission factors are derived from the MOBILE6 database, after considering the data characteristics, the zero-mile level emissions and the deterioration rate primarily. To represent an average emission rate, representative of the whole fleet, a composite base emission rate has been generated. The vehicle registries provided a list of vehicle identification numbers (VIN's). These were narrowed down to the metropolitan region of concern. The VIN's were decoded and every vehicle was categorized as per CALMOB6 vehicle classification. For each vehicle class, an age distribution was generated. It is assumed that the fleet is composed of vehicles with a maximum age of twenty-three. This applies for every calendar year, from 1990 to 2030. Combining the fleet-age distribution profile with the MOBILE6 base emission rates, a set of composite base emission rates, representative of region's traffic, is obtained. These are stored in the *Temp.xls* and *TempBus.xls* Excel files in CALMOB6.

Similarly, fuel consumption data for the light-duty fleet was obtained from Natural Resources Canada (NR Can). US EPA data was used for the heavy-duty fleet fuel consumption. The trends are projected up to year 2030. They give the fuel consumption rate in L/100km for each vehicle category as a function of the calendar year considered. Equations representing each trend are used in CALMOB6.

It is noteworthy that MOBILE does not give emission data representative of the actual driving conditions. The US EPA (United States Environmental Protection Agency) generates those base-emission rates (BER) after simulating real vehicles on standard FTP cycles in the laboratory. Similarly, NR Can uses the 55/45 City /Highway cycle. These cycles do not account for the different driving cycles on the road. Power-based emission and fuel consumption (E&FC) functions are derived by running an engine laboratory dynamometer at the University of Alberta. These model E&FC functions are simulated over the standard FTP cycle to generate a model gram/mile for each vehicle class used in CALMOB6. Emissions rates are stored in *Model Rates Emissions.xls* and *Model Rates FC.xls* Excel files. Power demand by an engine lab dynamometer does not correspond with the power demand of an on-road vehicle. Hence, the model emission rates differ from the composite base emission rates. A multiplicative factor (ratio of MOBILE6 gram/mile to Simulator gram/mile) is used to adjust the E&FC functions for every calendar year.

These adjusted E&FC functions are then applied to the driving cycles generated by CALMOB6. The emission model reads data from the EMME/2. Information on type of link, average speed on the link and speed limit on every link/zone are used by CALMOB6 to generate a model driving cycle. Thus, the vehicle operation data at every instant can be obtained. A resolution of 0.2 second was used. Each model vehicle is simulated over the driving cycle to obtain instantaneous power. The power-based E&FC functions are then applied to the instantaneous power data to obtain E&FC rate at every 0.2 second. Finally, CALMOB6 integrates the emission rates over the time span and the vehicle population to generate an overall E&FC inventory. As a result, effects of travel infrastructure such as road grade on E&FC can be accounted.

It is worthwhile pointing out that user-adjustable variables are included in CALMOB6. This widens the flexibility of the on-road vehicle emission model.

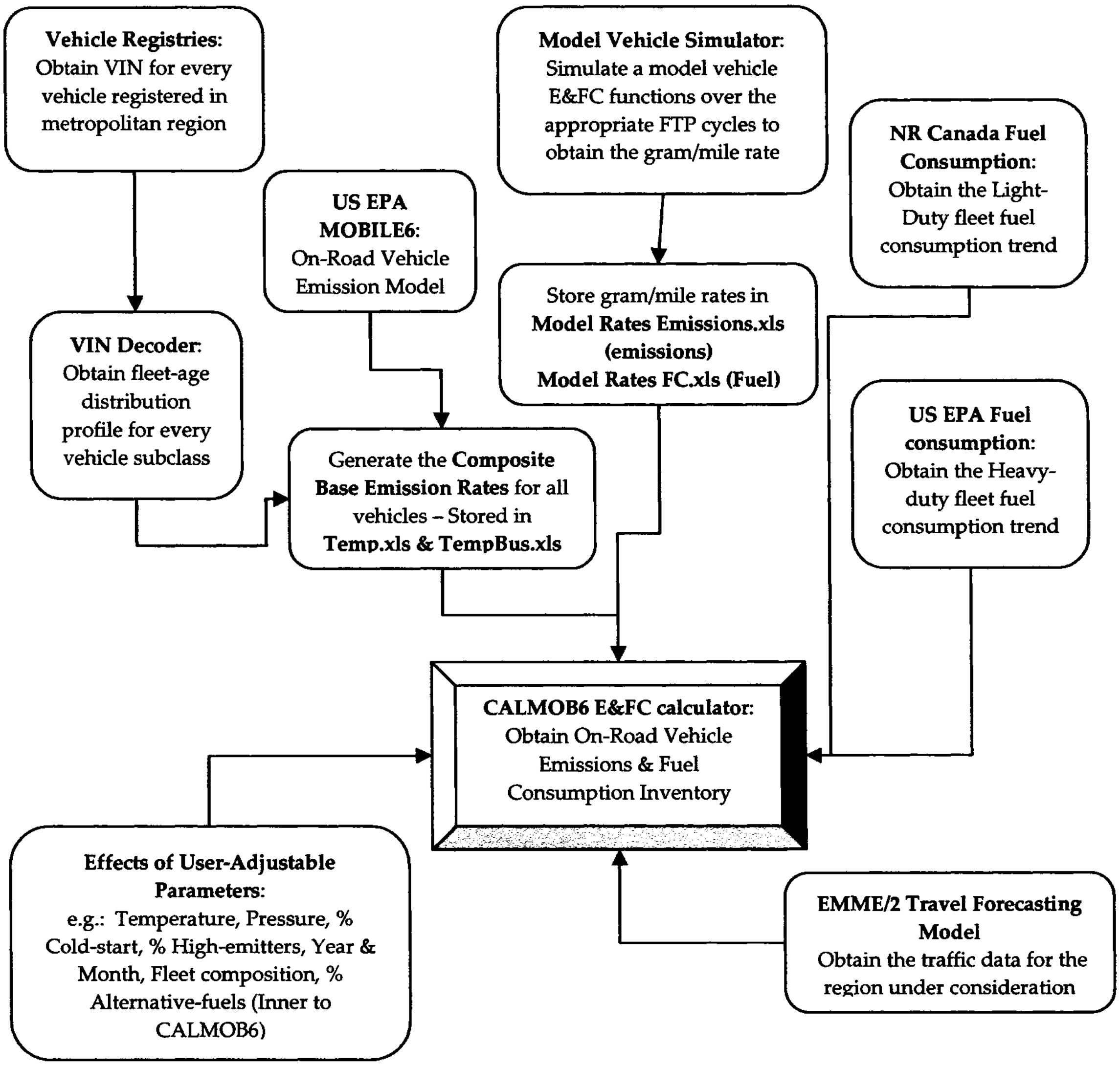

Figure 3-1: Basic schema of information required by CALMOB6 from the main components.

3.1 ON-ROAD VEHICLE CLASSIFICATION

It is imperative to know what type of vehicle classification has been adopted by CALMOB6. Then only, the usefulness of the emission and transportation models as well as other information sources can be discussed.

To be useful, an emissions calculator requires a fleet model that is both representative of the actual on-road fleet and is classified in the same manner as the fleet in MOBILE6 which is being used as a calibration base. The fleet developed for the Edmonton version of CALMOB6 includes twenty-seven of the twenty-eight MOBILE6 vehicle classes. (Motorcycles are not considered since their population and in-use emissions are negligibly small in most fleets and they are not included in Edmonton's transportation forecasting model). Table A-2, Appendix A, gives the basic CALMOB6 vehicle classification.

CALMOB6 Vehicle Classifications				MOBILE6 Group No.
S/N	***Abbreviation***	***Classification 1***	***Classification 2***	
1	LDV - MINI	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
2	LDV - ECONOMY	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
3	LDV - LARGE	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
4	LDT 1	LIGHT-DUTY TRUCK	LIGHT-DUTY VEHICLE	2,15
5	LDT 2	LIGHT-DUTY TRUCK	LIGHT-DUTY VEHICLE	3,15
6	LDT 3	LIGHT-DUTY TRUCK	LIGHT-DUTY TRUCK	4,28
7	LDT 4	LIGHT-DUTY TRUCK	LIGHT-DUTY TRUCK	5,28
8	HDV2b / MDV2b	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	6,16
9	HDV3 / MDV3	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	7,17
10	HDV4 / MDV4	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	8,18
11	HDV5 / MDV5	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	9,19
12	HDV6	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	10,20
13	HDV7	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	11,21
14	HDV8a	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	12,22
15	HDV8b	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	13,23
16	TL: Transit Long	BUS	BUS	25,26
17	TN: Transit New	BUS	BUS	25,26
18	TO: Transit Old	BUS	BUS	25,26
19	TS: Transit Short	BUS	BUS	25,26
20	SL: School Long	BUS	BUS	25,27
21	SS: School Short	BUS	BUS	25,27

Table 3-1: Different vehicle groupings under the two CALMOB6 vehicle classification schemes and corresponding MOBILE6 group number.

In the US EPA MOBILE6 model, the vehicle fleet is split into Light-Duty Vehicle (passenger car), Light-Duty Truck, Heavy-Duty Vehicle, Buses and Motorcycles. These super-classes are also separated according to fuel type, (gasoline or diesel), and are further subdivided as shown in Appendix A, Table A-1.

It is normal for traffic forecasts to split vehicles into a smaller number of classifications; e.g. Light Duty (cars and light trucks), Medium Duty Vehicle (single body trucks), Heavy Duty Vehicle (large trucks and trailers) and Transit Bus. The CALMOB6 program accommodates this by allowing the user to specify the traffic in terms of these vehicle classes. The program then uses either a default distribution of MOBILE6 vehicle types (i.e. Classification 1) in each vehicle class or it allows the user to specify a particular distribution of MOBILE6 vehicle types (Classification 2). This is illustrated in Table 3-1. Besides, to better represent the urban passenger car fleet and capture possible trends of changing vehicle size, the program allows the user to further split the Light Duty category into three sub-categories of passenger cars, (Mini, Economy and Large)[7] as well as 4 categories of light-duty trucks, (LDT1, LDT2, LDT3 and LDT4). Further, bus types are customized for the City of Edmonton fleet. CALMOB6 categorizes the transit bus fleet into New (the New-Flyer 40 ft low-floor buses), Old (the 2-Stroke engine GM buses), Long (The New-Flyer 60 ft low-floor buses) and Short (the Fords). Likewise, the school buses are classified into: Long and Short. The Bus and Light-Duty Vehicle splits are made to better represent actual vehicle characteristics (mass, frontal area, coefficient of rolling resistance and coefficient of drag). Thus, these features improve the capability to test the effects of future changes in vehicle type, usage pattern, etc. Table 3-2 summarises the characteristics of the vehicles employed in CALMOB6. It is not critical that the

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[7] The following are examples of the Light-Duty Vehicle sub-categories as considered in this thesis:
Mini: *Toyota Echo, Nissan Micra, Ford Festiva, Toyota Tercel and, Mini.*
Economy: *Ford Focus, Chevrolet Cavalier, Dodge Neon, Honda Civic, Nissan Sentra, Pontiac Sunfire, Toyota Corolla, Audi A4, Mazda Protégé, Hyundai Excel and Volkswagen Jetta.*
Large: *Ford Taurus, Chevrolet Impala, Honda Accord, Toyota Camry, Nissan Maxima, Mazda 6, Volkswagen Passat, Chrysler Intrepid, Ford Crown Victoria and Mercury Grand Marquis.*

average vehicle properties be precise; only that they be reasonable and in good proportion to each other.

CALMOB6 Vehicle Characteristics						
S/N	***Abbreviation***	***Mass / kg***	***Frontal Area / m^2***	***Coefficient of Drag***	***Coefficient of Rolling resistance***	***Applicable Power Limit / kW***
1	LDV - MINI	1005	1.900	0.300	0.013	n/a
2	LDV - ECONOMY	1295	1.951	0.327	0.013	n/a
3	LDV - LARGE	1735	2.118	0.313	0.013	n/a
4	LDT 1	1606	2.346	0.360	0.013	n/a
5	LDT 2	2120	2.633	0.368	0.013	n/a
6	LDT 3	2676	3.122	0.390	0.013	n/a
7	LDT 4	3025	3.126	0.410	0.013	n/a
8	HDV2b / MDV2b	3260	3.655	0.410	0.010	100
9	HDV3 / MDV3	3655	3.800	0.500	0.010	125
10	HDV4 / MDV4	4175	3.900	0.600	0.010	155
11	HDV5 / MDV5	5025	4.000	0.700	0.010	180
12	HDV6	6490	4.200	0.800	0.010	235
13	HDV7	8210	4.500	0.900	0.010	300
14	HDV8a	18100	4.960	0.900	0.010	425
15	HDV8b	23800	5.160	0.900	0.010	450
16	TL: Transit Long	19945	6.370	0.550	0.010	430
17	TN: Transit New	13595	6.370	0.550	0.010	360
18	TO: Transit Old	10955	5.993	0.550	0.010	300
19	TS: Transit Short	3750	4.520	0.550	0.010	130
20	SL: School Long	11000	5.712	0.550	0.010	325
21	SS: School Short	3600	4.718	0.550	0.010	125

Table 3-2: CALMOB6 Vehicle Characteristics.

Apart from defining the subclass population fractions, the user has the ability to specify the fraction of alternative-fuelled vehicles for each vehicle category. Light duty vehicles are assumed to be gasoline while heavy duty trucks and buses are assumed to be diesel. The user specifies the fraction using other fuels: natural gas, propane, methanol, ethanol, electric and either diesel or gasoline. The default distribution of vehicle classifications was obtained by using vehicle registration data from provincial registries. The total vehicle population registered in the Edmonton region was extracted using postal code data and this population was broken down into subclass fractions using a computer program which decodes vehicle identification numbers. CALMOB6 presents the ability to set up, modify and save a model fleet file which is a requisite for running the emissions and fuel consumption model. Hence, the emissions effects of different fleet composition scenarios can be tested using the model.

3.2 TRAVEL FORECASTING MODEL AND LINK WITH CALMOB6

City of Edmonton uses both the macro-analytical model EMME/2 and the micro-simulation model VISSIM for analyzing its traffic data. However, optimum use of VISSIM is not being made. Consequently, the individual vehicle operation data cannot be retrieved at present. As a result, the city uses primarily EMME/2 to model traffic flow over the regional road network.

In EMME/2, major streets are classified as *links* which run from an assigned starting node to an end node. The average slope and permissible speed on each link is known. Similarly, neighbourhoods around nodes are classified as *zones* and each zone has an average travel distance, average slope and maximum speed specified. The traffic forecasting process specifies the number of vehicles originating and stopping at each zone during a particular period and the traffic forecasting model, EMME/2, predicts the distribution of traffic flow across all available links. Considering the actual capacity of those links, the forecast assigns an average speed for each type of vehicle on each link and zone across the network being modeled. This information is stored in a tabular form for all links and zones involved in a traffic simulation.

The CALMOB6 program is set up to read tabular data files in a comma separated variable (.CSV) format such as can be produced by most data management and spread sheet programs. Each line of the file relates information for one traffic link or zone including the key parameters describing the link or zone plus the additional parameters to describe traffic for each vehicle class on that link or zone. Table 3-3 shows a typical example. The link or zone is defined by:

- *starting/ending nodes,*
- a *link type* (internal to the city to separate results accordingly; any number between 1 and 20. Therefore, result can be classified into a maximum of 20 groups),
- a *link length* (or zone average travel distance in km),
- a *volume delay function – vdf* (used again to classify the type of link or zone: '2' for links and '99' for zones),
- a *maximum travel speed* (in km/hr), and
- a road *gradient* (vertical rise over horizontal distance from node to node)

Description of the Link							Description of the Traffic					
inode	jnode	Link	Length	vdf	MaxSpeed	Gradient	Passenger Cars			...		
		Type	(km)		(km/hr)		No.	km/hr	% cold	No.	km/hr	% cold
1101	*2001*	*1*	*1*	*2*	*70*	*0*	*50*	*70*	*5*			
1101	*2105*	*1*	*0.3*	*99*	*50*	*0.003*	*45*	*37*	*3*			
1102	*2001*	*1*	*0.8*	*2*	*70*	*-0.001*	*75*	*65*	*0*			

Table 3-3: Data input file model describing link or zone model parameters and traffic to CALMOB6.

This is followed by a set of three or four values describing the traffic for each vehicle class on the link. For each vehicle class, the three values consist of:

- the *number of vehicles* in that class,

- the *average speed* (in km/hr) along the link, and
- the *percentage of cold start* vehicles of that class on this link.

However, the cold start fractions are functional only for the passenger car and the light-duty trucks. Thus, for medium duty and heavy duty, the two values used for these classes are simply the number of vehicles and the average speed. In addition to the latter values, transit vehicles use the dwell time. This parameter denotes the maximum amount of time, in minutes, a transit / school vehicle lies on a link or a zone.

Depending on the vehicle classification scheme (as shown in Table 3-1), the data input file will differ. If Classification 1 is opted for, there will be a maximum of twenty columns – seven for the link description, three for each of passenger car, light-duty truck, heavy-duty truck and four for the bus. If Classification 2 is chosen, the link description will be unchanged. Instead, an additional vehicle group is included in the traffic description section – the medium-duty vehicle category. In this case, the data input file will consist of twenty-three columns.

3.3 TRAFFIC MOTION MICRO-SIMULATION [2, 3]

The traffic motion model is identical to the one developed for EMITPP06. CALMOB6 uses the EMME/2 model output to generate a second-by-second speed trace for each vehicle category on the network. CALMOB6 then builds a realistic traffic cycle. This cycle consists of accelerations, decelerations, cruise period and idling period and maximum speeds. The model uses different acceleration/deceleration rates at different split speeds. These split speeds and accelerations differ for light-duty vehicles and heavy-duty vehicles. The set of conditions should satisfy the requirement that the model travel time over each link/zone matches the actual travel time. This actual travel time is obtained from the following EMME/2 output data: the traveled distance and the predicted average speed over the link/zone. It is noteworthy that, for light-duty vehicles, the traffic motion model differs for a link and a zone. Model Speed-Time traces are displayed in Appendix B. There are four main classes of traffic motion altogether:

- *Class 1 - No delay*: All vehicles drive through at the maximum speed
- *Class 2 - Some stops*: Some vehicles cruise through and some make one stop and possibly idle
- *Class 3 - All stop once*: All vehicles make a complete stop but with an idle time of less than 30 seconds. The free speed is adjusted accordingly.
- *Class 4 - Congested*: The vehicles make more than one stop and the maximum speed is reduced.

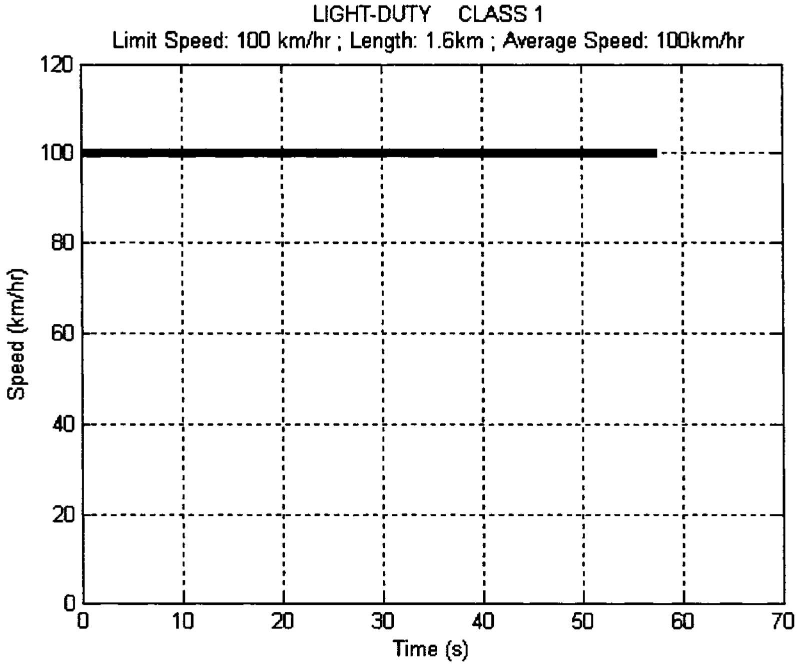


Figure 3-2: Model Speed-Time trace for a *Class 1 link* (applicable for both the *Light-duty* and the *Heavy-Duty* Vehicles).

3.3.1 ACCELERATION RATES, SPLIT SPEEDS AND POWER LIMITS

For light-duty vehicles (passenger car and light-duty truck), CALMOB6 assumes that acceleration/deceleration rates are at 1.5 m/s^2 for vehicle speed less or equal to 50 km/hr. For speeds higher than 50 km/hr, 2/3 of that rate is used; i.e. 1 m/s^2. As for heavy-duty vehicles (heavy-duty trucks and buses), there are two split speed – 35 km/hr and 52.5 km/hr. For any speed less than or equal to 35 km/hr, a base acceleration rate of 0.9 m/s^2 is chosen. This rate is reduced by 1/3 to 0.6 m/s^2 when heavy-duty vehicles exceed 35 km/hr but less than or equal to 52.5 km/hr. For any speed above 52.5 km/hr, the latter rate is again reduced by 1/3 to 0.4 m/s^2. Specific for the heavy-duty vehicles, a power limit is assigned to each of the heavy-duty and bus subclasses. The peak power is sensitive to the acceleration rate and the road gradient. If, at any instant, in the effort to building the traffic motion model, the power limit is reached, the base acceleration will be reduced accordingly. Appropriate reduction in acceleration rates is made so that the maximum is just less or equal to the power limit.

3.3.2 BUILDING TRAFFIC MOTION MODEL FOR LINKS

It is crucial to obtain instantaneous vehicle operation data. This can be achieved using the above rules on acceleration rates and with additional assumptions.

'clssfy', 'clssfyTRK' and 'clssfyBUS' are those subroutines, in CALMOB6, that build the traffic motion model on the links/zones for light-duty vehicle, heavy-duty vehicle and bus respectively. Relative to the straight-through-cruise at the limit speed of the link, the level of congestion is rated. Subsequently, one of the four traffic motion models, described above, is assigned.

The decision criteria to classify the link are done by 'cruise' subroutine. For each link/ zone, 'cruise' calculates the following:

- Free time, T_{FREE}, for the vehicle to cover the distance at permissible cruise speed.
- Time for a vehicle to make a stop with no idling (T_{1STOP}); The vehicle decelerate from the limit speed to zero and back to maximum speed by considering the acceleration rates and the split speed(s).
- Number of stops that is possible, depending on the travel time (T_{EMME}) calculated from EMME/2 data.
- For buses, a dwell time is specified in minutes. This represents the time lapse that the bus is expected to stay on the link/zone. It is used if the model travel time does not attain the EMME/2 travel time. This applies only for Class 3 and Class 4. This dwell time is used to increase the idle time such that the model travel time matches EMME/2 specified time.

The following sub-sections depict the decision criteria for the four classes:

3.3.2.1 CLASS 1 – NO DELAY [$T_{FREE} \leq T_{EMME} + 0.1S$]

If the average travel time from EMME/s is within 0.1 seconds of the time for a vehicle to cruise over the link at limit speed, the link will be classified as Class 1. All vehicles travel at the free cruise velocity over the entire travel time.

3.3.2.2 CLASS 2 – SOME STOPS [$T_{EMME} + 0.1S < T_{FREE} \leq T_{1STOP}$]

If the average travel time is more than 0.1 second over the free cruise speed but less than the time needed for a complete stop, Class 2 model will be opted for. In this case, all vehicles cannot stop once since there is not enough delay. It is assumed that all vehicles move at the maximum speed for at least part of the link, rather than reducing the cruising speed. Hence, some vehicles stop with no idle while the rest cruise through at the maximum speed. To match the actual average travel time (obtained from EMME/2), the number of vehicles is assigned accordingly to each of the two motions.

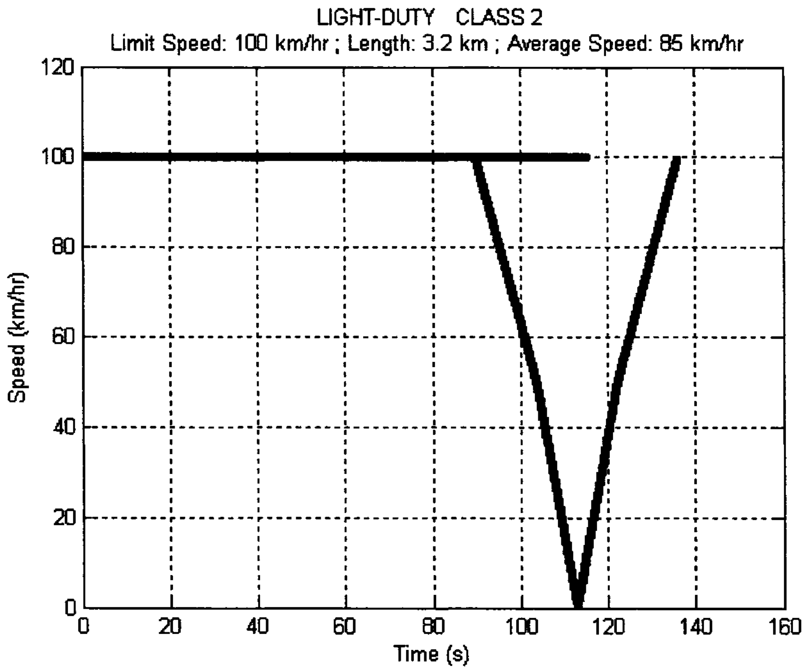


Figure 3-3: Model Speed-Time trace for a *Class 2 link* (applicable to *Light-Duty* Vehicles only).

3.3.2.3 CLASS 3 – ALL STOP ONCE [$(T_{CRUISE} + T_{1STOP}) < T_{FREE} \leq (T_{CRUISE} + T_{1STOP} + 30\text{ s})$]

If the average travel time lies in between the time for a vehicle to cruise over the link at maximum speed, come to a stop (with no idle) and accelerate back to cruise speed, and within 30 seconds of the latter time, then the link will be set to

Class 3. The extra time required to match the EMME/2 travel time is assigned as idle time at the one stop.

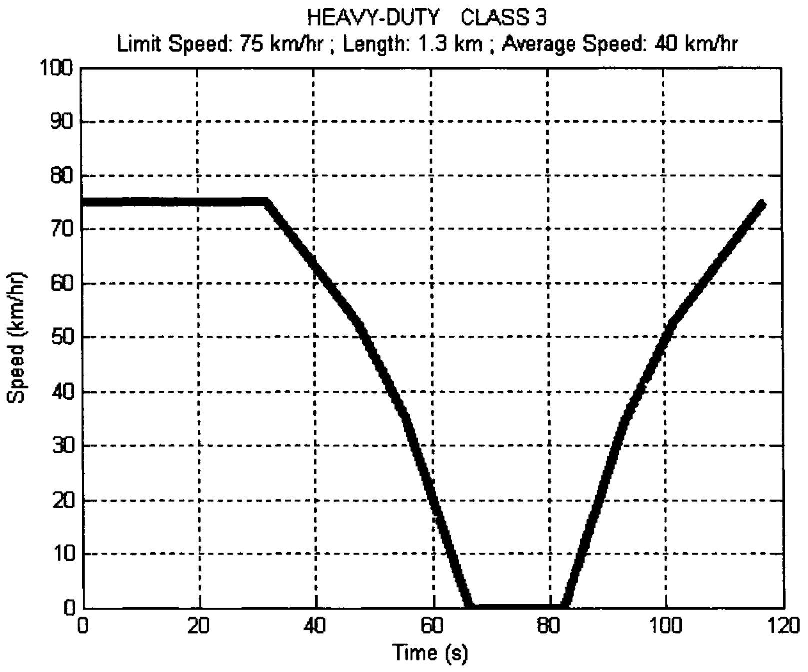


Figure 3-4: Model Speed-Time trace for a *Class 3 link* (applicable to *Heavy-Duty* Vehicles only).

3.3.2.4 CLASS 4 – CONGESTED [$T_{FREE} > (T_{CRUISE} + T_{1STOP} + 30\ s)$]

If the average travel time exceeds the Class 3 link limit, the link will be set to Class 4. In this case, the permissible speed is reduced by 2/3. Traffic is congested. In this traffic cycle, a maximum number of stops are included such that the idle period assigned to each stop does not exceed 30 seconds. However, if, with this reduced cruise speed, there is only one stop possible, the link will be classified to Class 3 with longer than 30 seconds of idle time.

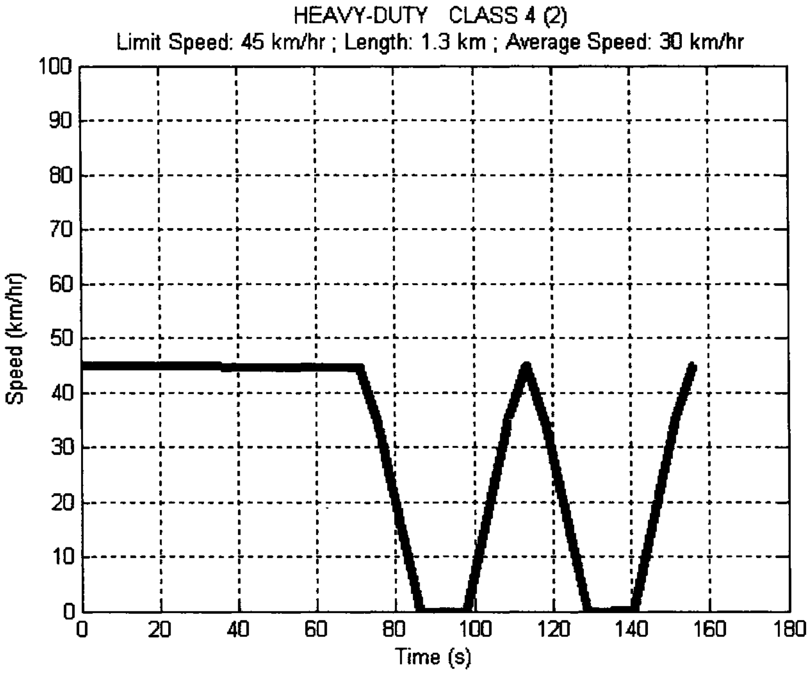


Figure 3-5: Model Speed-Time trace for a *Class 4 link* – Congestion with more stops and idling times. (applicable to *Heavy-Duty* Vehicles only).

3.3.3 BUILDING TRAFFIC MOTION MODEL FOR ZONES

These feeder zones or neighbourhoods are identified by the volume-delay function (vdf) value of 99. Hence, any line where vdf is other than 99 is considered as link. EMME/2 assigns an average travel distance for every zone, where travel distance is also averaged. Heavy-duty vehicle traffic motion is similar for zones as it is for links. However, CALMOB6 assumes the following for light-duty vehicles:

- The free cruise speed is 4/3 of the average speed specified by EMME/2. However, if this new free cruise speed exceeds 80km/hr, it is limited to 80km/hr.

- Each vehicle starts from rest, accelerate to cruise speed, decelerate to a stop (with no idle) and accelerate back to cruise speed. This is a reference traffic motion in zones and is adjusted as per following;
  - If a delay of less than 30 seconds is required to match the EMME/2 travel time, an idle period is included when the vehicle stops. This idle is not more than 30 seconds.
  - If more than 30 seconds of idling is needed to match EMME/2 travel time, additional stops are considered. Decelerate/accelerate cycles are included as well as idle periods to match the required travel time.

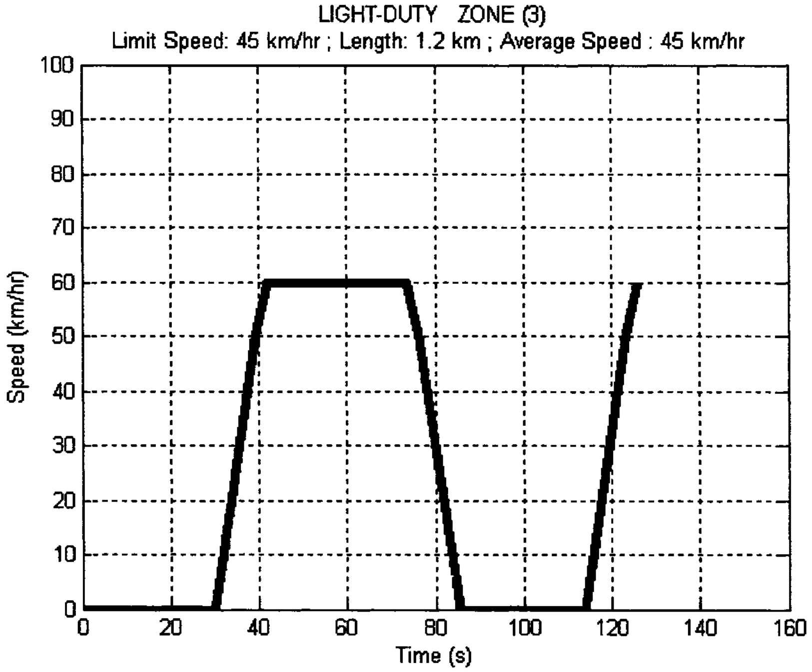


Figure 3-6: Model Speed-Time trace for a *Zone* with a cruise period and a stop with idling (applicable to *Light-Duty* Vehicles only).

  - The travel time can exceed the EMME/2 travel time with the stop or the average distance is too small to accommodate a stop (decelerate and re-accelerate). In such cases, the vehicle accelerates once to the cruise speed and it cruises through till it leaves the zone.

  - The average distance of zones may not be long enough for the vehicles to attain the EMME/2 travel time. In this case, a few seconds longer than EMME/2 travel time is added to the model travel time.

- Traffic cycle, in zones, starts with a 30 seconds idle period. This time allows vehicles to move out of parking spaces and get on to streets or to get off the streets and park the vehicle before shutting off the engine.

These models for the link and zone are applicable for both the light-duty vehicles (passenger car and light-duty truck) and heavy-duty vehicle (medium and heavy-duty trucks and buses). They are internally created in CALMOB6 which only require EMME/2 output data to do so. The traffic motions are realistic and respond reasonably to changes in EMME/2 data.

3.4 VEHICLE TRACTIVE POWER

Vehicle tractive power is the best overall predictor of emissions and fuel consumption. The generated traffic motion models (i.e. the speed traces) are used together with vehicle dynamic models to calculate vehicle tractive power traces. Figure C-1 illustrates the basis of a vehicle dynamic model. The vehicle motion is affected by the balance between the resistive forces, (Rolling resistance, Slope resistance and Aerodynamic resistance), and the driving force, (Tractive force). The resultant of those forces gives the vehicle acceleration term, (Mass x Acceleration).

Equation 3-1 summarizes the main forces affecting engine power demand of vehicles. In equation form, the tractive force (in Newtons, *N*) can be calculated from the other terms as:

$$\boxed{\textbf{Tractive Force} = \textbf{Mass} \times \textbf{Acceleration} + \textbf{Rolling Resistance} + \textbf{Slope Resistance} + \textbf{Aerodynamic Resistance}}$$

Equation 3-1: Relationship between the dynamic forces that influence vehicle power demand.

The vehicle speed trace provides acceleration and the combination of vehicle class models and link information gives all the the other parameters on the right hand side of Equation 3-1. Hence a tractive force trace can be calculated from the vehicle speed trace, link and model parameters. Further multiplying the tractive force trace by current speed gives a tractive power trace. Tractive power is the rate at which energy is applied through the wheels to overcome wind and rolling resistance, climb grades and accelerate the vehicle. It is notable that the actual engine power is generally higher than the tractive power since the engine is also running accessories and overcoming internal friction losses in the drivetrain. To account for these relatively small differences, the engine fuel consumption and emission functions are either based on tests where tractive power was measured or a calibration process is used to account for the added loads.

3.5 EMISSION AND FUEL CONSUMPTION FUNCTIONS

Once a tractive power trace is available, time traces of pollutant emissions and fuel consumption are calculated; using functions relating those quantities to the instantaneous tractive power. Emissions and fuel consumption functions were obtained by plotting the datasets from laboratory engine dynamometer at the

University of Alberta and from specific vehicles [2]. Figure 3-7 shows the power based NMHC emission function for a gasoline-fuelled vehicle. Further examples of such functions for other pollutants and other fuel are shown in Appendix D.

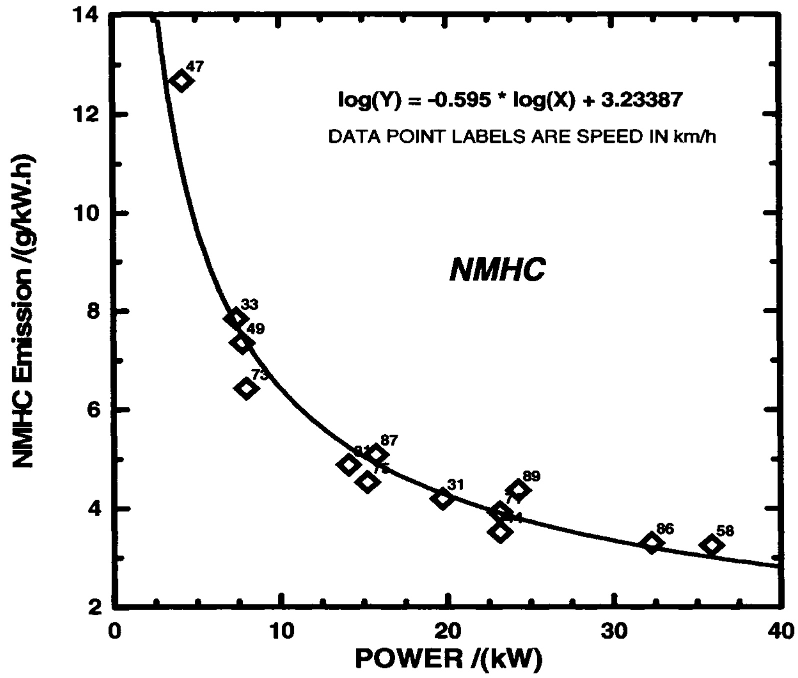


Figure 3-7: Power based emission functions of NMHC for a GASOLINE-fuelled vehicle [2].

The plotted E&FC functions provide the specific emission and consumption rates respectively (in g/kWh) or E&FC rates (in g/s) as functions of tractive power (in kW) and vehicle speed (in m/s). In these tests, a laboratory engine dynamometer and the vehicles were run over specific FTP City/Highway cycles. In this way, E&FC can be obtained at different power and speed operating points which are representative of the typical urban and highway driving conditions.

All the E&FC functions for gasoline vehicles were obtained by running a laboratory engine dynamometer. As for the diesel-fuelled vehicles, only the fuel consumption function was obtained from a laboratory engine dynamometer [3]. Datasets from a 4-stroke medium-duty diesel truck engine (Isuzu) was used to derive CO and NOx emission functions. Similarly, HC and PM emission functions were obtained by running a 2-stoke Detroit diesel bus engine.

Different sets of equations were derived according to the heavy-duty vehicle instantaneous velocities. For example, if the vehicle is accelerating (with actual velocity higher than the previous instantaneous velocity) then the functions below indicated with A=1 (Max Torque test) were used; else those indicated A=0 (13 Mode test) were considered for cruising, idling and decelerating trucks. Pmax, as denoted in Figure 3-8, is the maximum power that these engines could develop. These are the power limits, assumed for the heavy-duty vehicles. They are tabulated in Table 3-2.

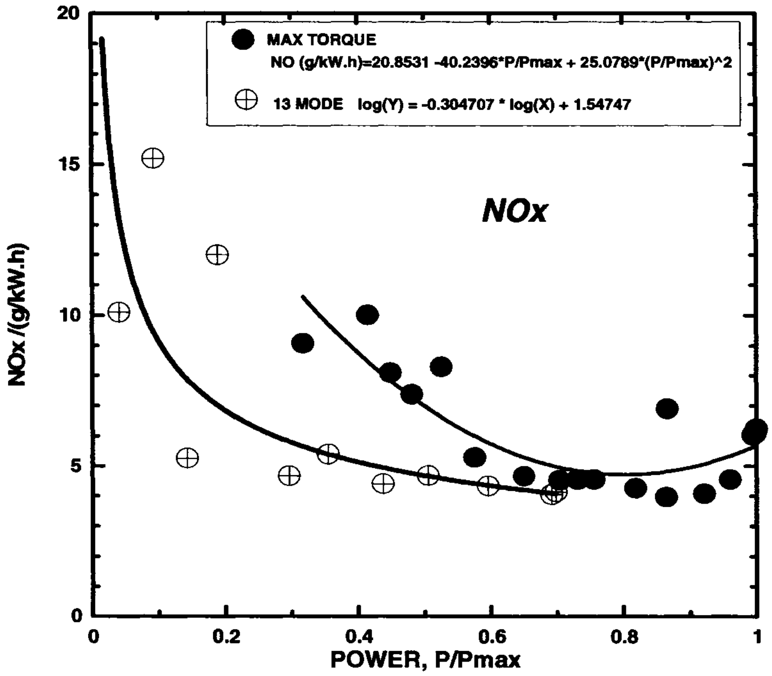


Figure 3-8: Power based emissions functions of NOx for a DIESEL-fuelled vehicle [3].

Actually, there is a lack of proper E&FC functions to estimate emissions and fuel consumption quantities for on-road vehicles. In an attempt to improve these functions for the newer light-duty vehicles, a simultaneous on-road vehicle E&FC measurement project is underway. Passenger cars (Economy and Small versions) and light-duty trucks (model LDT 2 and LDT 3), all gasoline-fuelled, were run over various speed traces, closely matching the LA4 driving cycle, otherwise known as FTP 75 cycle. The work aims to obtaining real-time E&FC measurements which may generate more appropriate functions for use in CALMOB6. However, the E&FC functions from the latter project are not available yet.

As for the heavy-duty vehicles, emission functions were searched for in technical literature. A research team from the West Virginia University was identified to make performance test on heavy-duty vehicles [4]. They have developed an extensive database of continuous transient gaseous emissions levels from a particular transit bus (Model year: 1989, GVW: 36,900lb, Test Weight: 19249lb) and a tractor truck (Model Year: 1992, GVW: 80,000lb, Test Weight: 41,953lb). Each of the vehicles is powered by a Detroit Diesel 6V-92 engine having horsepower 253hp (188kW) and 300hp (223kW) respectively. The workers have tried correlating emissions with the real world activity in terms of the instantaneous power delivered by the vehicle. Axle power was lone measured variable in the study. The transient cycles used to generate the continuous data were the Central Business District cycle (CBD), 5-peak WVU test cycle, WVU 5-mile route and the New York Composite cycle (NYComp). They found that CO emissions could not be modeled reliably on the basis of axle power. Only CO_2 and NOx emissions have shown reliable relationship with that parameter. They are still attempting to derive function for the particulates. Similarly, diesel-fuel consumption values were obtained from a heavy-duty engine manufacturer. All E&FC functions are analyzed and compared in Appendix E.

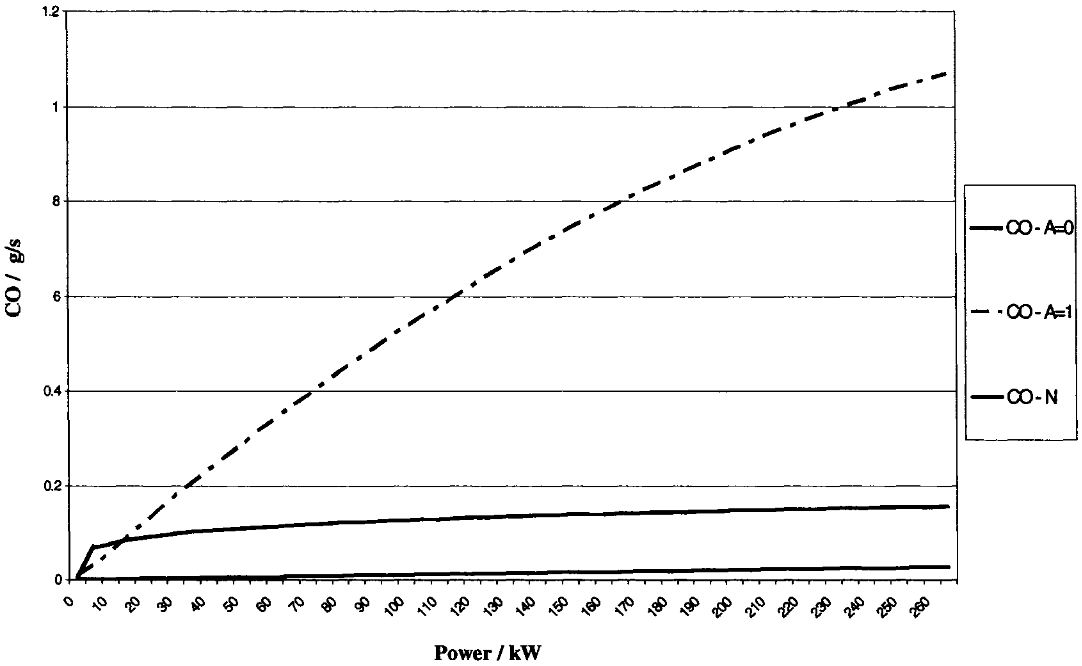


Figure 3-9: CO emission rate in g/s as a function of Power in kW.

Figure 3-9 shows a plot of the previously obtained carbon monoxide functions for EMITPP06. These are illustrated by curves indicated as A=0 and A=1. Simultaneously, the CO emission function, obtained by the West Virginia University team is plotted for comparison. The latter function is *N*-indicated for newly obtained relationship.

It is concluded that no better or more reliable functions are available for use in CALMOB6 than those derived previously for EMITPP06. In most cases, similar trends in those quantities for both the previously obtained functions and those obtained from technical literatures are observed. This is, however, a positive aspect given that the trends can be adjusted by different calibration factors.

It is noteworthy that E&FC functions to estimate the applicable quantities for the light-duty gasoline vehicles are also used for the heavy-duty gasoline vehicles.

Similarly, E&FC functions plotted for both the heavy-duty diesel vehicles are employed for the light-duty diesel vehicles.

Carbon dioxide is the major product of combustion. The amount of CO_2 emitted is related to the quantity of fuel consumed and the proportion of carbon in the fuel. Apart from CO_2 emissions, carbon combustion results in carbon monoxide formation as well as minor traces of hydrocarbons. As a result, a mass balance is effected between the amount of fuel consumed and the resulting carbon monoxide emissions. Typically, diesel fuels are close to 87% carbon whereas gasoline fuels are close to 85% carbon. Ratio of CO_2 mass to carbon mass is 44/12. Similarly, CO contains 12/28 (i.e. 0.429) carbon by mass [2 & 3]. As a result, the following equations are employed for estimating carbon dioxide emissions for the diesel and gasoline fuelled vehicles:

Gasoline:

$$M_{CO2} = (0.85 \times M_{FUEL} - 0.429 \times M_{CO}) \times 44 / 12, \quad \ldots\ldots\ldots\ldots \textit{Eq 3-2}$$

Diesel:

$$M_{CO2} = (0.87 \times M_{FUEL} - 0.429 \times M_{CO}) \times 44 / 12, \quad \ldots\ldots\ldots\ldots \textit{Eq 3-3}$$

All the power-based emissions and fuel consumption functions provide raw information of E&FC variation with power. An on-road vehicle is faced with multiple resistive forces and power losses. Moreover, effects of road grade, temperature, traffic characteristics are some of the various factors that affect emissions and fuel consumption. The engine laboratory dynamometer cannot capture all the opposing forces.

However, different governmental agencies have run on-road vehicles on specific FTP cycles. From these tests, they were able to compile voluminous sets of data to produce yearly estimates of E&FC for each vehicle category. The speed traces of the FTP cycles used are known. Using the model vehicle characteristics for each vehicle category, the power developed can be estimated. The power-based functions are then applied to instantaneous power developed to estimate instantaneous E&FC rates. When integrated over a time-scale, the total E&FC quantities can be computed. These E&FC are used in the functions calibration process which is addressed further in this chapter.

3.6 FUEL CONSUMPTION RATES

In view of calibrating the fuel consumption functions, accurate and reliable databases of fuel consumption is required. These databases can be used to estimate past and present fuels consumption amounts as well as predict them. Information from Natural Resources Canada (NR Can) [5, 6] is used to estimate gasoline passenger cars and light-duty trucks fuel consumption. As for the heavy-duty fleet and the diesel light duty vehicles, the United States Environmental Protection Agency (US EPA) databases are reliable.

3.6.1 LIGHT-DUTY GASOLINE VEHICLES AND NR CANADA DATABASE

Natural Resources Canada has a database of rated fuel consumption values (in L/100km) for light-duty cars and trucks sold in Canada. These values are based on a 55%/45% split of City/Highway driving cycles. The yearly rate considers the annual vehicle sales and dates from 1979, extending to 2001. NR Canada describes the passenger car and light duty truck fleet as shown in Table F-1 which also gives the corresponding CALMOB6 vehicle class. These vehicles are representative of the Canadian Light –Duty fleet [5, 6].

Fuel consumption depends primarily on the vehicle type, mass and technology. It is important to isolate these three main factors to make better estimates of fuel consumption and particularly better forecasts for the future. To clarify the mass effect, fuel consumption was plotted against vehicle mass for same-type vehicles of a given model year. Such plots were made for car model year 1980, 1990, 1995 and 2001 and for truck model years 1981, 1990, 1995, 1997, 2000 and 2001. Examples are shown in Figures 3-10 and 3-11. All graphs are illustrated in Figures F-1 – F-10, Appendix F.

The equations obtained from this analysis are in the form: $y = \text{'m'}.x + c$ where the slope 'm' is the fuel consumption effect of mass. With the mixed units of (L/100 km)/lb, 'm' has an average value of 0.0028 for both cars and light duty trucks and is generally lower for newer model years and for heavier vehicle classes (e.g. trucks).

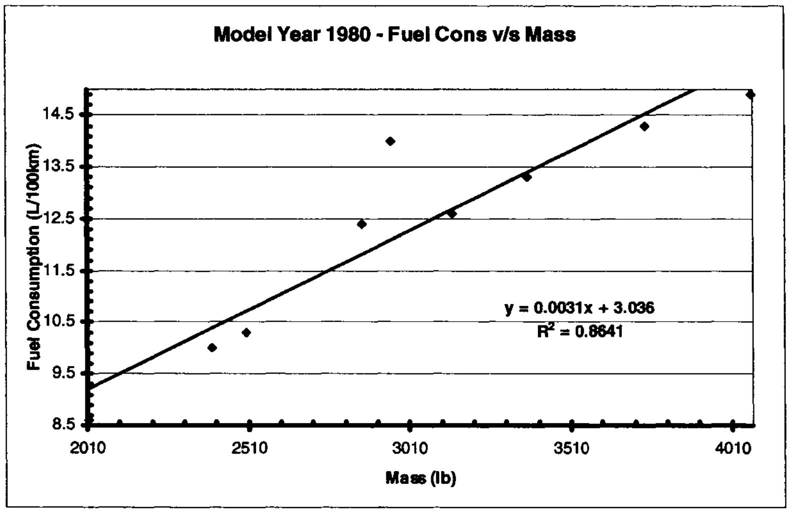


Figure 3-10: Mass effect on fuel consumption for same-class vehicles - 1980 cars.

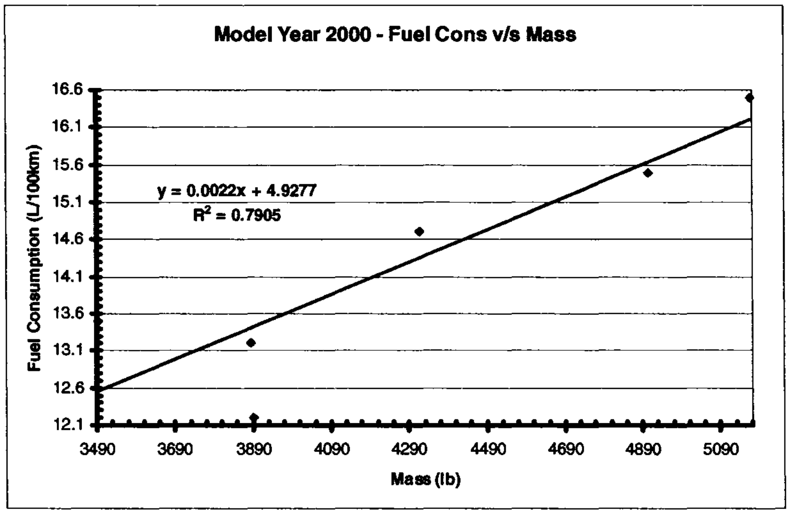


Figure 3-11: Mass effect on fuel consumption for same-class vehicles – 2000 light – duty trucks.

Using the values of mass sensitivity thus obtained, the fuel consumption for a particular vehicle category could be adjusted for actual mass using:

$$\mathbf{F.C_{adjusted} = F.C^{*} - `m\text{'}\{\ Weight^{*} - Weight_{average}\ \}} \quad \ldots\ldots\ldots\ldots\ldots \ \textit{E.q 3-4}$$

where,

- F.C*: Fuel Consumption in City (L/100km) as tabulated for a vehicle category.
- Weight*: Tabulated Vehicle Curb Weight (lb)
- $\text{Weight}_{\text{average}}$: Average Curb Weight of a particular vehicle category over years 1979 to 2001.

Looking at trends of $\text{FC}_{\text{adjusted}}$ with time then gives a measure of the effect of vehicle technology improvement on fuel consumption, (independent of the trend for mass growth in particular model classes). Figure 3-12 gives an example for a particular vehicle class, showing the substantial gains made in same-mass fuel consumption over recent decades.

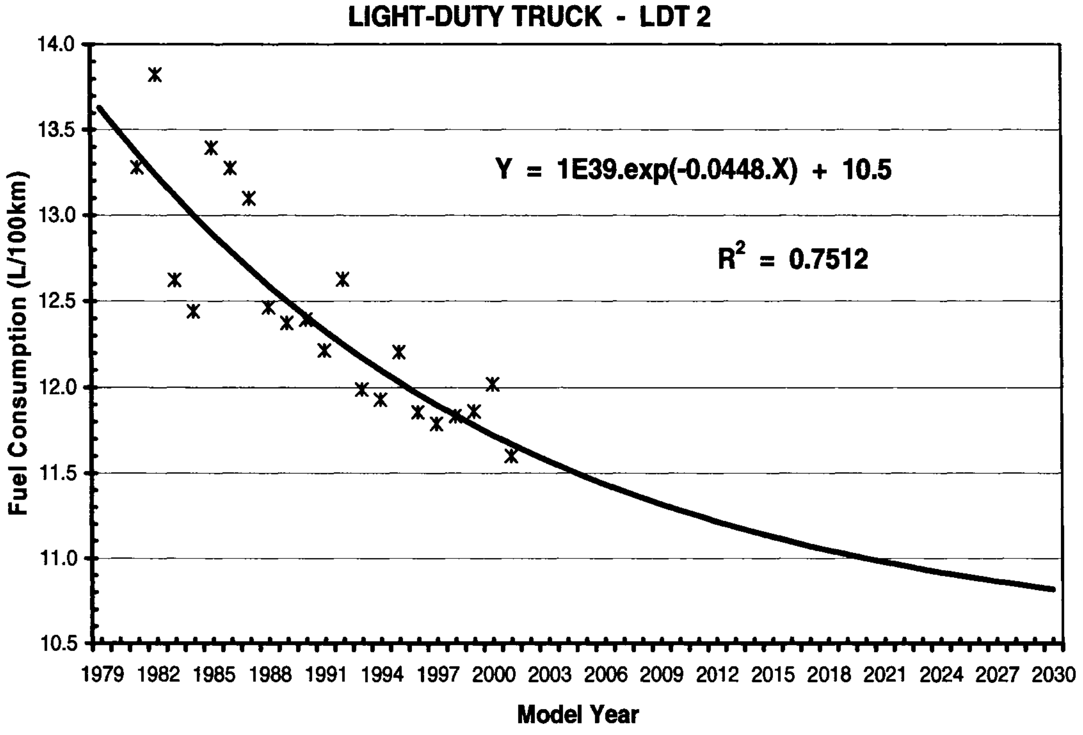


Figure 3-12: Example of the predicted fuel consumption trend extending up to 2030. (LDT 2 class fuel consumption based on past values adjusted for fixed mass)

The fuel consumption rates for future year fleets must be projected based on a combination of real expectations and progress in the past. A simple linear extrapolation would be unrealistically low for the future and polynomial extrapolations tend to go wildly positive or negative. The conservative modeling approach adopted for this study was to select a future asymptote somewhat below the current new-vehicle value and fit an exponential function for future model years

Before concluding, it is worth pointing out that City driving fuel consumption rate is also available [6]. Hence, to better represent city driving conditions, the latter fuel rate has been used. Moreover, diesel-fuelled light-duty vehicles in Canada are negligible compared to gasoline vehicles sales. As a result, it is assumed that the trends relate to gasoline fuel consumption.

An equation is generated to address the annual fuel consumption rates for each vehicle class. This equation is employed in CALMOB6 to determine past, present and future fuel-consumption rates. For the LDT 2 gasoline vehicles, the equation is displayed in Figure 3-12. The remaining graphs and generated functions are shown in Figures F-11 – F-17. Figure 3-13 compares the light-duty fleet predicted gasoline fuel consumption.

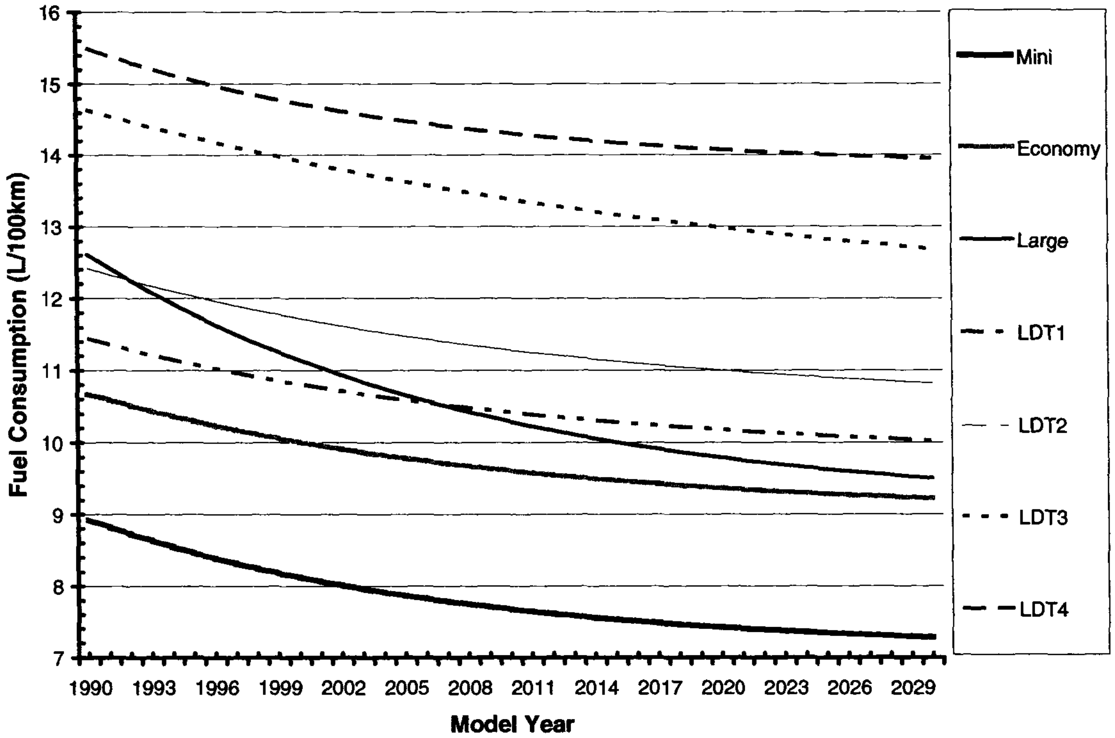


Figure 3-13: Comparison of the Light-Duty fleet predicted GASOLINE fuel consumption.

3.6.2 LIGHT-DUTY DIESEL VEHICLES AND US EPA

US EPA has reported on annual fuel economy for the light-duty diesel vehicles [7]. It is presented in miles per gallon (MPG). They date back from year 1975 till 2001. It is noteworthy that these rates are based on their laboratory data. FTP and Highway Fuel Economy Test (HFET) tests were used to generate those values [8]. The Department of Transport (DOT) uses a composite of these values to set corporate average fuel economy (CAFE) standards.

However, EPA remarked that the in-use fuel economy is lower than that composite value set by DOT. The latter fuel economy considers both gasoline and diesel-propelled vehicles. Hence, EPA adopted a series of assumptions to introduce some multiplicative factors, which are used to adjust their laboratory results. Moreover, yearly diesel-vehicle sales fractions were used to separate the diesel and gasoline economy values over a twelve-year period [1978-1989]. Finally, they extended these data to year 2001 with further assumptions. Further, because of low diesel-vehicle sales volume, the light-duty diesel trucks have been classified only into LDDT 12 and LDDT 34.

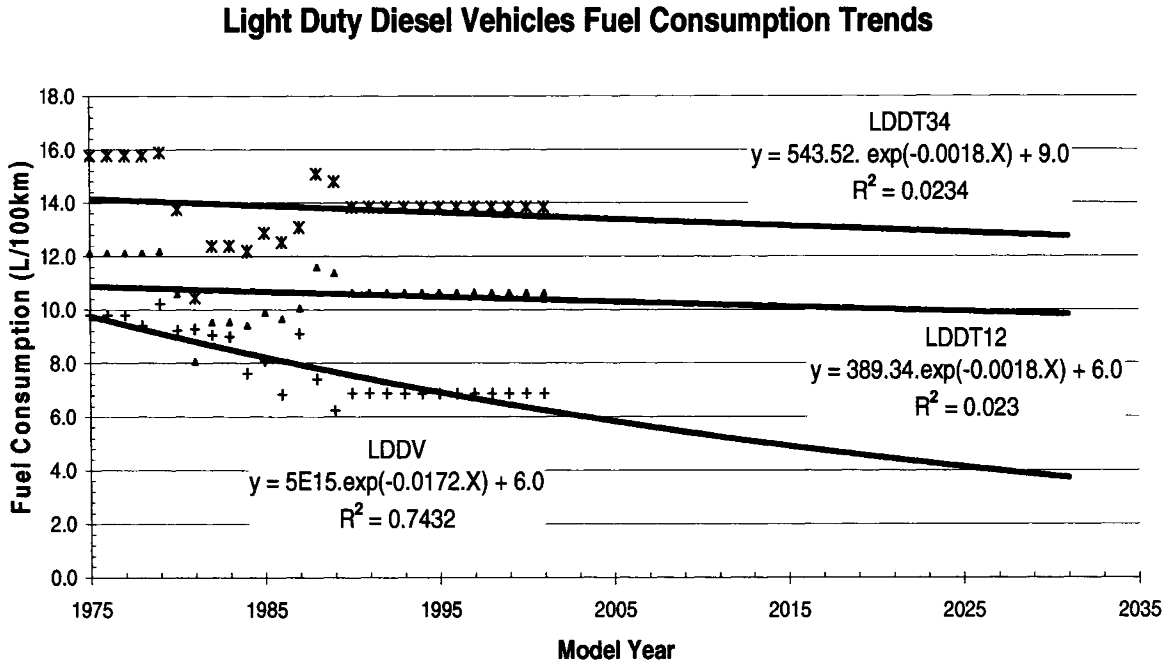


Figure 3-14: Comparison of the Light-Duty fleet predicted DIESEL fuel consumption. (based on US EPA available past and estimated data [8]).

These results were further expanded till 2030 as illustrated in Figure 3-14. An exponential trend was observed for each of the LDDV, LDDT 12 and LDDT 34. These inclinations were described by suitable equations as illustrated in the figure. CALMOB6 employs these trends to predict diesel-fuel consumption of light-duty vehicles.

3.6.3 HEAVY-DUTY VEHICLES AND US EPA

As reported in the US EPA's "Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6" [9], the average truck fuel economy was calculated using the *1992 Truck Inventory and Use Survey* (TIUS) data [10]. Similarly, US EPA uses the American Public Transit Association (APTA) *1995 Transit Passenger Vehicle Fleet Inventory* report to obtain the trend in bus fuel economy.

To extrapolate the fuel economies beyond 1992 for the trucks, EPA uses a power curve fit of the form $y=ax^b$. These curves fits are made for every heavy-duty vehicle class fuel economy in mpg. This applies for both the diesel and gasoline trucks. Table 3-4 lists the translated data to reflect the evolution of fuel consumption in L/100km. The latter equations are employed by CALMOB6 to predict heavy-duty vehicle fuel consumption

For CALMOB6 calibration purposes, it is assumed that the heavy-duty vehicles were tested on the EPA FTP Transient cycle. Further, it is worth mentioning that TIUS provided no data for the Class 8B gasoline trucks. As a result, the same calibration factors obtained for the Class 8A gasoline trucks were used to adjust the fuel consumed by the gasoline Class 8B trucks.

WEIGHT	**GASOLINE**	**DIESEL**
2B	$y = 1887.3\ X^{-0.9624}$	$y = 2194.2\ X^{-1.0506}$
3	$y = 2033.0\ X^{-0.9632}$	$y = 2378.4\ X^{-1.045}$
4	$y = 5751.1\ X^{-1.1902}$	$y = 468.6\ X^{-0.6598}$
5	$y = 532.7\ X^{-0.6348}$	$y = 950.8\ X^{-0.8078}$
6	$y = 6959.2\ X^{-1.2015}$	$y = 440.8\ X^{-0.6117}$
7	$y = 1842.0\ X^{-0.8909}$	$y = 58.5\ X^{-0.1374}$
8A	$y = 3635.6\ X^{-1.0285}$	$y = 1519.0\ X^{-0.8194}$
8B	n/a	$y = 19766.5\ X^{-1.3742}$

Table 3-4: Curve fits of Fuel Consumption (L/100km) for heavy-duty vehicles.

Note: X *= Model Year – 1900*
y: Fuel Consumption (L / 100 km)

As for the intercity buses, which travel on freeways and on main arterials in between cities, the COM driving cycles is suitable. Intercity buses are similar to transit buses. For CALMOB6, however, emissions and fuel consumption (E&FC) are estimated city wise only. In this area, buses stop more and drive at lower speeds. Consequently, the Central Business District (CBD) cycle is most appropriate to represent the CALMOB6 transit, school and intercity bus operation.

The US EPA report [9] has tabulated the estimated bus-fuel economies in mpg. This applies for the transit, intercity and school buses. Data are available for both the diesel and gasoline buses over the range of years 1987 to 1996. As per the above argument, the intercity bus data will not be used. CALMOB6 estimates E&FC for six bus types. Transit buses are split into Long, New, Old and Short. School buses are split in Long and Short. All calibration for the transit and school buses were made against the New Transit and Long School buses, respectively. Thereafter, the same calibration factors were used to adjust the fuel consumption to each of the vehicle categories – transit and school.

Figure 3-15 gives the model diesel- consumption trend for the transit vehicles. All the fuel consumption trends for the remaining buses are displayed in Figures F-20 – F-23. Each trend has been described by an equation, which is being used by CALMOB6 to estimate and predict bus fuel consumption.

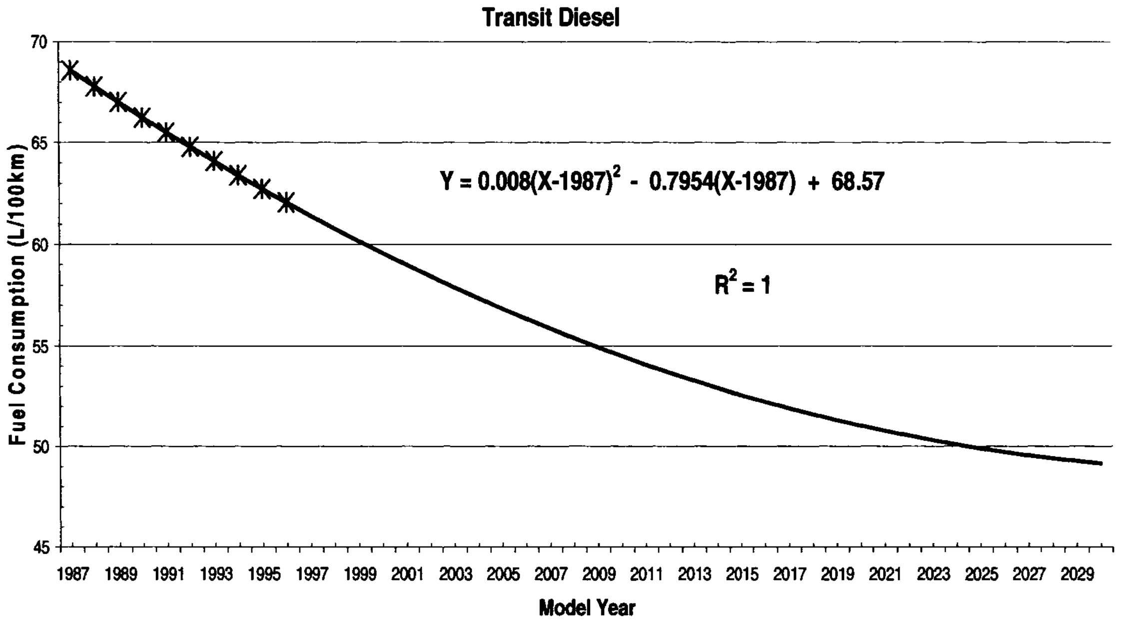


Figure 3-15: DIESEL TRANSIT Bus predicted fuel consumption trend extending up to 2030.

3.7 MOBILE6 BASE EMISSION RATES

MOBILE6 includes a database of emissions to be expected when specific classes of vehicles are run over standard FTP (Federal Test Procedure) cycles. The criteria pollutants considered are CO, NOx and HC. Apart from these pollutants, particulate-matter is also measured. These are the pollutants of concern to CALMOB6.

For light duty vehicles the MOBILE6 values are presented in terms of cold start emissions offset in grams and running emissions in gram/mile values for new vehicles of various model years back to the 1960's. On the other hand, running emissions only are given for the heavy-duty vehicles.

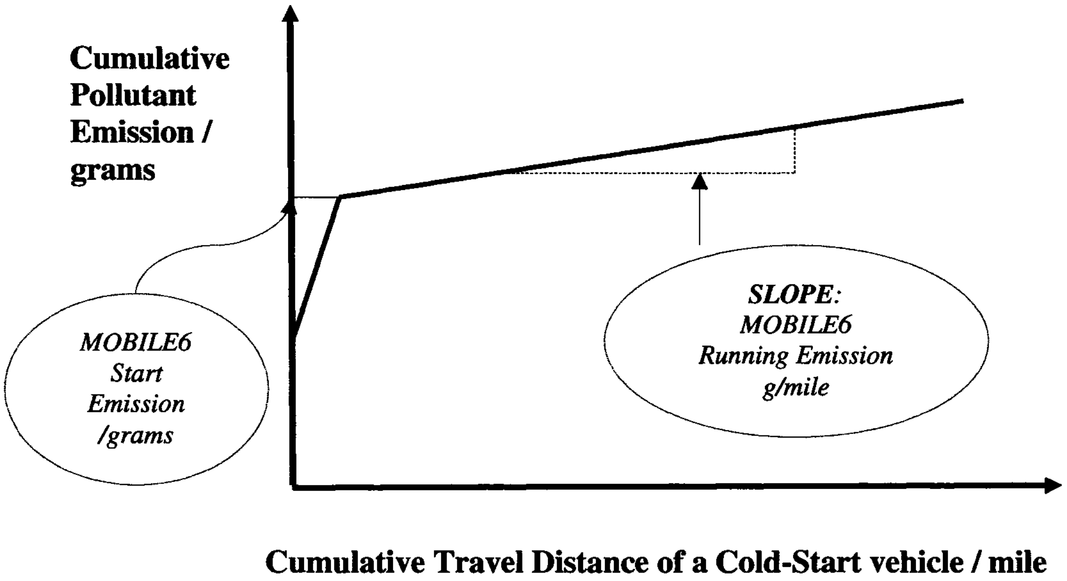


Figure 3-16: Cumulative emission trace for a cold-started vehicle.

The absolute start emission in grams is the amount of excess emission resulting when a vehicle is cold-started in comparison to an already hot running vehicle with no engine start. CALMOB6 assumes that a light-duty vehicle runs to a maximum of 2 km before the vehicle reaches its design operating conditions. As a result, all the excess emissions from a cold-started vehicle are released in that limited distance. MOBILE6, however, does not provide CO_2 emission rate due to cold-start. Technical literature data has been used to estimate such CO_2 data. Appendix G details on the methodology adapted to estimate CO_2 emissions for cold-started light-duty vehicles.

Moreover, there are deterioration rates for these parameters to account for progressive increase in the fraction of altered, malfunctioning or worn out components which affect emissions. Each of these two factors (i.e. start and running) is further broken down into a zero-mile-level (ZML) rate and a deterioration rate (DR or DET). ZML refers to the emission factor when the vehicle is brand new and the DET calculates how much the emission factor increases with increasing vehicle mileage.

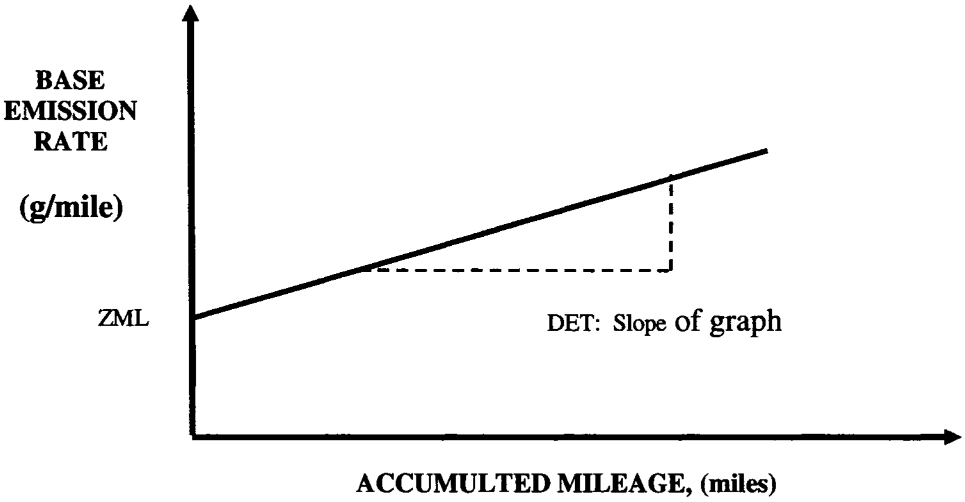


Figure 3-17: Illustration of estimating the MOBILE6 base emission rates (ZML and DET).

For a given mileage, Mil, the resulting base emission rate (BER) is calculated as follows:

$$BER_S = ZML_S + [DET_S \times Mil] \;, \;........... \; E.q\ 3\text{-}5$$

$$BER_R = ZML_R + [DET_R \times Mil] \;, \;........... \; E.q\ 3\text{-}6$$

where,

BER_S = Base Start Emission Rate (grams)

BER_R = Base Running Emission Rate (grams/mile)

Mil = Vehicle accumulated mileage (miles/10,000)

ZML_S = Start Zero-Mile Level (grams)

ZML_R = Running Zero-Mile Level (grams/mile)

DET_S = Start Deterioration (grams/10,000 miles)

DET_R = Running Deterioration (grams/mile/10,000 miles)

To estimate running BER, for example, the accumulated vehicle mileage is, first, divided by 10,000. Subsequently, the ZML_R and DET_R of the appropriate vehicle category, for the desirable pollutant and for the corresponding year of estimate are plugged into Equation 3-6.

For heavy duty vehicle classes, emission rates (i.e. ZML and DET) are given on a g/bhp (grams per brake horsepower) and g/bhp/10,000miles basis respectively. There are conversion factors (bhp/mile) to adjust the emission factors to a gram/mile rate for vehicles of varying weight class running standard test programs. Since no data on heavy-duty vehicle start emission is available only Equation 3-6 is useful for estimating the base emission rate.

Moreover, MOBILE6 separated its emission rates for the low and high altitudes cases. Low-altitude emission factors apply to altitude of around 500 feet above sea level. High-altitude emission factors represent conditions around 5,500 feet above mean sea level [21]. Edmonton is located at an elevation of 668 m (i.e.2192 ft) [34], closer to the low altitude range. Hence, the low-atitude emission rates have been extracted from MOBILE6.

Finally, it is important to point out that exhaust particulates (PM) emission rates were obtained directly with correspondence from the EPA team. Spreadsheets of exhaust PM emission rates (ZML and DET) were forwarded [35] by the EPA. At this time, CALMOB6 estimates exhaust particulate matter (PM10 and PM2.5) level diesel vehicles solely. This is because no function that properly describes PM emission with vehicle power demand is available for the gasoline vehicles. Moreover, other non-considered particulates emission by CALMOB6 are: tire-wear, brake wear, sulfur dioxide, sulfates and ammonia. It is noteworthy that MOBILE6 values give the emission rate for particle sizes of 1-10 microns. All PM emissions from diesel vehicles exhaust are 10 microns or less [36]. However, for gasoline vehicles, exhaust emission of particles between 1 and 10 microns is a fraction of the total exhaust PM. Hence, the data forwarded by the EPA can be used to work out the base PM10 emission rates from the exhaust of diesel vehicles. In addition, reference 36 illustrates that 92% of all diesel exhaust (i.e. 0.92 of diesel PM10 from exhaust) emission is composed of particles with sizes 2.5 micron and less. Thus, CALMOB6 assumes 92% of all its PM emission from diesel vehicles exhaust is composed of PM sizes 2.5 microns and lower.

This MOBILE6 data base provides a useful source of emission rates for past, current and future years for vehicles running standard test cycles.

3.8 FLEET: AGE DISTRIBUTION AND COMPOSITION

To run urban simulations for a given year, emission rates that represent a vehicle fleet of typical vintage is needed; some new vehicles and a lot more ageing vehicles from previous model years. The actual fleet age distribution is obviously important in setting the emission rates during any simulation. To accommodate this, the fleet for each class of vehicles is considered to consist of vehicles over an age span of zero to twenty-three years, (with vehicles more than twenty-three years old added to the ‘Age 23’ fraction of the fleet). Light-duty vehicle and heavy-duty vehicle (HDV 2B-HDV 8B) information has been obtained from the registries. Bus fleet information, however, has been obtained from the Edmonton public transit organization.

Moreover, depending on the vehicle characteristics, energy demand by each vehicle subclass varies and hence do the fuel consumption and pollutant level. Consequently, it is important to specify the percentages of each subclass that CALMOB6 has adapted. Further, CALMOB6 presents the ability to estimate E&FC from alternative-fuelled vehicles. E&FC from these vehicles differ from normal gasoline or diesel vehicles. These compositions by vehicle subclass and fuel type are obtained after decoding the VIN (Vehicle Identification Number) of every vehicle in the fleet.

3.8.1 LDV, LDT AND HDV FLEET AGE PROFILE

Information on the fleet distribution for Edmonton region has been extracted from year 2005 registration data for the City of Edmonton [51] and the surrounding regions. The VIN numbers in this registration database were decoded to classify vehicles into CALMOB6 categories and produce an actual age distribution for each class of vehicles. Such fleet age profiles are generally similar to the jagged solid line shown in Figure 3-18.

Illustrated in Figures H-1 – H-5, are five age profiles that were extracted to represent the following vehicles or group of vehicles:

- passenger car,
- LDT 1 and LDT 2,
- LDT 3 and LDT 4,
- HDV 2B and HDV 3, and finally
- HDV 4 – HDV 8B.

Figure 3-19 gives an overall comparison of the fleet age profile for the above vehicles.

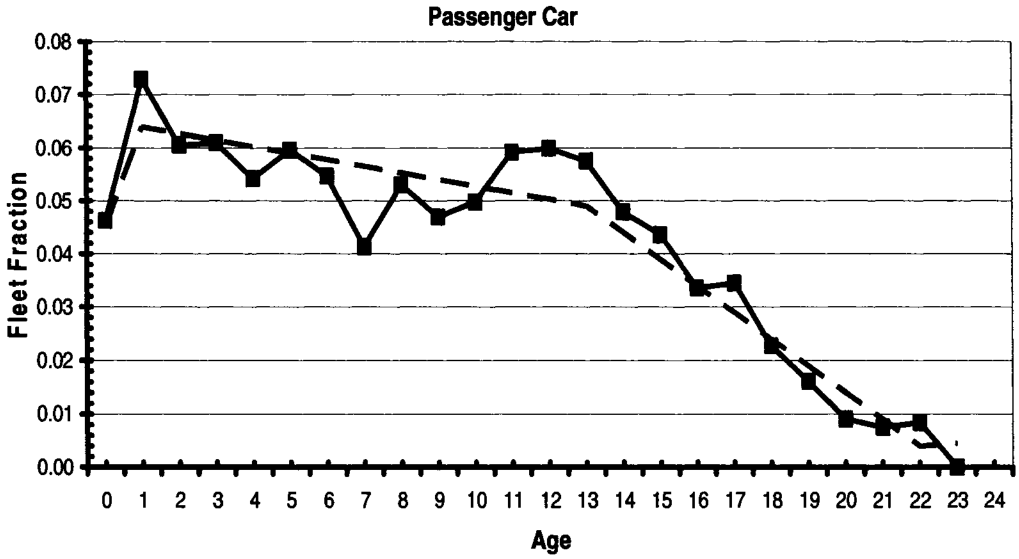


Figure 3-18: Fleet age distribution extracted from 2005 registration data [51] for Edmonton region passenger cars (solid). The modeled general trend for that category is also shown (dotted).

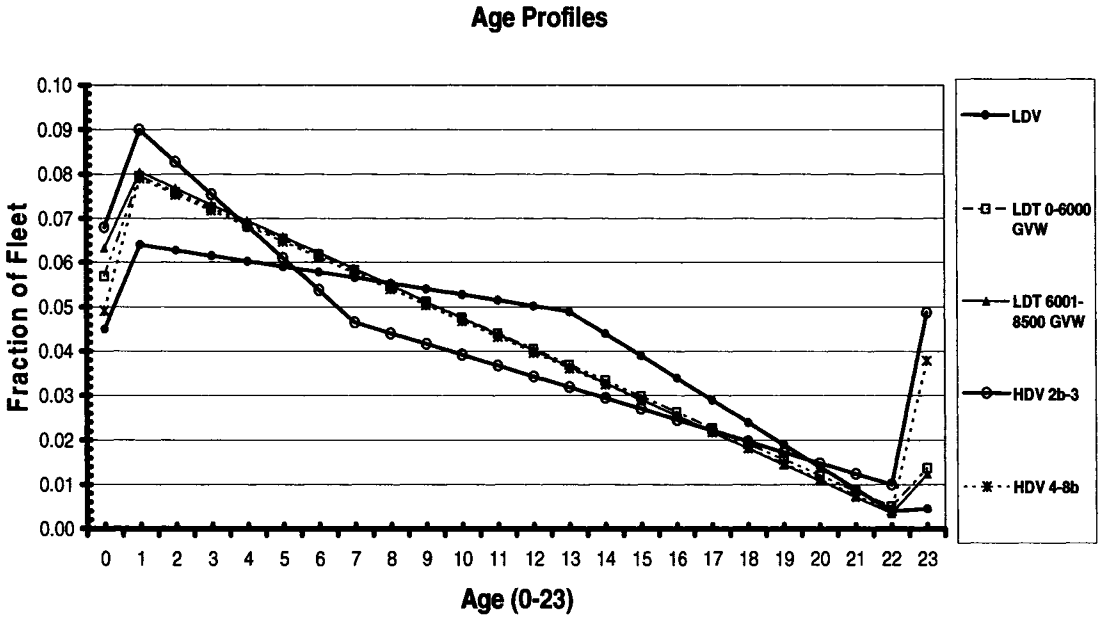


Figure 3-19: Comparison of the modeled general trend for the passenger car, LDT 1 and LDT 2, LDT 3 and LDT 4, HDV 2B-3 and HDV 4-8B.

Real fleet age profiles like that in Figure 3-18 generally include anomalous peaks and valleys associated with trends in popularity and availability of specific vehicle models as well as past economic conditions in the region. Since modeling requires generating a representative age profile for past and future year simulations, it is necessary to extract a more general fleet age distribution from the specific age profile captured in current registration data. The dotted line in Figure 3-18 demonstrates the key features of such a general fleet age profile. Current year models appear at some fraction and the fleet fraction hits a peak for one-year old vehicles. There is then a steady, low attrition rate for more than a decade as a few vehicles per year are lost to accidents and major mechanical failures. Beyond a 'corner age' at about nine to twelve years, the attrition slope is steeper, leading to some minimal fraction of vehicles remaining in service by age 22. To complete the fleet distribution, the fraction of vehicles at age 23 years includes all vehicles still operating which are 23 years of age or older. Similar fleet age distribution models were developed for each of the vehicle classes (but buses) used in CALMOB6 and are used in the calibration of emission and fuel consumption functions.

3.8.2 BUS FLEET AGE PROFILE

For buses, specific information about the fleet can be obtained. The Edmonton public transit has a list of buses operating in a particular year [18]. Unfortunately, the list was not kept up-to-date every year. Moreover, because no information about the school bus fleet was available, the transit bus age-profile was used to represent that of the school bus.

The list of transit buses operating in each of the following years was obtainable: 1989, 1994, 1996, 2000 and 2005. Each bus can be identified by a number, internal to the transit system. With this number, the year that the bus came into service can be found. Hence, the age of the bus can be determined. In this way, for any of the above model years, buses of a particular age (anything between 1 and 23, inclusive) can be grouped. Knowing the sizes of each of the twenty-three groups, for a particular model year, the bus fleet age distribution can be obtained. Hence, the fleet age distribution of buses operating in the above-mentioned years was known. Examples are given below.

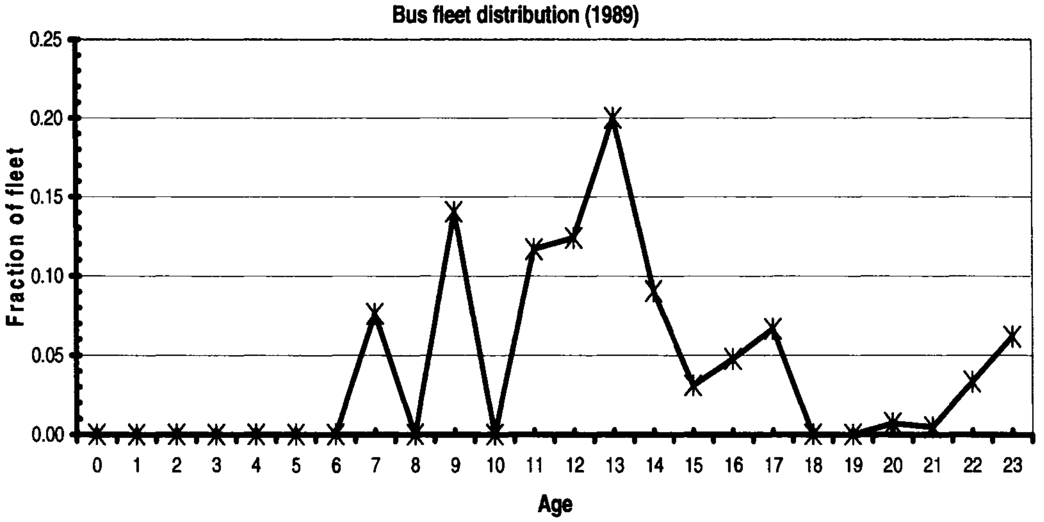


Figure 3-20: Bus fleet age distribution extracted from the list of vehicles operating in 1989.

It is noteworthy that no bus was purchased over a 10-year period; from 1983 to 1992. This is reflected in the Figures 3-20 and 3-21.

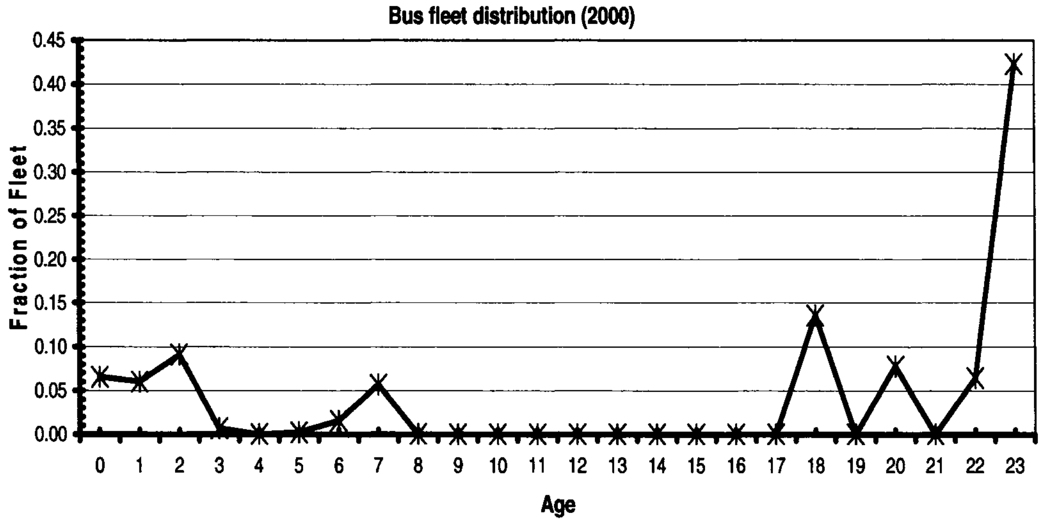


Figure 3-21: Bus fleet age distribution extracted from the list of vehicles operating in 2000

As it can be observed, the bus fleet profile has been changing drastically over past fifteen years. This is demonstrated by the set of Figures H-7 – H-11. Unlike the light-duty vehicles and the heavy-duty vehicles (HDV 2B – HDV 8B), the bus fleet is expected to change continuously in the future. Hence, there is a need to know the expected future bus-fleet age-distribution in order to calibrate the set the future emission rates.

In this context, the Edmonton Transit [19] supplied a 2006-2015 expected bus purchases plan. It is notable that the Transit System is planning to include the BRT (Bus Rapid Transit) and Hybrid (Diesel/Electric) vehicles in its coming fleet. Actually, there is no function to relate the resulting emission and fuel consumption rates with power for these buses. As a result, these buses are not considered when estimating future bus-fleet composition. Edmonton Transit has a 'bus replacement plan' and a 'growth plan'.

In the former plan, the most unreliable buses are replaced. An overall bus replacement of 38 per year is scheduled. From 2006 to 2015, Edmonton Transit expects to replace:

- 35 of the 12-m long (40 ft) buses annually, and
- 3 of the community buses per year.

On the other hand, the 'growth plan' allows the bus population to expand, taking into account the expected population growth and the resulting bus travel demand. In this context, the expected increase in the number buses is available for the period 2006-2015. This is tabulated below.

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
12 m New	4	12	15	14	~	26	12	13	13	14
12m Low-floor	6	~	~	~	8	~	~	1	1	~
Community	2	2	2	2	~	4	2	~	~	~
Articulated	~	~	~	~	6	~	~	ˋ	ˋ	~
TOTAL	*12*	*14*	*17*	*16*	*14*	*30*	*14*	*14*	*14*	*14*

Table 3-5: Edmonton Transit expected increase in number of each bus type from 2006 to 2015.

To draw the picture of the fleet age distribution for the future buses population, some basic assumptions have been made. The first one concerns the bus replacement plan. It is logical that some buses have shorter lives; others longer. However, it is assumed that only the oldest buses in the bus fleet are being scrapped for every bus being bought under the 'replacement plan'. The number of vehicles under the 'growth plan, are simply added to the bus fleet in the respective model year.

Further, to estimate the fleet-age distribution after 2015, it is assumed that Edmonton Transit continues with the same replacement plan; i.e. substituting 38 of its oldest buses annually with new buses. Under the 'growth plan', Table 3-5 shows that 14 buses have been added to the bus fleet yearly from 2012 to 2015 –

over a four-year period. For post 2015 (till 2030), it is assumed that the bus fleet grows at a rate of 14 buses/year.

With the above sets of assumptions, the future bus population and corresponding distribution by age has been estimated. These estimates have been conducted for years 2006 to 2030. The age distributions, however, has been produced over 5-year periods for years 2010, 2015, 2020 (shown below), 2025 and 2030.

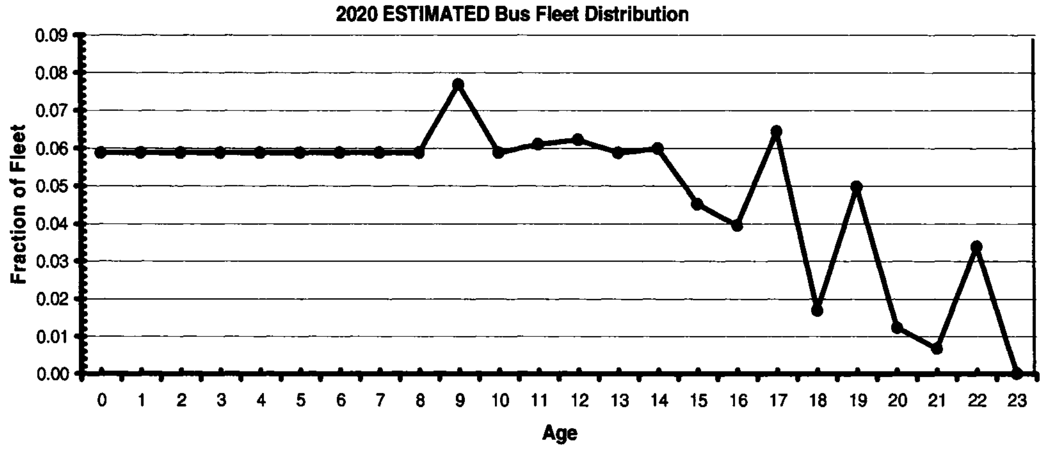


Figure 3-22: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2020.

3.8.3 FLEET COMPOSITION BY VEHICLE TYPE

The vehicle fleet is composed of a wide variety of vehicle types and vehicle subclasses. From subclass to subclass, vehicle characteristics differ. As a result, energy demand for each vehicle subcategory differs. Hence, fuel consumption and emission rates vary from one subclass to another. To improve upon the emission inventory, it is important to consider all subclasses. In this context, the VIN-decoded information from the registries was used to determine the fleet composition by vehicle type. This is tabulated in Table 3-6.

CLASSIFICATION 1

Light-Duty Vehicle:	
Small	41.9
Economy	47.8
Large/Luxury	10.3
Light-Duty Truck:	
LDT 1	13.8
LDT 2	48.2
LDT 3	25.6
LDT 4	12.4
Heavy-Duty Vehicle:	
HDV 2B	27.9
HDV 3	18.2
HDV 4	8.8
HDV 5	3.4
HDV 6	3.0
HDV 7	7.5
HDV 8A	10.4
HDV 8B	20.7
Buses:	
Small School	16.2
Long School	32.5
Transit New	17.6
Transit Old	31.2
Transit Long	0.8
Transit Short	1.7

CLASSIFICATION 2

Light-Duty Vehicle:	
Small	28.3
Economy	32.3
Large/Luxury	6.9
LDT 1	7.2
LDT 2	25.2
Light-Duty Truck:	
LDT 3	67.5
LDT 4	32.5
Medium-Duty Vehicle:	
MDV 2B	47.7
MDV 3	31.2
MDV 4	15.1
MDV 5	5.9
Heavy-Duty Vehicle:	
HDV 6	7.3
HDV 7	18.0
HDV 8A	24.9
HDV 8B	49.8
Buses:	
Small School	16.2
Long School	32.5
Transit New	17.6
Transit Old	31.2
Transit Long	0.8
Transit short	1.7

Table 3-6: Vehicle subclass percentages given for each vehicle category. (Note that there are 2 different vehicle classifications and composition for each of them differ).

3.8.4 FLEET COMPOSITION BY FUEL TYPE

Accounting for the fleet composition by the various fuel types is necessary when developing an emissions inventory. Alternative-fuelled vehicles emit differently compared to standard vehicles. Again, the percentages of such vehicles were obtained using the VIN-decoded information.

CLASSIFICATION 1

	Gasoline	*Diesel*	*Natural Gas*	*Propane*	*Methanol*	*Ethanol*	*Electric*
Light-Duty Vehicle:	99.43	0.56	0.00	0.00	0.01	0.00	0.00
Light-Duty Truck:	96.89	3.00	0.00	0.06	0.00	0.05	0.00
Heavy-Duty Vehicle:	36.44	63.27	0.19	0.10	0.00	0.00	0.00
Buses:	1.11	92.09	0.00	0.12	0.00	0.00	6.67

CLASSIFICATION 2

	Gasoline	*Diesel*	*Natural Gas*	*Propane*	*Methanol*	*Ethanol*	*Electric*
Light-Duty Vehicle:	99.53	0.43	0.00	0.00	0.01	0.03	0.00
Light-Duty Truck:	92.23	7.63	0.00	0.14	0.00	0.00	0.00
Medium-Duty Vehicle:	58.24	41.72	0.02	0.02	0.00	0.00	0.00
Heavy-Duty Vehicle:	6.27	93.13	0.42	0.18	0.00	0.00	0.00
Buses:	1.11	92.09	0.00	0.12	0.00	0.00	6.67

Table 3-7: Extracted percentages of alternative-fuelled vehicles from the database of VIN-decoded information.

3.9 GENERATING COMPOSITE BASE EMISSION RATES

The fleet is made up with a mix of old and new vehicles. Each of those vehicles emit differently. Luckily, there is a method of categorizing vehicles into passenger car, light-duty trucks, heavy-duty trucks and buses. These have been further subdivided. Emissions from these vehicle sub-categories differ. The methodology adopted for extracting composite base emission rates for buses (stored in TempBus.xls) differ from the rest of the vehicle fleet (stored in Temp.xls), as presented below.

3.9.1 LDV, LDT AND HDV COMPOSITE BASE EMISSION RATES

In an attempt to generate an emission inventory, it is vital to consider emission rates from each of the vehicle subclasses, over a wide age-distribution. These two requirements have been met in the previous sections. For a particular calendar year, MOBILE6 gives the base emission rates for vehicles of a certain age. Likewise, the fraction of vehicles by age (between 1 and 23) has been extracted from the registration data. This applies for each calendar year and for each vehicle category. It is logical that these fractions add up for a particular model year.

It is worth mentioning that in each calendar year, each class of vehicles is assumed to consist of vehicles over an age span of zero to twenty-three years only. The fraction of vehicles over twenty-three years old was added to the 'Age 23' fraction of the fleet. This summation is performed as it is assumed that vehicles of 'Age 23' and over emit at the same rates.

To generate a composite base emission rate for a calendar year and for each vehicle subclass, matrices of the MOBILE6 base emission rates and of the fleet-age distribution are required. Sum of the product of these two '23 x 1' and '1 x 23' order matrices give the composite base emission rates for a model year.

3.9.2 BUS COMPOSITE BASE EMISSION RATES

Generation of composite base emission rates for buses has been dealt differently. This is so because of the continuous evolution of the bus fleet, as described in section 3.8.2.

Contrary to the rest of the fleet where the same fleet-age distribution has been assumed, different age profiles have been observed for the buses over the years. Past and actual bus-fleet profiles were obtained for years 1989, 1994, 1996, 2000 and 2005. Additionally, distribution has been predicted for years 2010, 2015, 2020, 2025 and 2030.

For each of the years above, the composite base emission rates have been computed using the same matrix system as in section 3.9.1. Subsequently, linear interpolation between the resulting composite base emission rates has been made. In this way, composite base emission rates for the years in between the gaps are available.

Figure 3-23 illustrates the progress in the Edmonton's bus composite base nitrogen oxides emission rates. The nomenclatures (HDGB, HDDBT, HDDBS) refer to the buses as per designated by the MOBILE6 classification scheme.

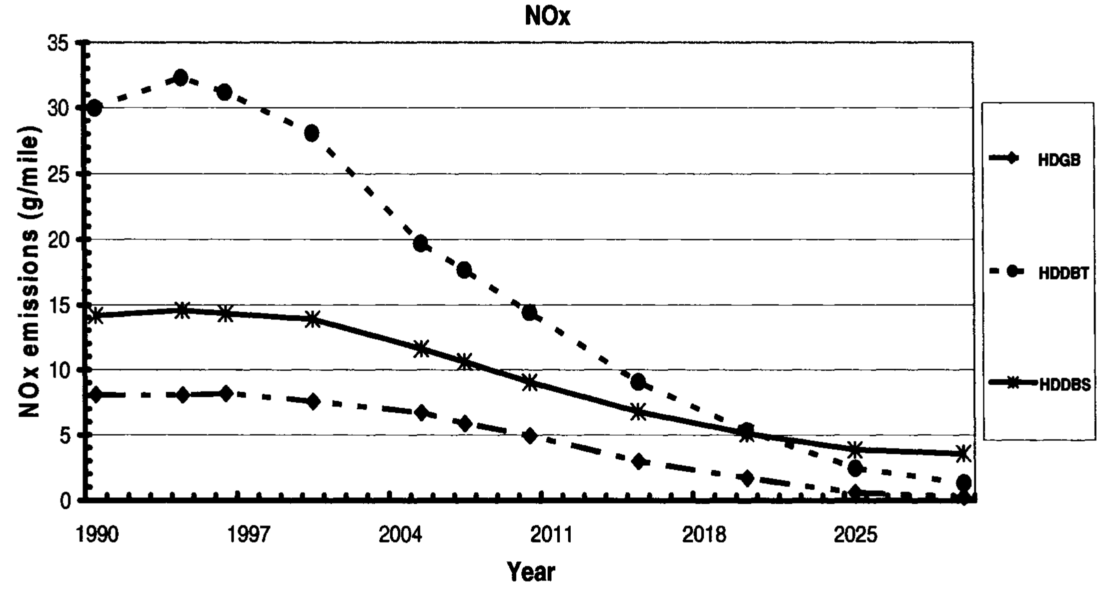


Figure 3-23: Bus composite base emission rate of Nitrogen Oxides.

3.10 EMISSIONS AND FUEL CONSUMPTION MODEL FUNCTIONS CALIBRATION

The emissions and fuel consumption functions, in themselves, give a unique quantity when a particular vehicle follows a speed-time trace. These functions were developed by running performance tests on laboratory engine dynamometers [2, 3]. In such tests, the dynamometers are not faced with rolling resistance, aerodynamic losses and other accessory power demand. Hence, the resulting E&FC amount from the dynamometer is expected to be lower than that from an on-road vehicle running over the same speed-trace. To shift that low amount to the required a simple multiplicative factor is used – otherwise referred to as the calibration factor. Further, to be able to estimate past and current and predict future E&FC quantities, reliable databases are required for such purpose. Thence, the use of the composite base emission rates and of the trustworthy fuel consumption trends, over the range years (1990-2030) is adequate.

3.10.1 GENERATING E&FC RATES USING CERTIFICATION CYCLES

Generating the E&FC amounts for each vehicle category or vehicle sub-class is the baseline in the calibration process. In this case, it is crucial to know which certification cycles have been adopted by the US EPA and the NR Canada when developing their databases of emissions and fuel consumption.

A model vehicle simulator program (see Figure 3-1) was developed to generate the emissions and fuel consumption rate. The program contains the speed traces of various certification cycles. It also contains the vehicles characteristics that have been adopted by CALMOB6. Hence, emission and fuel consumption rates can be obtained for a model vehicle simulated over a specific certification cycle. The model emission rates for all vehicle subclasses are stored in the 'Model Rates Emissions.xls' worksheet. Similarly, the fuel consumption rates have been stored in 'Model Rates FC.xls'. CALMOB6 employs these worksheets to do its emission and fuel consumption functions calibration internally.

Vehicle	US EPA - Driving Cycle	NR Can - D.
Passenger Car	Hot Running LA4 – FTP72 (E) [13]	FTP 72 (FC) [5]
Light-Duty Truck	Hot Running LA4 – FTP 72 (E) [13]	FTP 72 (FC) [5]
Heavy-Duty truck	FTP Transient (E&FC) [22]	n/a
Bus	FTP Transient (E) [22] CBD cycle (FC) [9]	n/a

Table 3-8: Certification cycles for testing Light and Heavy duty vehicles. E and FC represent the cycles used for emission and fuel economy certification, respectively.

As stated in section 3.6.1, NR Canada's data is based on the 55/45 City/Highway proportion. However, in the dataset forwarded by NR Can [7], City driving fuel consumption rate is also available separately. Hence, to better represent city driving conditions, the latter fuel rate has been used. Moreover, diesel-fuelled light-duty vehicles in Canada are negligible compared to gasoline vehicles sales. As a result, it is assumed that the trends relate to gasoline fuel consumption.

It is worth pointing out that the cycles in the above table have been used to generate running emission rates only. These are on a g/mile basis. The start emissions for the light-duty vehicles are dealt otherwise.

Each vehicle of model mass, frontal area, coefficient of drag and coefficient of rolling resistance is simulated to follow the respective speed-time traces. EPA uses such traces to estimate emissions and the heavy duty's fuel consumption. For instance, the City cycle (FTP 72) is used to simulate the light-duty's motion when dealing with the latter emissions and fuel consumption. Table 3-8 gives the complete list of cycles that have been used to certify emissions and fuel consumption rate for the listed vehicle categories. Each of the certification cycles has different speed traces to better represent the actual world driving conditions of those vehicles. See Figure 3-24A for a model speed trace.

Knowing the specific vehicle characteristics, the power trace can be modeled to best represent the tractive force on the vehicle (Figure 3-24B). Finally, using appropriate power-based emissions and fuel consumption functions derived previously at the University of Alberta [2, 3], second-by-second emissions and fuel consumption traces can be generated. By integrating Figures 3-24A and 3-24C over the travel time, the distance traveled and the total emissions produced or total fuel consumed over the cycle is obtained. The ratio of these two quantities gives the model emissions and fuel consumption rates in gram/mile. Fuel consumed is then converted to the L/100km rate.

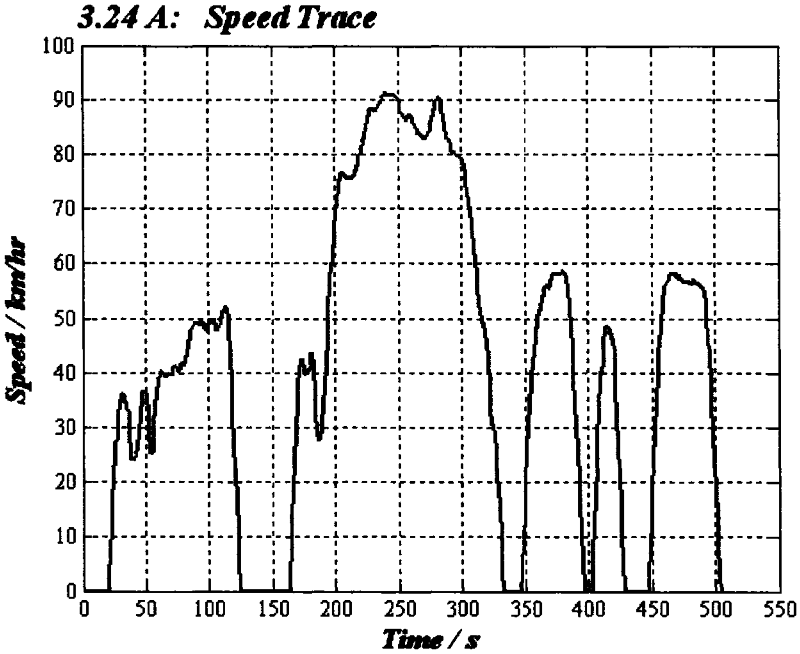


Figure 3-24 A: Example of a speed trace for an emission and/or fuel consumption certification cycle.

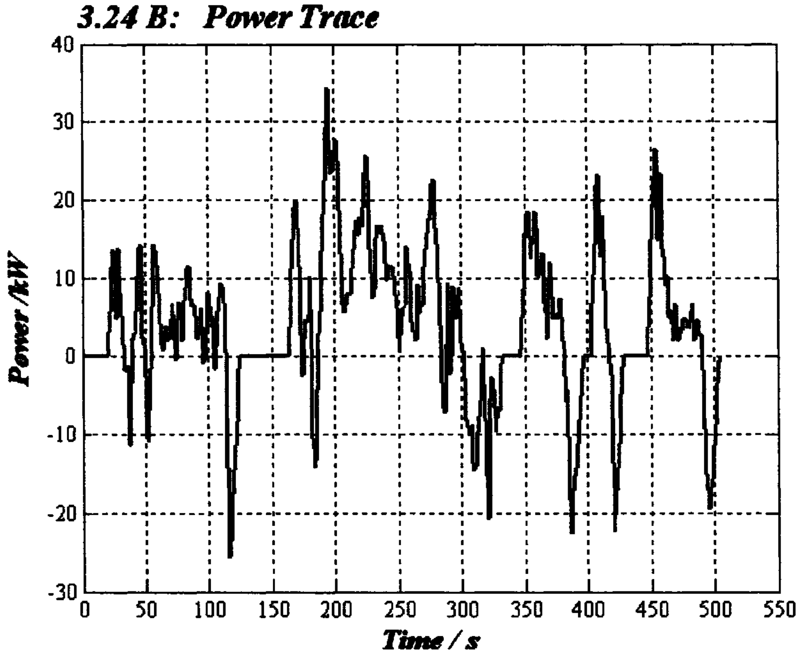


Figure 3-24 B: Modeled power trace of a vehicle following the above speed trace.

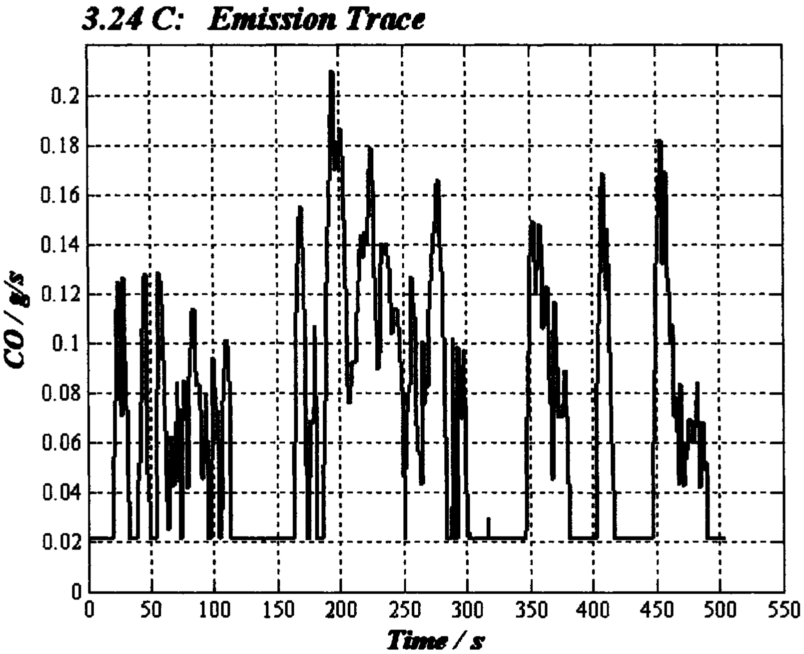


Figure 3-24 C: Second-by-second emission trace obtained after applying the power-based emission functions on the power trace.

		HC_RN	CO_RN	NO_RN	PA_RN	FUEL
		g/mile	**g/mile**	**g/mile**	**g/mile**	**L/100km**
1	**LDGV - MINI**	2.089	8.536	0.849	n/a	10.462
2	**LDGV - ECONOMY**	2.201	9.447	1.078	n/a	11.363
3	**LDGV - LARGE**	2.342	10.594	1.401	n/a	12.456
4	**LDGT 1**	2.329	10.505	1.364	n/a	13.048
5	**LDGT 2**	2.489	11.827	1.771	n/a	14.494
6	**LDGT 3**	2.653	13.236	2.247	n/a	16.197
7	**LDGT 4**	2.737	13.966	2.517	n/a	16.968
8	**HDGV 2B**	2.777	13.709	2.573	n/a	19.587
9	**HDGV 3**	2.895	14.739	3.009	n/a	21.055
10	**HDGV 4**	3.024	15.978	3.536	n/a	22.672
11	**HDGV 5**	3.181	17.474	4.252	n/a	24.636
12	**HDGV 6**	3.395	19.569	5.356	n/a	27.318
13	**HDGV 7**	3.619	21.831	6.671	n/a	30.221
14	**HDGV 8A**	4.335	29.599	12.328	n/a	39.046
15	**HDGV 8B**	4.658	33.340	15.580	n/a	43.209
16	**Gasoline Bus Long School**	3.759	23.300	7.708	n/a	33.650
17	**Gasoline Bus Small School**	2.971	15.481	3.305	n/a	23.065
18	**Gasoline Bus Transit Long**	4.379	30.121	12.853	n/a	40.249
19	**Gasoline Bus Transit New**	3.979	25.655	9.333	n/a	36.040
20	**Gasoline Bus Transit Old**	3.769	23.402	7.765	n/a	33.653
21	**Gasoline Bus Transit Short**	2.990	15.663	3.387	n/a	23.379
22	**LDDV - MINI**	0.806	3.807	2.376	0.147	12.600
23	**LDDV - ECONOMY**	0.840	4.385	2.896	0.178	13.054
24	**LDDV - LARGE**	0.881	5.265	3.558	0.224	13.678
25	**LDDT 1**	0.887	5.435	3.659	0.232	14.023
26	**LDDT 2**	0.929	6.560	4.372	0.287	14.988
27	**LDDT 3**	0.967	7.799	5.026	0.344	16.239
28	**LDDT 4**	0.985	8.495	5.349	0.375	16.845
29	**HDDV 2B**	1.122	7.056	4.410	0.270	20.256
30	**HDDV 3**	1.212	8.146	5.109	0.319	23.023
31	**HDDV 4**	1.321	9.476	5.946	0.377	26.352
32	**HDDV 5**	1.426	11.124	6.894	0.447	29.901
33	**HDDV 6**	1.634	14.016	8.583	0.573	36.474
34	**HDDV 7**	1.878	17.432	10.582	0.722	44.390
35	**HDDV 8A**	2.457	30.762	17.218	1.272	70.133
36	**HDDV 8B**	2.633	37.206	19.941	1.481	83.179
37	**Diesel Bus Long School**	1.987	20.443	11.924	0.854	65.561
38	**Diesel Bus Small School**	1.224	8.402	5.325	0.328	32.418
39	**Diesel Bus Transit Long**	2.479	32.275	17.690	1.323	94.817
40	**Diesel Bus Transit New**	2.154	24.146	13.826	1.006	74.342
41	**Diesel Bus Transit Old**	1.920	20.065	11.646	0.831	63.248
42	**Diesel Bus Transit Short**	1.243	8.660	5.468	0.340	33.160

Table 3-9: E&FC Running Rates generated from the model-vehicle simulator program.

3.10.2 Calibration of Emission and Fuel Consumption Functions

A calibration factor (or rather a multiplicative factor) is used to adjust the emissions/fuel consumption functions as follows:

$$\mathbf{\begin{matrix}\text{Model Year}\\ \text{Emissions}\\ \text{Calibration}\\ \text{Factor}\end{matrix} = \frac{\text{Composite MOBILE6 Rate [gram/mile]}}{\text{Vehicle Model Simulator [gram/mile]}}}$$

Equation 3-7: Calibration factor for emission functions.

$$\mathbf{\begin{matrix}\text{Model Year}\\ \text{Fuel}\\ \text{Consumption}\\ \text{Calibration}\\ \text{Factor}\end{matrix} = \frac{\text{NR Can (LD) or US EPA (HD) Rate [L/100km]}}{\text{Vehicle Model Simulator [L/100km]}}}$$

Equation 3-8: Calibration factor for fuel consumption functions.

Note: LD: Light-Duty; HD: Heavy-Duty

For a calendar year in which emissions and fuel consumption is to be estimated, CALMOB6 retrieves the corresponding composite base emission rates of every pollutant for every vehicle from *Temp.xls* worksheet. Simultaneously, the expected fuel consumption rate for every vehicle in that calendar year is searched for in *TempBus.xls* spreadsheet. These values correspond to the numerators of Equations 3-7 and 3-8. The denominators of the latter equations are obtained from the look-up Table 3-9. In this way, CALMOB6 calculates the multiplicative factors which are used to adjust its E&FC functions.

For instance, consider a light-duty gasoline truck LDT 2 (0-6,000 lbs. GVWR and 3,751-5,750 lbs. LVW) that is gasoline fuelled. The CALMOB6 model assumes 2120 kg vehicle mass, 2.633 m^2, frontal area, 0.368 drag coefficient and 0.013 rolling resistance coefficient. Running this model vehicle through the certification speed-time trace on which MOBILE6 test results are based gives an un-calibrated CO emission rate of 11.83 g/mile (Table 3-9). MOBILE6 CO emission rates for LDT 2 trucks are shown in Table 3-10. For fleet years ranging from 1990 to 2030, the MOBILE6 hot running emission rates vary from 23.35 g/mile to 3.24 g/mile for Edmonton's fleet distribution of LDT 2 vehicles. CALMOB6 calibration values are obtained by dividing the fleet emission rate by the un-calibrated CALMOB6 value, giving the calibration values in the fourth column of Table 3-10. This calibration procedure was followed for each vehicle category used in CALMOB6 and for each of the criteria pollutants (CO, HC and NOx) as well as for the particulates.

The cold start emissions also shown in Table 3-10 are the excess emissions resulting when a vehicle is cold-started after a significant cool-down period. CALMOB6 assumes that the excess emissions from cold-starting vehicles are spread evenly over the first 2 km of travel. Hence, for links or zones with cold-starting vehicles, a fraction of the fleet cold-start emission value is added to the calculated emissions based on the number of cold-starting vehicles and the length of the link.

MOBILE6 does not split passenger car and the bus categories, unlike CALMOB6. As a result calibration is made for those vehicle(s) that are most closely related to the MOBILE6 vehicle. Hence, for the passenger car calibration factors are obtained for the Economy version only. These factors are used to adjust the E&FC resulting from the Mini and Large/Luxury cars. As for the buses, calibration is made for CALMOB6 Transit New and Long School buses. These calibration factors are used to adjust E&FC for the rest of the transit and school buses respectively.

Simulation Year	Cold Start CO emission (g)	Composite Hot Running CO Emission (g/mile)	Hot Running Calibration Values
1990	199.466	23.347	1.974
1991	182.247	21.645	1.830
1992	166.633	20.117	1.701
1993	151.708	18.649	1.577
1994	137.084	17.259	1.459
1995	121.639	15.815	1.337
1996	107.966	14.586	1.233
1997	95.670	13.458	1.138
1998	84.021	12.349	1.044
1999	74.267	11.435	0.967
2000	65.576	10.618	0.898
2001	57.430	9.879	0.835
2002	51.657	9.035	0.764
2003	45.977	8.446	0.714
2004	37.488	7.808	0.660
2005	33.984	7.279	0.615
2006	30.978	6.765	0.572
2007	27.076	6.431	0.544
2008	25.006	5.995	0.507
2009	23.265	5.599	0.473
2010	21.698	5.286	0.447
2011	19.526	4.938	0.417
2012	18.175	4.752	0.402
2013	16.997	4.586	0.388
2014	15.977	4.433	0.375
2015	15.017	4.286	0.362
2016	14.244	4.150	0.351
2017	13.294	3.987	0.337
2018	12.727	3.883	0.328
2019	12.253	3.782	0.320
2020	11.829	3.676	0.311
2021	11.444	3.579	0.303
2022	11.109	3.492	0.295
2023	10.850	3.424	0.290
2024	10.555	3.346	0.283
2025	10.436	3.314	0.280
2026	10.364	3.295	0.279
2027	10.166	3.240	0.274
2028	10.166	3.240	0.274
2029	10.166	3.240	0.274
2030	10.166	3.240	0.274

Table 3-10: MOBILE CO Emissions values and CALMOB6 calibration ratios for Light-Duty Gasoline Truck, LDT2.

3.11 OTHER ADJUSTMENT FACTORS

Adjustment factors are obtained from technical literatures. These are used to modify the estimates when accounting for a fraction of high emitters and for different ambient temperatures. Emissions and fuel consumption from alternative-fuelled vehicles [8] are computed by using multiplicative factors to provide values based on a ratio of the normal fuel emissions. The reference for the light-duty fleet is baseline gasoline values and the reference for the heavy-duty fleet is baseline diesel values.

3.11.1 ALTERNATIVE-FUELLED VEHICLES

In view of matching closely the fleet properties, it is necessary to include the alternative-fuel vehicles. Today, the fleet is composed of majority of light-duty gasoline vehicles and higher proportion of heavy-duty diesel vehicles. Several published literatures have attempted to relate the relative emissions and fuel consumption from alternative-fuel vehicles as a benefit or a drawback. Many of these available publications, if not all, have compared these resulting E&FC quantities with respect to gasoline for the light-duty fleet. Diesel was used as reference for the heavy-duty vehicles.

In this context, CALMOB6 has been adapted to include emission and fuel consumption for various vehicles including those powered by natural gas, propane (liquefied petroleum gas), methanol (M85), ethanol (E85) and electricity. Comparative factors were used to adjust E&FC from gasoline/diesel vehicles to those from alternative-fuel vehicles. This is described by the following equation:

$$\mathrm{E\&FC}_{\mathrm{ALT.\text{-}FUEL}} = \textbf{\textit{COMPARATIVE FACTOR}} \ \mathrm{x} \ \mathrm{E\&FC}_{\mathrm{GASOLINE/DIESEL}} \ \ldots\ldots\textbf{\textit{E.q 3-9}}$$

CALMOB6 applies these comparative factors to adjust the already calibrated E&FC functions for gasoline and diesel vehicles. Tabulated below are the set of relative factors that have been employed by CALMOB6. The relative factors were calculated using data that were gathered from published technical literatures. These are referenced to in the squared-brackets.

	NMHC	CO	NOx	Fuel
Natural Gas	0.27 [24]	1.24 [24]	1.15 [24]	1.08 [26]
Propane	2.78 [24]	0.52 [24]	1.95 [24]	1.04 [43]
Methanol	1.24 [24]	1.03 [24]	1.09 [24]	1.76 [27]
Ethanol	1.31 [25]	0.96 [25]	0.41 [25]	1.35 [25]

Table 3-11: Comparative factors obtained/calculated for the Light-Duty fleet with Gasoline as reference.

	NMHC	CO	NOx	PM	Fuel
Natural Gas	5.16 [24]	0.55 [24]	0.52 [24]	0.07 [24]	1.28 [29]
Propane	0.62 [24]	0.05 [24]	0.45 [24]	0.06 [24]	2.09 [44]
Methanol	2.57 [24]	0.87 [24]	0.62 [24]	0.24 [24]	2.3 [45]
Ethanol	1.98 [46]	4.30 [46]	0.74 [46]	0.35 [46]	2.03 [46]

Table 3-12: Comparative factors obtained/calculated for the Heavy-Duty fleet with Diesel as reference.

Dhaliwal *et al* [24] has already compiled a set of relative indexes for emissions from alternative vehicles. These indexes are averaged and converted to obtain the CALMOB6 comparative factors. Chandler *et al* [25] and Kelly *et al* [26] have tabulated average emissions and fuel consumption results for ethanol and natural gas light duty vehicles respectively. Similarly, the results from the different laboratory results obtained by Kelly *et al* [27] have been used to obtain an average methanol (M85) consumption rate. On a gasoline equivalent-energy basis, Sun *et al* [43] obtained a 4% lower fuel economy with LPG vehicles relative to the baseline gasoline vehicles. Clark *et al* [29] found that the energy-equivalent fuel consumption of the CNG (Compressed Natural Gas) was 28.1% poorer than for the diesel buses. Similarly, Turner *et al* [44] found that propane fuel economy averaged to 94 L/100km, compared to 45 L/100km with diesel for a class 8 propane powered truck. Besides, assuming same efficiency a methanol and diesel heavy-duty vehicle, a comparative factor of 2.3 is obtained [45]. Finally, WVU (West Virginia University) team made some test on ethanol heavy-duty vehicles. The tests were destined for the NREL (National Renewable Energy Laboratory). The results were compared with diesel vehicles [46]. Appendix K provides a literature review of all the results.

CALMOB6 uses the set of comparative factors to adjust the E&FC functions for the light duty gasoline vehicles (using data from Table 3-11). In the same way, CALMOB6 should have used diesel as base for the heavy-duty vehicles. Instead, the gasoline E&FC functions have been used. However, these are adjusted accordingly by a factor. The latter considers the amount diesel consumption relative to that amount of gasoline consumption when the same vehicle model is simulated over an FTP cycle. This way, the following adjustment has been made to accommodate use of E&FC functions for gasoline vehicles.

$$\begin{array}{c}\textbf{E\&FC amount}\\\textbf{from}\\\textbf{alternative-fuel}\\\textbf{vehicles}\end{array} = \begin{array}{c}\textbf{E\&FC amount}\\\textbf{from Gasoline-}\\\textbf{fuelled, heavy-}\\\textbf{duty vehicles}\end{array} \times {}^{1}\left(\frac{\textbf{E\&FC}_{\textbf{Alt-Fuel}}}{\textbf{E\&FC}_{\textbf{Diesel}}}\right) \times {}^{2}\left(\frac{\textbf{E\&FC}_{\textbf{FTP, Diesel}}}{\textbf{E\&FC}_{\textbf{FTP, Gasoline}}}\right)$$

Equation 3-10: CALMOB6 E&FC adjustment equation for alternative-fuel vehicles.

The first ratio (with '1' as superscript) is available from the published technical literatures. They are listed in Table 3-12. The ratio, with superscript '2', relates to the E&FC amounts obtained when a diesel vehicle and a gasoline vehicle are run on FTP cycles. For emissions, the quantities in ratio '2' apply to MOBILE6 composite base emission rates. Diesel and gasoline consumption quantities are obtained using the equations in Table 3-4. As a result, the ratio '2' is subject to change year after year. It depends on emissions control and fuel-consumption rate improvement of heavy-duty vehicles. The Equation 3-10 can hence be used to estimate the amount of emission and fuel consumption from heavy-duty vehicles using the E&FC function for gasoline vehicles.

For the electric vehicles, only emissions of carbon dioxide and nitrogen oxides are estimated. The grid electrical energy is used to estimate such emissions at power plants. The grid electrical energy is derived from the modeled energy requirement of the vehicle. The same assumptions made by Checkel [48] are used to estimate the grid electrical energy and the emissions. In this way, the tractive system of electric vehicles is assumed 68.8% efficient. Moreover, 3.68% of the remaining energy is wasted for running different accessories. Batteries and chargers operate at an estimated efficiency of 80% and 90% respectively. To predict improvement in future electric vehicle technology, the same yearly fuel calibrations ('fuelCal(year X)') as to gasoline vehicles are used. Thus, if 'ENETOT' is the tractive energy required by model vehicle, the electrical energy at the grid is estimated as follows (in Equation 3-11):

$$\text{Electrical Energy at the Grid, (kWh)} = \frac{\text{ENETOT (kWh)} \times \text{fuelCal(year X)}}{68.8\% \times (100-3.68)\% \times 80\% \times 90\%}$$

Equation 3-11: Deriving electrical energy at grid after obtaining the modeled tractive energy of a model vehicle

Finally, Checkel [48] assumes that 1.095 kg of CO_2 and 2.28 g of NOx are emitted for every kWh of electrical energy produced at the coal power plants. Thus, CALMOB6 is able to compute the CO_2 and NOx emissions due to electric vehicles. The software specifies that these emissions occur at power plants and not at the vehicle.

3.11.2 SUPER-EMITTING VEHICLES

High-emitters contribute largely to the emissions inventory. They result from four basic common cases [30]. Such high emissions result from at least one of the following cases:

- excessively lean fuel-air ratio,
- excessively rich fuel-air ratio,
- partial combustion such as misfire, and
- severe deterioration in catalyst performance.

It is worth mentioning that when extracting the MOBILE6 base emission rates for post 1980 light-duty vehicles, the effect of super-emitters have already been accounted for [11, 12, 14, and 15]. These are separated between the start and running parts. Further, EPA has characterized the US fleet with a fraction of high emitting light-duty vehicles over accumulated mileages. On the other hand, EPA does not account for high-emitting heavy-duty vehicles.

In view of demarcating the high-emitters from the normal emitters, EPA uses threshold values. These limits are multiples of the intermediate life (50,000miles) certification emission standards. This applies to the post Tier1 and later light-duty vehicles [14,15]. Thus, EPA defines high emitter for NOx and HC as 2.0 times the intermediate certification standard. For CO, the threshold is 3.0 times. Wenzel *et al* [30], on the other hand, assumes high emitters to exceed the emissions of typical properly functioning vehicles by a factor of 2.5.

In order to provide more flexibility to the traffic planners, CALMOB6 provides the option of changing the percentage of vehicles that emit beyond limit. As a result, emissions for all CALMOB6 high-emitting vehicles (light- and heavy-duty) assume the same threshold multiplicative factors. However, these factors are used to adjust the resulting emissions accordingly, independent of the 50,000 miles certification standards.

For fuel consumption, a threshold amount of 1.05 times has been assumed by CALMOB6. CO_2 emissions are calculated using a mass balance between fuel mass and CO emissions.

3.11.3 AMBIENT TEMPERATURE EFFECT

Most emission factors are determined from chassis dynamometer experiments where the temperature is stable - usually between 20 and 25 ^{0}C. Driving profiles and ambient conditions [32] have dramatic effect on vehicle emissions.

Hawirko *et al* [32] has presented the relative increases in HC, CO and NOx emissions at -20 ^{0}C relative to those at 25 ^{0}C. Hence, comparison has been made relative to conditions prevailing at standard certification cycles.

Thus, at -20 ^{0}C, the emissions were increased as per following:

- HC by 6.5 times,
- CO by 8.0 times, and
- NOx by 1.1 times.

CALMOB6 estimates emission between three ranges of temperatures with cut-points at 5 and -15 ^{0}C. Emission rates are not affected for temperatures at 5 ^{0}C and higher. Below -15 ^{0}C, the same emission rates are assumed as those occurring at -20 ^{0}C. Hence, the above factors obtained by Hawirko *et al* [32] are employed. Finally, if temperatures are between -15 ^{0}C and 5 ^{0}C, the above rates are reduced by 1/2, except for NOx. Thus, the following increase in emission factors are assumed for ambient temperatures in between -15 ^{0}C and 5 ^{0}C:

- HC by 3.3 times,
- CO by 4.0 times, and
- NOx by 1.05 times.

Finally, an increase in fuel demand of at least 5% has been assumed at any low ambient temperatures (< 5^0C). Carbon dioxide emission is estimated by using Equations 3.2 and 3.3, depending on the fuel used.

3.12 CALMOB6 – GUIDELINES FOR ITS USE

This section describes the use of the vehicle emissions inventory software – CALMOB6. It provides the guidelines through the different stages in the making the proper running of the program. The GUI's (Graphical User Interfaces) involved are used to better illustrate the stages. CALMOB6 can be used to process a single set of inputs or a batch of those sets. Likewise, the user can specify the number and type of links he/she wants the results to be classified. It is worth pointing out that CALMOB6 operates on MATLAB platform.

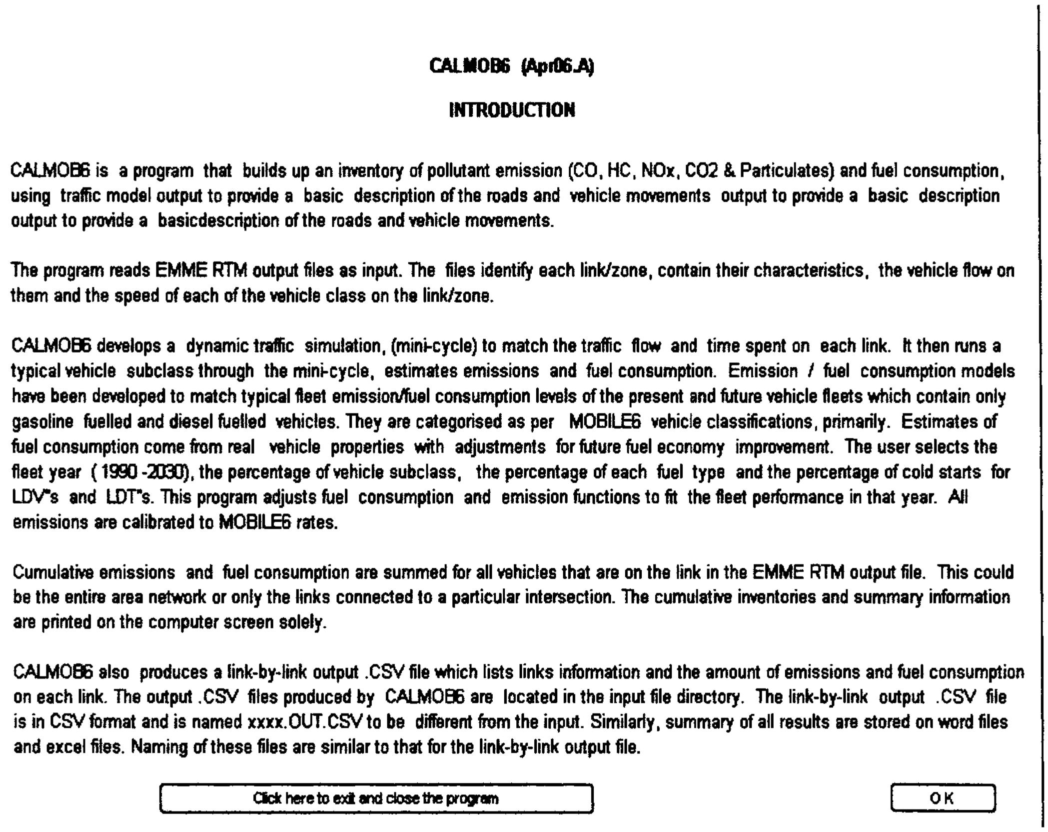
3.12.1 INTRODUCTORY PART

At the command line, 'Runmain' is the command that starts the software.

```
>> Runmain
```

This launches the 'Introduction' window (Figure 3-25) which describes the content of the program, its use and how the results are classified.

'Apr06.A' is the version of the program. The version is always indicated within brackets next to the software name. It indicates the relevant updates and it can be changed within the program. If the user wants to stop the program, the 'Click here to exit and close the program' pushbutton will have to be applied. On the other hand, to continue with the program, click 'OK'.



CALMOB6 (Apr06.A)

INTRODUCTION

CALMOB6 is a program that builds up an inventory of pollutant emission (CO, HC, NOx, CO2 & Particulates) and fuel consumption, using traffic model output to provide a basic description of the roads and vehicle movements output to provide a basic description output to provide a basicdescription of the roads and vehicle movements.

The program reads EMME RTM output files as input. The files identify each link/zone, contain their characteristics, the vehicle flow on them and the speed of each of the vehicle class on the link/zone.

CALMOB6 develops a dynamic traffic simulation, (mini-cycle) to match the traffic flow and time spent on each link. It then runs a typical vehicle subclass through the mini-cycle, estimates emissions and fuel consumption. Emission / fuel consumption models have been developed to match typical fleet emission/fuel consumption levels of the present and future vehicle fleets which contain only gasoline fuelled and diesel fuelled vehicles. They are categorised as per MOBILE6 vehicle classifications, primarily. Estimates of fuel consumption come from real vehicle properties with adjustments for future fuel economy improvement. The user selects the fleet year (1990-2030), the percentage of vehicle subclass, the percentage of each fuel type and the percentage of cold starts for LDV"s and LDT"s. This program adjusts fuel consumption and emission functions to fit the fleet performance in that year. All emissions are calibrated to MOBILE6 rates.

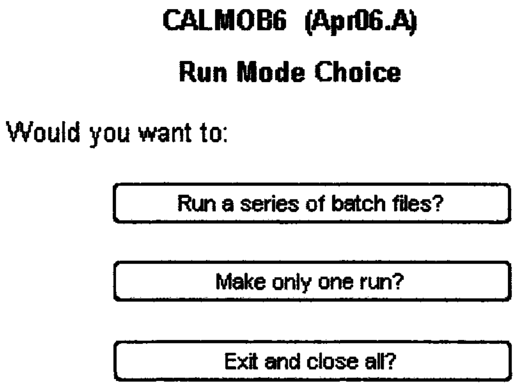
Cumulative emissions and fuel consumption are summed for all vehicles that are on the link in the EMME RTM output file. This could be the entire area network or only the links connected to a particular intersection. The cumulative inventories and summary information are printed on the computer screen solely.

CALMOB6 also produces a link-by-link output .CSV file which lists links information and the amount of emissions and fuel consumption on each link. The output .CSV files produced by CALMOB6 are located in the input file directory. The link-by-link output .CSV file is in CSV format and is named xxxx.OUT.CSV to be different from the input. Similarly, summary of all results are stored on word files and excel files. Naming of these files are similar to that for the link-by-link output file.

Figure 3-25: Introductory window that describes the content of the program, its use and the result classification.

If 'OK' in 'Introduction' window is chosen, the program will prompt the user to choose between the types of run that is expected. Figure 3-26 illustrates such GUI. Pushbutton 'Make only one run?' allows the user to enter a single set of inputs to the program. 'Run a series of batch file' enables the user to make multiple runs. Each run can have different inputs to the program.

For demonstration purpose, the single run will be shown firstly. Subsequently, the use of batch-file processing will be illustrated.



CALMOB6 (Apr06.A)

Run Mode Choice

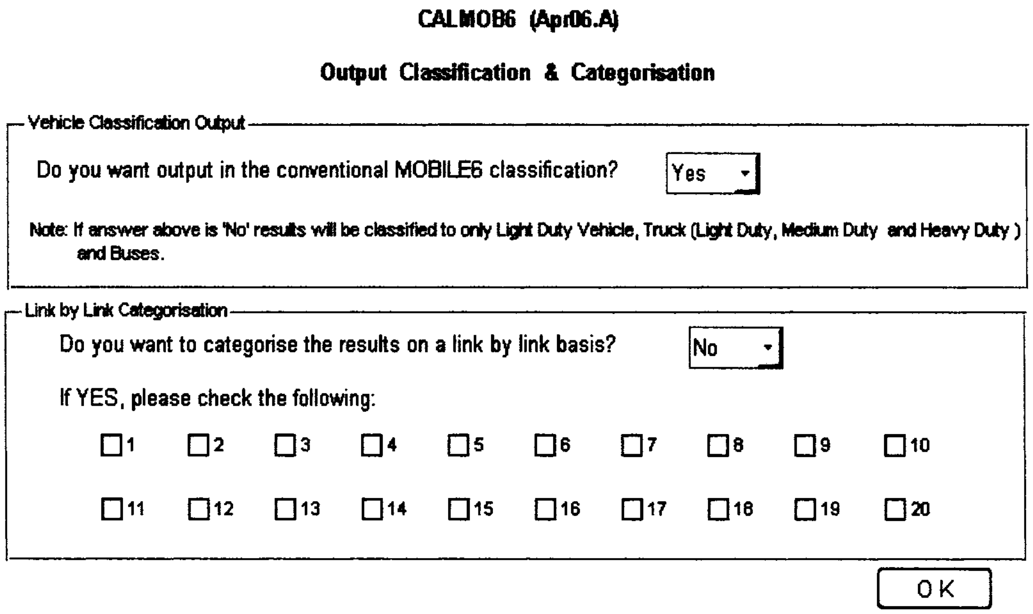
Would you want to:

Figure 3-26: Choice between the types of runs – run using a single set of inputs or variety of such sets.

3.12.2 MAKING ONLY ONE RUN

Choosing to make one run from Figure 3-26 will pop out the 'Output Classification & Categorization' window. Two panels are included in this screen – the 'Vehicle Classification Output' and the 'Link by Link Categorization'. The objectives of each are as follows:

- 'Vehicle Classification Output': The user has the option to choose between one of the two vehicle classification-schemes. Description of the vehicle classification is given in section 3.1, Table 3-1. If 'Classification 1' from Table 3-1 is required, the user has to choose 'Yes' for the conventional MOBILE6 classification (Figure 3-27). For illustration purposes, here, classification 1 is chosen.


CALMOB6 (Apr06.A)

Output Classification & Categorisation

Vehicle Classification Output

Do you want output in the conventional MOBILE6 classification? Yes

Note: If answer above is 'No' results will be classified to only Light Duty Vehicle, Truck (Light Duty, Medium Duty and Heavy Duty) and Buses.

Link by Link Categorisation

Do you want to categorise the results on a link by link basis? No

If YES, please check the following:

☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10

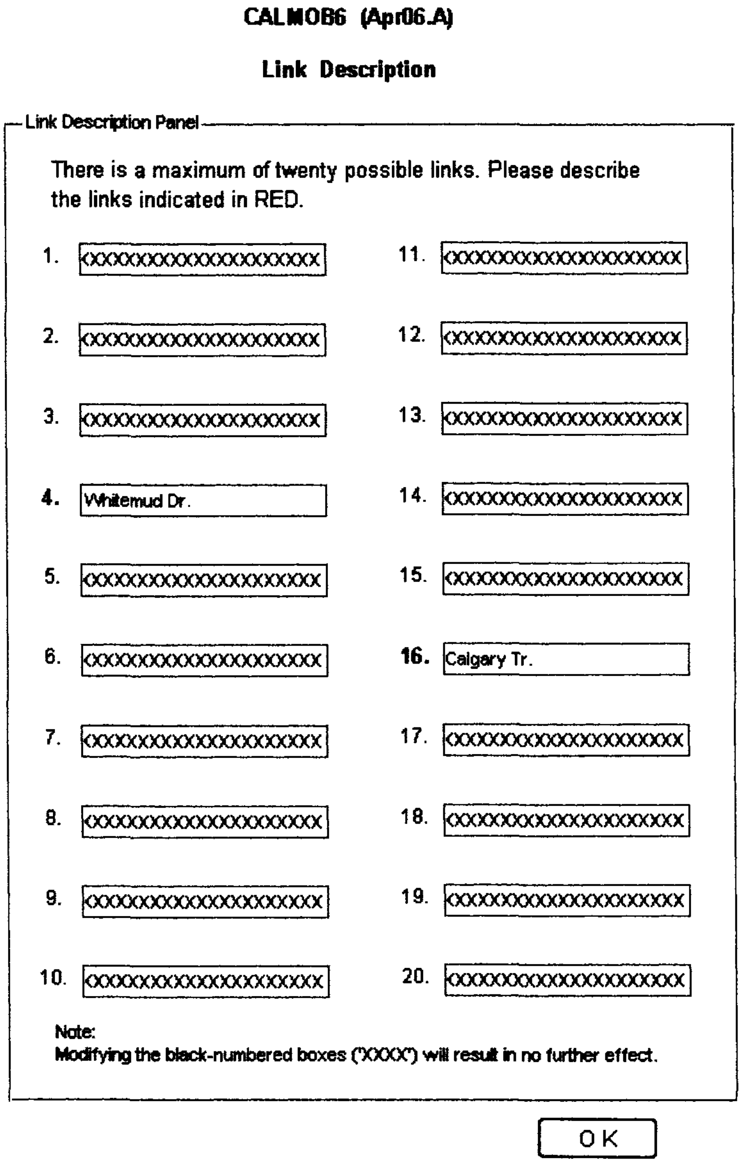
☐11 ☐12 ☐13 ☐14 ☐15 ☐16 ☐17 ☐18 ☐19 ☐20

Figure 3-27: Opting for the vehicle classification scheme and the categorization of E&FC on a link-by-link basis.

- 'Link by Link Categorization': This option provides traffic planners the option to demarcate emissions and fuel consumption (E&FC) amounts from different links, areas and zones. There are twenty such separations. The link number is indicated in the EMME/2 output file. Column 3 of Table 3-3 with header 'Link Type' is used to assign each separation a number between 1 and 20 inclusive. Subsequently, CALMOB6 reads all links and classify calculated E&FC accordingly in separate output files. If user choose 'No' for link-by-link classification in Figure 3-27, no such classification is made. However, if 'Yes' is chosen, the user has to indicate the link types by checking an unrestricted number of the twenty possible separations. Error messages appear in the following two conditions:
  - if the user chooses 'No' but checked the boxes, or
  - if the user chooses 'Yes' and clicks 'OK' without having checked any of the boxes.

3.12.2.1 LINK DESCRIPTION

If the user opts to classify all the E&FC results according to the different regions (by choosing 'Yes' in the 'Link by Link Categorization' panel of Figure 3-27), CALMOB6 will enable the user to identify all such separations. This can be done though the window indicated in Figure 3-28.



There is a maximum of twenty possible links. Please describe the links indicated in RED.

1. XXXXXXXXXXXXXXXXXXXXX
2. XXXXXXXXXXXXXXXXXXXXX
3. XXXXXXXXXXXXXXXXXXXXX
4. Whitemud Dr.
5. XXXXXXXXXXXXXXXXXXXXX
6. XXXXXXXXXXXXXXXXXXXXX
7. XXXXXXXXXXXXXXXXXXXXX
8. XXXXXXXXXXXXXXXXXXXXX
9. XXXXXXXXXXXXXXXXXXXXX
10. XXXXXXXXXXXXXXXXXXXXX
11. XXXXXXXXXXXXXXXXXXXXX
12. XXXXXXXXXXXXXXXXXXXXX
13. XXXXXXXXXXXXXXXXXXXXX
14. XXXXXXXXXXXXXXXXXXXXX
15. XXXXXXXXXXXXXXXXXXXXX
16. Calgary Tr.
17. XXXXXXXXXXXXXXXXXXXXX
18. XXXXXXXXXXXXXXXXXXXXX
19. XXXXXXXXXXXXXXXXXXXXX
20. XXXXXXXXXXXXXXXXXXXXX

Note:
Modifying the black-numbered boxes ('XXXX') will result in no further effect.

Figure 3-28: Describing the links for which E&FC classifications are made.

If the user checks on '4' and '16' in Figure 3-27, the corresponding input boxes in Figure 3-28 will be highlighted red. The user is expected to define the link assignment. For the remaining links, the boxes are crossed out thus 'XXX'. No input is expected in those boxes. CALMOB6 will display an error message if no data is input in the red-indicated boxes and the user click on 'OK'. However, for the crossed boxes, CALMOB6 will remind the user that no input is effective, should the user modify these boxes.

3.12.3 THE MAIN PANEL

The main panel is displayed right after the following two cases:

- the user chooses 'No' for link-by-link categorization in Figure 3-27, or
- proper link description is made in Figure 3-28

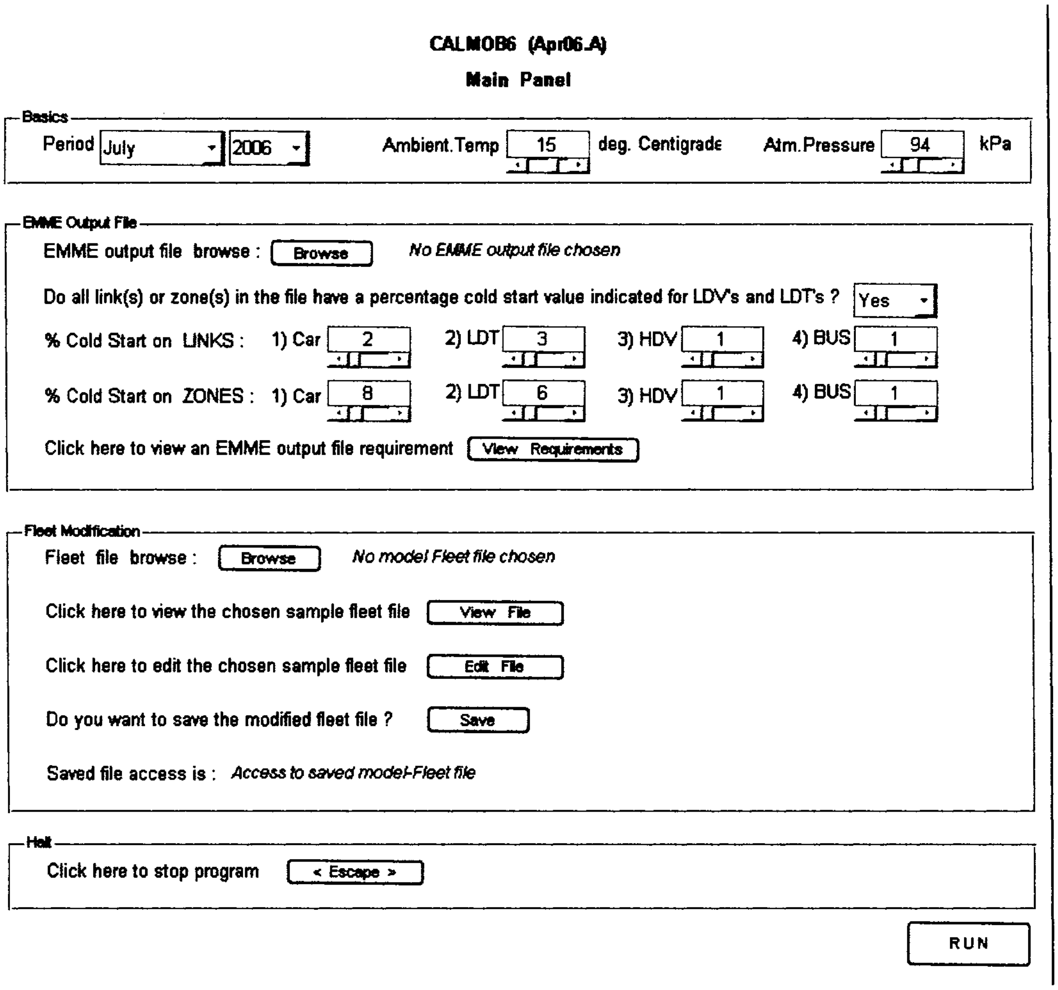
This panel, displayed in Figure 3-29, determines all the inputs to CALMOB6. It is split into four sections: 'Basics', EMME Output File', 'Fleet Modification' and 'Halt'. The latter section is used to stop all operations and close the program immediately.

'Basics' allows the user to define the period in which the E&FC estimation is needed. Choosing the month will automatically adjust the ambient temperature to the default mean temperature of that month. The monthly average temperature applies to that of City of Edmonton. These are given in Table 3-13. However, the user can further modify the ambient temperature directly in the appropriate box or by using the sliders.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature / ^{0}C	-12.5	-8.9	-3.6	4.9	11.6	18.5 *	21.0 *	19.0 *	11.1	5.9	-4.2	-10.5

Table 3-13: City of Edmonton's monthly average temperature [47]. Those indicated in asterisk (*) are not given in the City's website and have been assumed.

The range of temperature considered is within -60 ^{0}C and 45 ^{0}C. Similarly, the limits for the atmospheric pressure are 90 kPa and 110 kPa. Any inputs in temperature and pressure lying out of range are notified by an error message.



CALMOB6 (Apr06.A)
Main Panel

Basics
Period July 2006 Ambient.Temp 15 deg. Centigrade Atm.Pressure 94 kPa

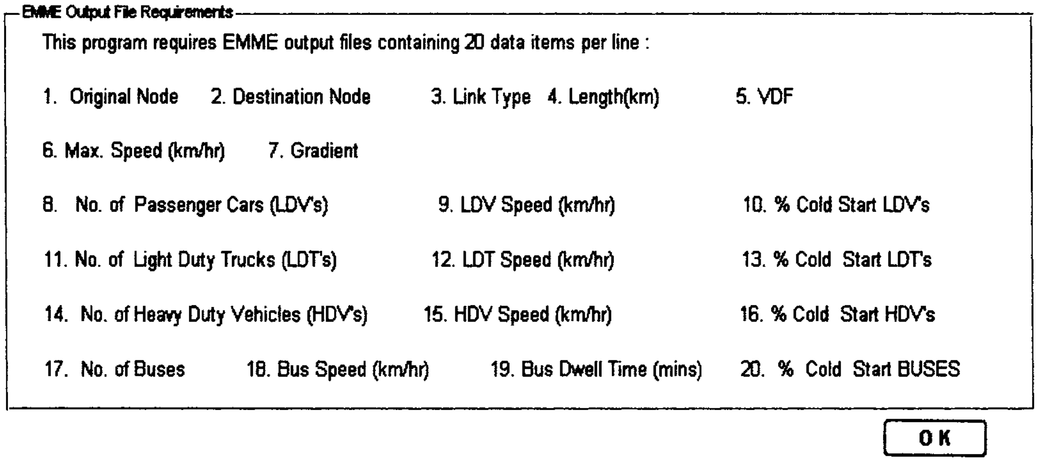
EMME Output File
EMME output file browse : No EMME output file chosen
Do all link(s) or zone(s) in the file have a percentage cold start value indicated for LDV's and LDT's ? Yes
% Cold Start on LINKS : 1) Car 2 2) LDT 3 3) HDV 1 4) BUS 1
% Cold Start on ZONES : 1) Car 8 2) LDT 6 3) HDV 1 4) BUS 1
Click here to view an EMME output file requirement

Fleet Modification
Fleet file browse : No model Fleet file chosen
Click here to view the chosen sample fleet file
Click here to edit the chosen sample fleet file
Do you want to save the modified fleet file ?
Saved file access is : Access to saved model-Fleet file

Halt
Click here to stop program

Figure 3-29: CALMOB6 main panel where all inputs are defined.

The 'EMME Output File' section enables the user to choose an appropriate EMME/2 output file. The requirements of such EMME/2 file can be viewed by clicking on the 'View Requirements' pushbutton. All the required column-by-column dataset of EMME/2 output is then displayed in the 'EMME Output File Requirements' panel as in Figure 3-30. It is worth pointing out that such requirement is meant for classification 1. Additional three columns for the medium-duty vehicle are needed when classification 2 is opted. CALMOB6 reads and verifies the whole EMME output file before displaying the EMME/2 path and file names.



EMME Output File Requirements

This program requires EMME output files containing 20 data items per line :

1. Original Node 2. Destination Node 3. Link Type 4. Length(km) 5. VDF

6. Max. Speed (km/hr) 7. Gradient

8. No. of Passenger Cars (LDV's) 9. LDV Speed (km/hr) 10. % Cold Start LDV's

11. No. of Light Duty Trucks (LDT's) 12. LDT Speed (km/hr) 13. % Cold Start LDT's

14. No. of Heavy Duty Vehicles (HDV's) 15. HDV Speed (km/hr) 16. % Cold Start HDV's

17. No. of Buses 18. Bus Speed (km/hr) 19. Bus Dwell Time (mins) 20. % Cold Start BUSES

Figure 3-30: EMME/2 column-by-column dataset required.

Traffic planners are left with the option to specify the percentage of cold start vehicles either on the EMME/2 output file or within the 'EMME Output File' panel of Figure 3-29. If no cold start is indicated in the EMME/2 files, CALMOB6 assigns the displayed percentages of each vehicle category on links and zones. To recall, CALMOB6 calculates E&FC for cold started passenger cars and light-duty trucks only. This is so, because MOBILE6 model does not provide information on cold-started heavy-duty vehicles. However, suitable provisions have been made (as shown in Figures 3-29 and 3-30) to include cold-start emissions data if such information becomes readily available.

The next section of the main panel is the 'Fleet Modification'. Similar to EMME/2 output file, there is a fleet file, which contains all information on the fleet. Fleet files are different for the two vehicle classification schemes. CALMOB6 verifies the appropriateness of the fleet files before displaying the pathname and the filename of such files. Subsequently, the file can be viewed, edited and/or saved.

- *Viewing the file*:

  The content of the chosen file can be viewed by pressing 'View File' pushbutton. One example is shown in Figure 3-31. The fleet file access, the vehicle composition by type, alternative fuel and high-emitters are easily presented. Clicking on 'View' for the legends and vehicle classification description (in Figure 3-31) will open the 'Legends and Vehicle Classifications' window as in Figure 3-32.

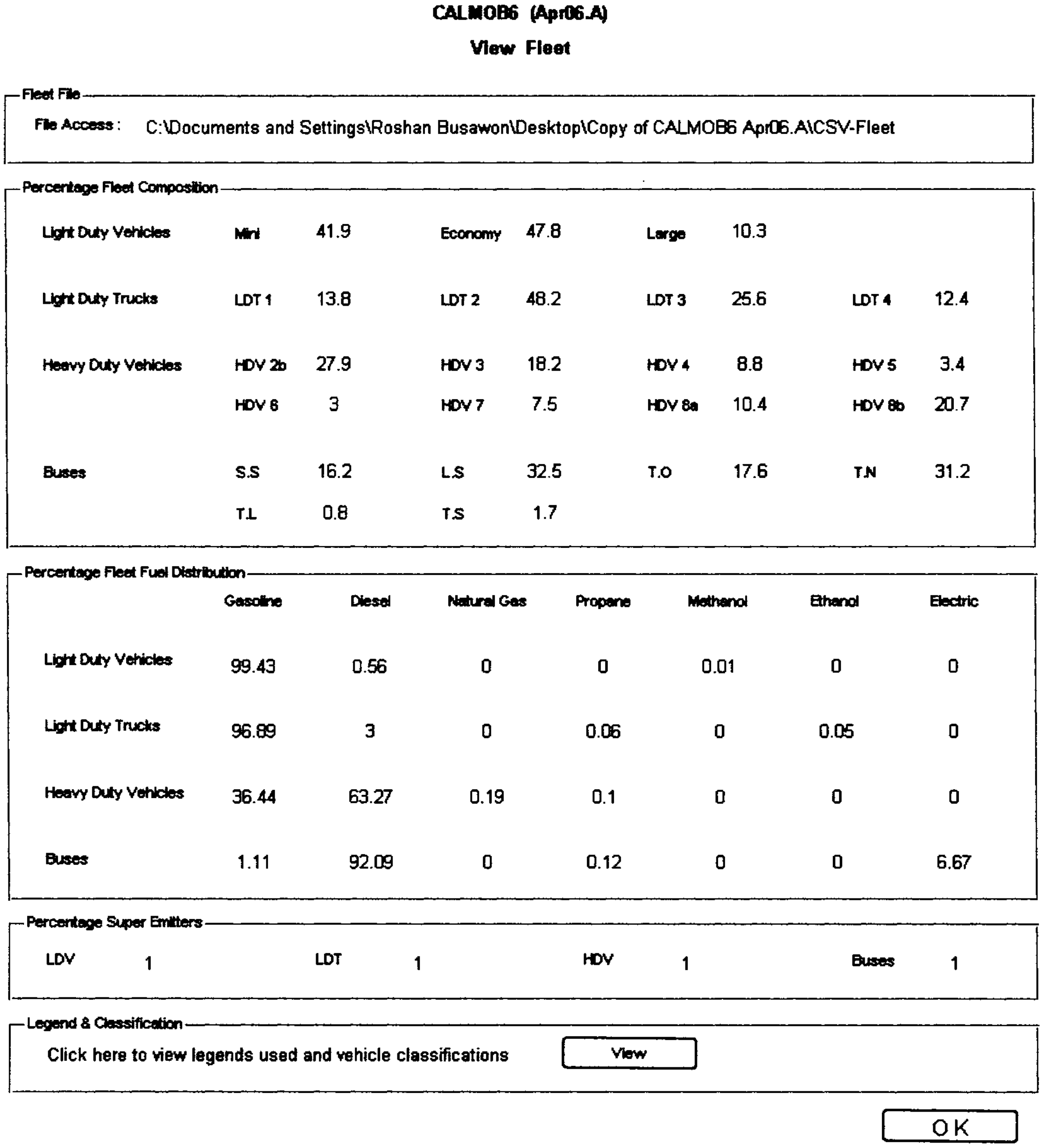
- *Editing the fleet file*:

  If the user wants to modify the chosen fleet file, pushbutton 'Edit File' in Figure 3-29 is applied. The 'Fleet Edit' window will pop out. This is illustrated in Figure 3-33. Next to the vehicle categories, are a series of 'Edit' pushbuttons and 'Ignore' checkboxes. Checking to ignore a vehicle category will reduce all the compositions of that vehicle category to zero - CALMOB6 does not consider the vehicle category in its calculation. The 'Edit' pushbutton displays a separate window. One example is shown in Figure 3-34 for the light-duty vehicle case. Finally, modification of the vehicle classification by type, alternative fuel and high-emitter can be performed separately for that vehicle category. Figures 3-35, 3-36 and 3-37 illustrate the respective panels.

- *Saving an Edited fleet file*:

  Fleet files can be saved in any filenames except 'Default-2005-1' and 'Default-2005-2'. These files contain specific information about the fleet.

‘Default-2005-1’ contains information designed for the vehicle ‘Classification 1’. Such information has been retrieved using the data from the Alberta registries and the Edmonton Transit. They are displayed in Tables 3-6 and 3-7.



CALMOB6 (Apr06.A)
View Fleet

Fleet File

File Access : C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6 Apr06.A\CSV-Fleet

Percentage Fleet Composition

Light Duty Vehicles	Mini	41.9	Economy	47.8	Large	10.3		
Light Duty Trucks	LDT 1	13.8	LDT 2	48.2	LDT 3	25.6	LDT 4	12.4
Heavy Duty Vehicles	HDV 2b	27.9	HDV 3	18.2	HDV 4	8.8	HDV 5	3.4
	HDV 6	3	HDV 7	7.5	HDV 8a	10.4	HDV 8b	20.7
Buses	S.S	16.2	L.S	32.5	T.O	17.6	T.N	31.2
	T.L	0.8	T.S	1.7				

Percentage Fleet Fuel Distribution

	Gasoline	Diesel	Natural Gas	Propane	Methanol	Ethanol	Electric
Light Duty Vehicles	99.43	0.56	0	0	0.01	0	0
Light Duty Trucks	96.89	3	0	0.06	0	0.05	0
Heavy Duty Vehicles	36.44	63.27	0.19	0.1	0	0	0
Buses	1.11	92.09	0	0.12	0	0	6.67

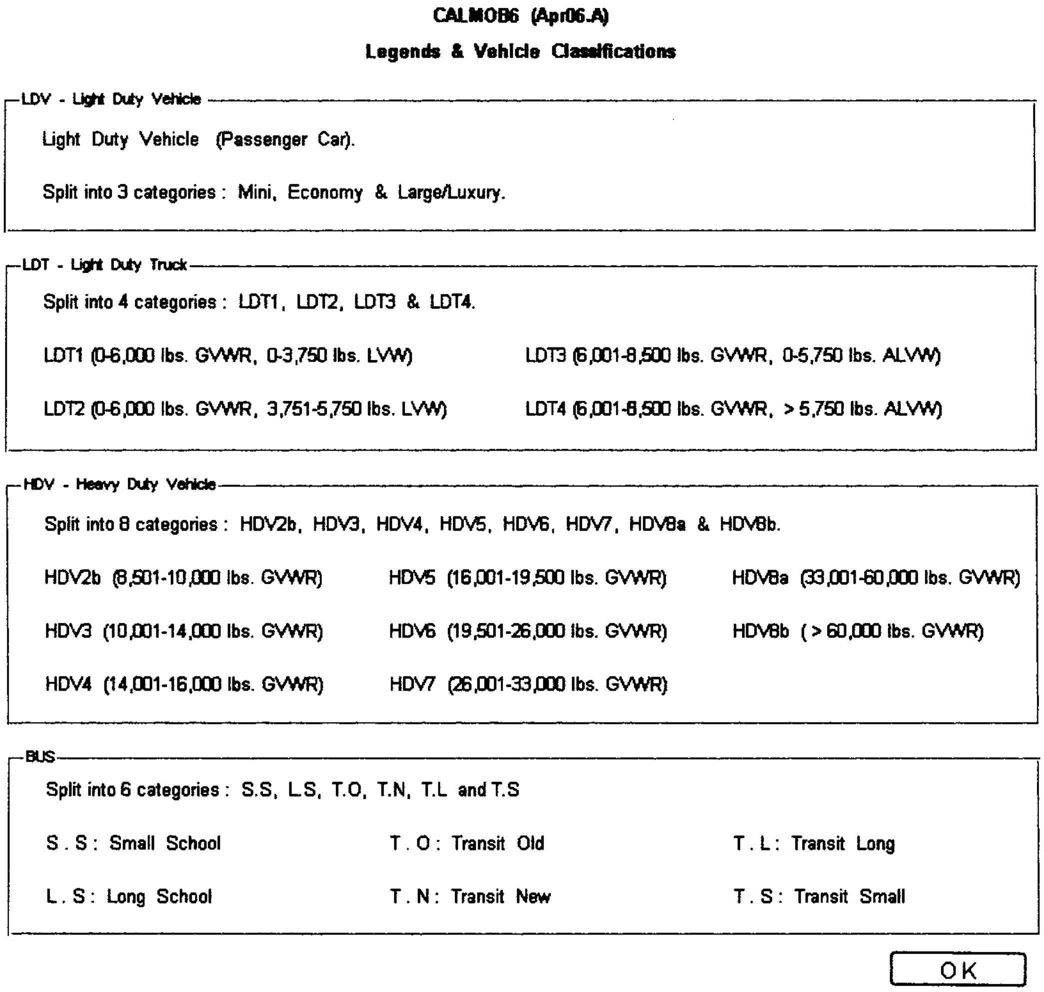
Percentage Super Emitters

LDV	1	LDT	1	HDV	1	Buses	1

Legend & Classification

Click here to view legends used and vehicle classifications

Figure 3-31: Content of the chosen fleet file.



CALMOB6 (Apr06.A)

Legends & Vehicle Classifications

LDV - Light Duty Vehicle

Light Duty Vehicle (Passenger Car).

Split into 3 categories : Mini, Economy & Large/Luxury.

LDT - Light Duty Truck

Split into 4 categories : LDT1, LDT2, LDT3 & LDT4.

LDT1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW)

LDT3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW)

LDT2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)

LDT4 (6,001-8,500 lbs. GVWR, > 5,750 lbs. ALVW)

HDV - Heavy Duty Vehicle

Split into 8 categories : HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7, HDV8a & HDV8b.

HDV2b (8,501-10,000 lbs. GVWR)

HDV3 (10,001-14,000 lbs. GVWR)

HDV4 (14,001-16,000 lbs. GVWR)

HDV5 (16,001-19,500 lbs. GVWR)

HDV6 (19,501-26,000 lbs. GVWR)

HDV7 (26,001-33,000 lbs. GVWR)

HDV8a (33,001-60,000 lbs. GVWR)

HDV8b (> 60,000 lbs. GVWR)

BUS

Split into 6 categories : S.S, L.S, T.O, T.N, T.L and T.S

S . S : Small School

L . S : Long School

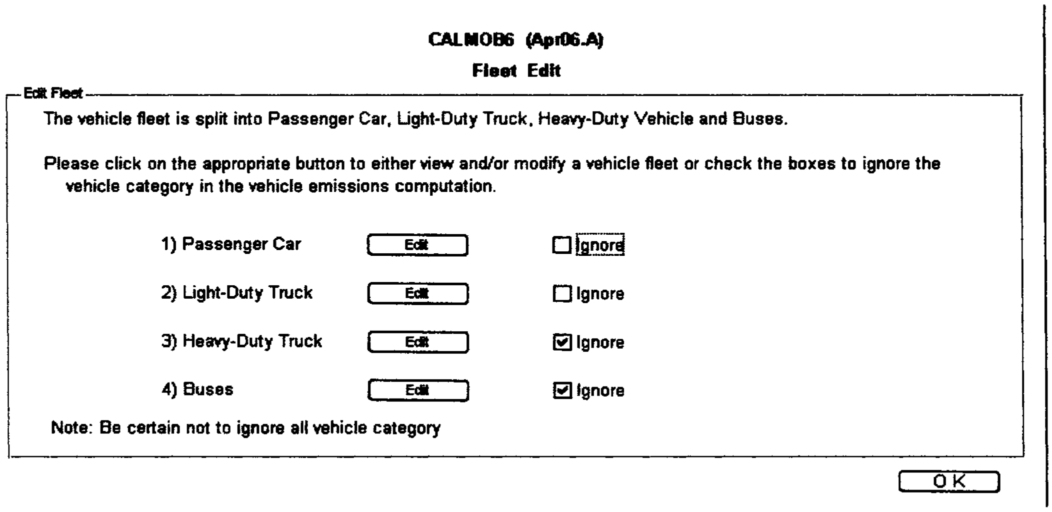
T . O : Transit Old

T . N : Transit New

T . L : Transit Long

T . S : Transit Small

Figure 3-32: Legends and vehicle classification for the ‘Classification 1’ mode.



CALMOB6 (Apr06.A)

Fleet Edit

Edit Fleet

The vehicle fleet is split into Passenger Car, Light-Duty Truck, Heavy-Duty Vehicle and Buses.

Please click on the appropriate button to either view and/or modify a vehicle fleet or check the boxes to ignore the vehicle category in the vehicle emissions computation.

1) Passenger Car ☐ Ignore

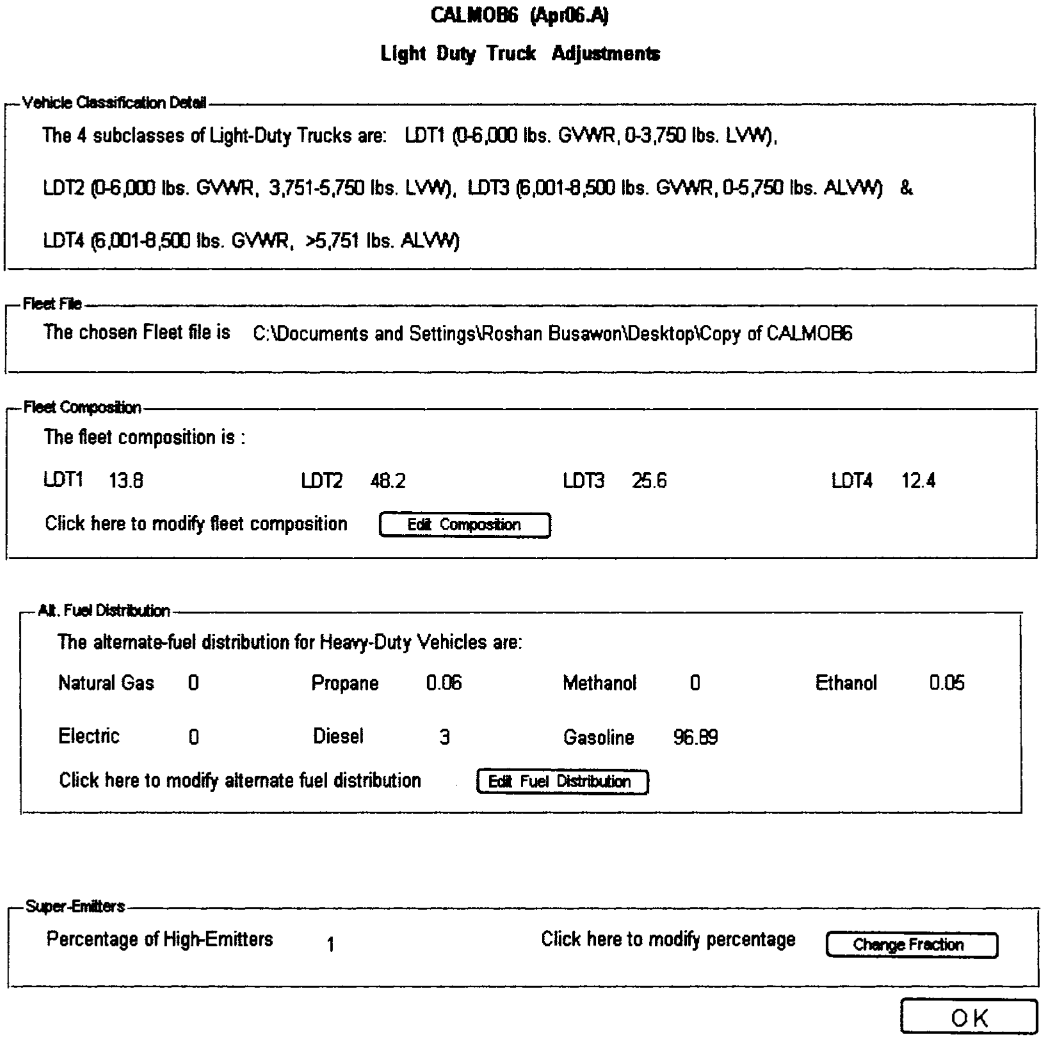
2) Light-Duty Truck ☐ Ignore

3) Heavy-Duty Truck ☑ Ignore

4) Buses ☑ Ignore

Note: Be certain not to ignore all vehicle category

Figure 3-33: Main window for editing the fleet.



CALMOB6 (Apr06.A)

Light Duty Truck Adjustments

The 4 subclasses of Light-Duty Trucks are: LDT1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW), LDT2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW), LDT3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW) & LDT4 (6,001-8,500 lbs. GVWR, >5,751 lbs. ALVW)

The chosen Fleet file is C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6

The fleet composition is :

LDT1	13.8	LDT2	48.2	LDT3	25.6	LDT4	12.4

Click here to modify fleet composition

The alternate-fuel distribution for Heavy-Duty Vehicles are:

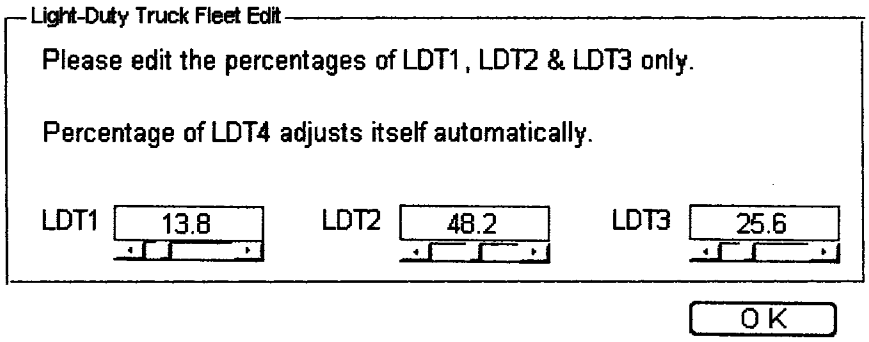
Natural Gas	0	Propane	0.06	Methanol	0	Ethanol	0.05
Electric	0	Diesel	3	Gasoline	96.89		

Click here to modify alternate fuel distribution

Percentage of High-Emitters 1

Click here to modify percentage

Figure 3-34: Sub-window for editing the fleet of the light-duty truck category.



Please edit the percentages of LDT1, LDT2 & LDT3 only.

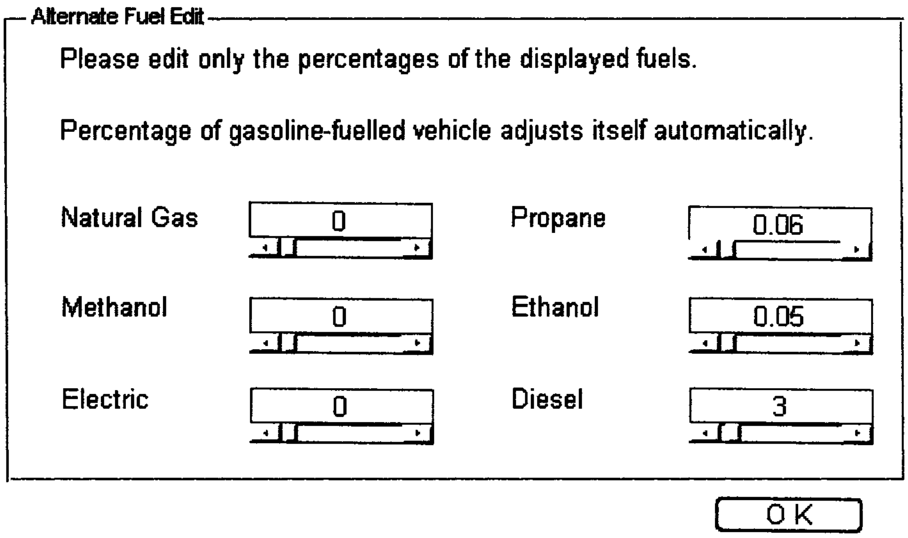
Percentage of LDT4 adjusts itself automatically.

LDT1 13.8

LDT2 48.2

LDT3 25.6

Figure 3-35: Sub-window for editing the fleet composition of light-duty truck category by the different subclasses.



Please edit only the percentages of the displayed fuels.

Percentage of gasoline-fuelled vehicle adjusts itself automatically.

Natural Gas 0

Propane 0.06

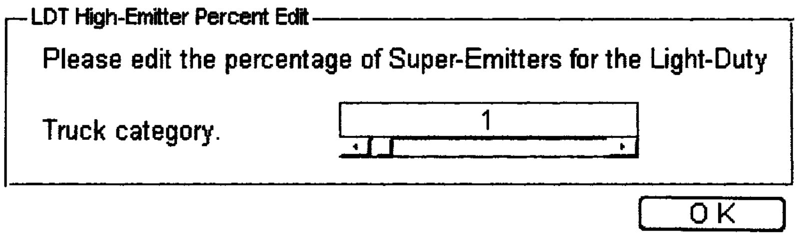
Methanol 0

Ethanol 0.05

Electric 0

Diesel 3

Figure 3-36: Sub-window for editing the alternative fuelled light-duty trucks.

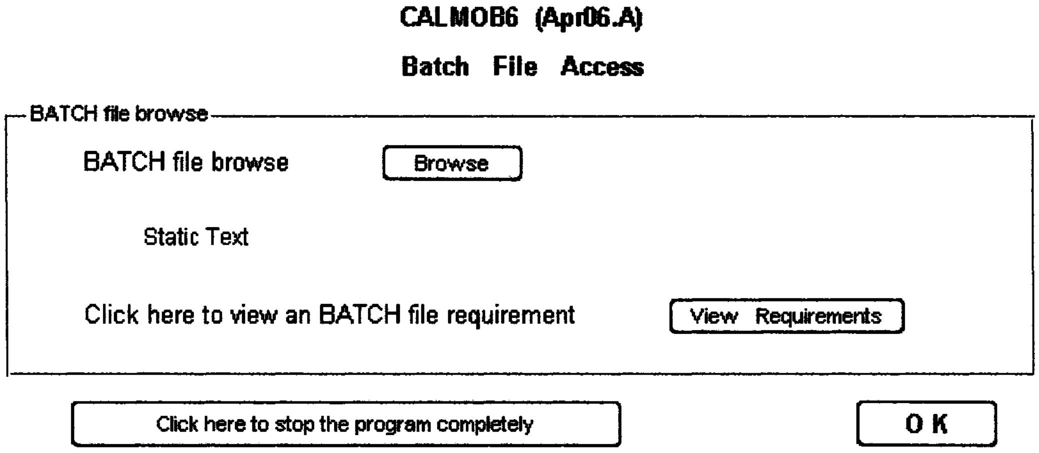


Please edit the percentage of Super-Emitters for the Light-Duty Truck category. 1

Figure 3-37: Sub-window for editing the percentage of high-emitters in the light-duty truck category.

3.12.4 RUNNING A BATCH FILE

To run a batch file, the user will have to opt for it in Figure 3-26 using the 'Run a series of batch files?' pushbutton. The aim of the batch file is to represent all the information on the Main Panel (used for single-set inputs and shown in Figure 3-29) in a .CSV file. Each line of the .CSV file represents one run. Each run can contain different sets on inputs - such as different years, different EMME output file, different fleet file, etc. However, no modification of the fleet file is possible with the batch file processing.



CALMOB6 (Apr06.A)

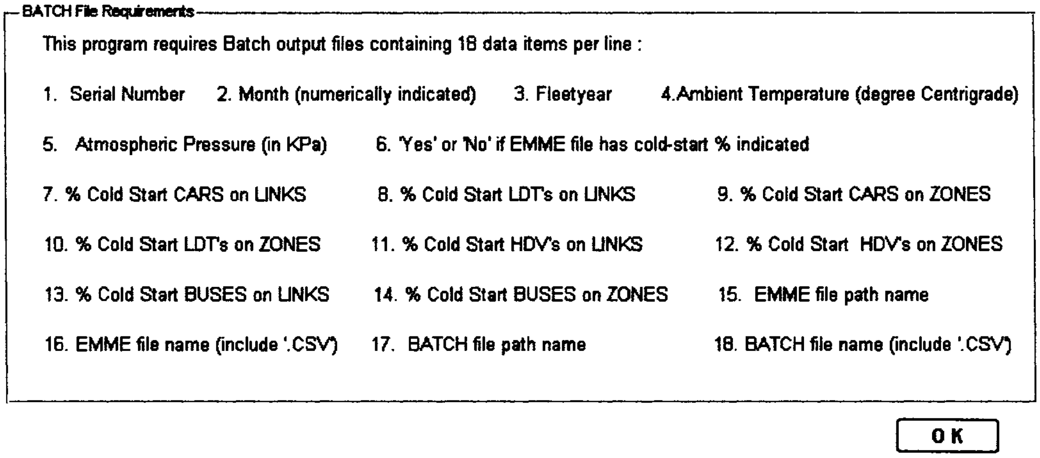
Batch File Access

Click here to view an BATCH file requirement

Figure 3-38: Window for choosing an appropriate batch file.

Choosing the appropriate batch file can be done through 'Batch File Access' window, displayed in Figure 3-38. CALMOB6 reads and verifies all information in the batch-file to check relevancy and accessibility. Subsequently, it displays the pathname and filename of the batch file in the 'Static Text' window.

'View Requirements' pushbutton makes the user aware of the column-by-column data needed by CALMOB6 for processing a batch file. Such batch file requirement is given in Figure 3-39.



This program requires Batch output files containing 18 data items per line :

1. Serial Number 2. Month (numerically indicated) 3. Fleetyear 4.Ambient Temperature (degree Centrigrade)
5. Atmospheric Pressure (in KPa) 6. 'Yes' or 'No' if EMME file has cold-start % indicated
7. % Cold Start CARS on LINKS 8. % Cold Start LDT's on LINKS 9. % Cold Start CARS on ZONES
10. % Cold Start LDT's on ZONES 11. % Cold Start HDV's on LINKS 12. % Cold Start HDV's on ZONES
13. % Cold Start BUSES on LINKS 14. % Cold Start BUSES on ZONES 15. EMME file path name
16. EMME file name (include '.CSV') 17. BATCH file path name 18. BATCH file name (include '.CSV')

Figure 3-39: Description of the column-by-column information required in a batch file (Vehicle Classification 1).

3.12.5 VEHICLE CLASSIFICATION 2

Up to now, all figures (namely Figures 3-25 – 3-34) apply to vehicle 'Classification 1'. For vehicle 'Classification 2', traffic planners have the ability to split vehicles into light-duty vehicle (passenger car), light-duty trucks, medium-duty vehicles, heavy-duty trucks and buses. With this re-classification to better represent the needs of the planners, an additional vehicle category (medium-duty vehicle) is included. Re-shuffling of the vehicle subclasses has obliged to create other but similar, sets of GUI's, EMME/2 input files, fleet files and batch files requirements. These are demonstrated in Appendix L.

3.13 CONCLUSION

This chapter describes the technical background of CALMOB6, an emissions and fuel consumption inventory tool. The latter uses traffic modeling outputs and vehicle dynamic modeling to calculate inventories of pollutant emissions and fuel consumption associated with the modelled traffic. Further, the chapter demonstrates the methodology adapted for the development and implementation of CALMOB6. It investigates on the types of information that have been retrieved from other emissions/transportation models for use in CALMOB6. MOBILE6 vehicle emissions model is used to generate emission factors. EMME/2 macro-analytical transportation model is used to generate individual vehicle operation data. Moreover, the optimum use of reliable data obtained from government agencies and private organizations is presented. One example is the NR Canada fuel-consumption trend data. Likewise, other factors available from published technical literatures are built in the model to make it state-of-the-art software. Finally, a basic demonstration of the capability and requirements of software CALMOB6 is illustrated with graphical user interfaces (GUI's).

It is good to emphasize that the model is calibrated for standard conditions with the US EPA MOBILE6 vehicle emissions model. However, it responds to the actual vehicle driving conditions (e.g. stop-start, accelerations, speeds and ambient conditions) as well as road characteristics (e.g. slopes, intersections and congestion). CALMOB6 can be used to generate past, current and future inventories and also show effects of regulatory change, fleet renewal, traffic growth and infrastructure development on emissions.

The model has been developed to predict the effect on transportation pollution and fuel consumption when altering traffic controls and/or infrastructure. The intent is to give traffic planners an additional tool to justify their initiatives in the area of traffic control, infrastructure development, mode choice programs and regulatory actions.

REFERENCES

1. National Academy of Sciences, "Modeling Mobile-Source Emissions", National Academy Press, 2000.
2. Checkel, M.D., "Vehicle Emissions Project – The City of Edmonton Transportation Master Plan", Mar 1996.
3. Checkel, M.D., "Truck and Bus Engine Emissions – The City of Edmonton Transportation Master Plan", Nov 1996.
4. Ramamurthy, R.; Clark, N.N.; Atkinson, C.A.; and Lyons, D.W., "Models for Predicting Transient Heavy Duty Vehicle Emissions", SAE 982652, Oct 1998.
5. Schingh, M.; Brunet, É.; Gosseling, P., "Canadian New Light Duty Vehicles: Trends in Fuel Consumption and Characteristics (1988-1998)", Transportation Energy Use Division, Office of Energy Efficiency, Natural Resources Canada, July 2000.
6. *Fuel Consumption Database forwarded by Edelweiss d'Andrea from Natural Resources Canada.
7. US EPA, "Updating Fuel Economy Estimates in MOBILE6.3 – DRAFT", EPA420-P-02-005, M6.GHG.001, Aug 2002.
8. US EPA, "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2005", EPA420-R-05-001, Jul 2005.
9. US EPA, "Update Heavy-Duty Engine Emission conversion factors for MOBILE6 – Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities", EPA420-R-02-006, M6.HDE.002, Jan 2002.
10. US Dept. of Commerce, "1992 Census of Transportation – Truck Inventory and Use survey", TC92-T-52, May 1995.
11. US EPA, "Determination of Running Emissions as a Function of Mileage for 1981-1993 Model Year Light-Duty Cars and Trucks", EPA420-R-02-002, M6.EXH.001, Jan 2002.
12. US EPA, "Determination of Start Emissions as a Function of Mileage and Soak Time for 1981-1993 Model Year Light-Duty Vehicles", EPA420-R-01-058, M6.STE.003, Nov 2001.
13. US EPA, "Basic Exhaust Emission Rates of Open Loop Vehicles for MOBILE6: Exhaust Emissions at High and Low Altitudes for Engine Starts and Running Emissions for Motorcycles, Light-Duty Diesel Vehicles and trucks and Pre-1981 Model Year Light-Duty Gasoline Vehicles and Trucks", EPA420-R-01-027, M6.EXH.005, Apr 2001.

14. US EPA, "Determination of CO Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs", EPA420-R-03-011, M6.EXH.012, Sept 2003.

15. US EPA, "Determination of NOx and HC Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs", EPA420-R-01-056, M6.EXH.007, Nov 2001.

16. US EPA, "MOBILE6 Estimates of Exhaust Emissions for 1994-and-later Light Duty Diesel Cars and Trucks", EPA420-R-01-041, M6.EXH.011, Jul 2001.

17. US EPA, "Federal and California Exhaust and Evaporative Emission Standards for the Light-Duty Vehicles and Light-Duty Trucks", EPA420-B-00-001, Feb 2000.

18. *List of Identified Buses being serviced in each of the years 1989, 1994, 1996, 2000 and 2005. Forwarded by James Bryant of Edmonton Transit.

19. *2006-2015 Bus Purchases Plan forwarded by James Bryant from Edmonton Transit.

20. US EPA, "Fleet Characterization Data for MOBILE6: Development and Use of Age Distributions, Average Annual Mileage Accumulation Rates and Projected Vehicle Counts for Use in MOBILE6", EPA420-P-99-011, M6.FLT.007, Apr 1999.

21. US EPA, "Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6", EPA420-R-99-010, M6.HDE.001, Apr 1999.

22. US EPA, "Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6 – Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors", EPA420-R-02-005, M6.HDE.004, Jan 2002.

23. US EPA, "Accounting for the Tier 2 and Heavy-Duty Requirements in MOBILE6", EPA420-R-01-057, M6.EXH.004, Nov 2001.

24. Dhaliwal, B.; Yi, N.; Checkel, M.D., "Emissions Effects of Alternative Fuels in Light-Duty and Heavy-Duty Vehicles", SAE 2000-01-0692, Mar 2000.

25. Chandler, K.,; Whalen, M.; Westhoven, J., "Final Results from The State of Ohio Ethanol-Fueled Light-Duty Fleet Deployment Project", SAE 982531, Oct 1998.

26. Kelly, K.J.; Bailey, B.K.; Coburn, T.C.; Eudy, L.; Lissiuk, P., "Round 1 Emissions Results from Compressed Natural Gas Vans and Gasoline Controls operating in the U.S Federal Fleet", SAE 961096, May 1996.

27. Kelly, K.J.; Bailey, B.K.; Coburn, T.C.; Clark, W.; Eudy, L.; Lissiuk, P., "FTP Emissions Test results from Flexible-Fuel Methanol Dodge Spirits and Ford Econoline Vans", SAE 961090, May 1996.

28. Kelly, K.J.; Bailey, B.K.; Coburn, T.C.; Clark, W.; Lissiuk, P., "Federal test procedure emissions test results from ethanol variable-fuel vehicle Chevrolet Luminas" SAE 961092, May 1996.

29. Clark, N.N.; Lyons, D.W.; Rapp, B.L.; Gautam, M.; Wang, W.; Norton, P.; White, C.; Chandler, K., "Emissions from Trucks and Buses Powered by Cummins L-10 Natural-Gas Engines", SAE 981391, May 1998.

30. Wenzel, T.; Ross, M., "Characterization of Recent-Model High-Emitting Automobiles", SAE 981414, May 1998.

31. Austin, S.; Ross, M., "History of Emissions Reduction: Normal Emitters in FTP-type Driving" SAE 2001-01-0229, Mar 2001.

32. Hawirko, J.D.; Checkel, M.D., "Quantifying vehicle Emission Factors for Various Ambient Conditions using an On-Road, Real-Time Emissions System", SAE 2003-01-0301, Mar 2003.

33. US EPA, "MOBILE6 Emission Factors for Natural Gas Vehicles", EPA420-R-01-033, M6.FUL.004, Apr 2001.

34. Wikipedia Encyclopedia, http://en.wikipedia.org/wiki/Edmonton,_Canada (site accessed on June 18, 2006)

35. *Particulate matter estimates distributed with the MOBILE6.2 model. Forwarded by David Brzezinski of US EPA.

36. US EPA, "MOBILE6.1 Particulate Emission Factor Model Technical Description – Final Report", EPA420-R-03-001, M6.PM.001, Jan 2003.

37. Vehicle Certification Agency – Job No.: P99-00/2842, "Communication Concerning Approval Granted of A Engine Type With Regard To Emissions or Measurement of Power of The Engine only, Pursuant to Regulation No. 24R-03", Jun 2000.

38. Jarett, R.P.; and Clark, N.N., "Evaluation of Methods for Determining Continuous Particulate Matter from Transient Testing of Heavy Duty Diesel Engines", SAE 2001-01-3575, Sept 2001.

39. Clark, N.N.; Jarett, R.P.; and Atkinson, C.M., "Field Measurements of Particulate Matter Emissions, Carbon Monoxide, and Exhaust Opacity from Heavy Duty Diesel Vehicles", Journal of the Air & Waste Management Association, PA 15222,V49, p76, Sept 1999.

40. Xu, S.; Clark, N.N.; Gautam, M.; and Wayne, W.S., "Comparison of Heavy-Duty Truck Diesel Particulate Matter Measurement: TEOM and Traditional Filter", SAE 2005-01-2153

41. US EPA, "User's Guide to MOBILE6.1 and MOBILE6.2 – Mobile Source Emission Factor Model", EPA420-R-03-010, Aug 2003.

42. Busawon, R.; Checkel, M.D., “Predicting On-Road Vehicle Emissions Inventories”, Association Québécoise du Transport et des Routes (AQTR), Québec, April 2006.

43. Sun, X.; Wiedmann, T.; Hussain, S., “Fuel Management and exhaust emissions of light- and heavy-duty trucks operating on CNG and LPG”, SAE 971661, May 1997.

44. Turner, J.E; Topaloglu, T.; Hrynyk, G.S., “Development and demonstration of class 8 propane-powered truck”, SAE 901499, Aug 1990.

45. New York State Energy Research and Development Authority (NYSERDA), http://www.nyserda.org/programs/pdfs/vol3sc3.pdf , (site accessed on June 23, 2006).

46. Norton, P., “The Ethanol Heavy-Duty Truck Fleet demonstration Project”, NREL (National Renewable Energy Laboratory), NREL/SR-540-2210, DE97050805, May 1997.

47. City of Edmonton, http://www.edmonton.ca/portal/server.pt/gateway/PTARGS_0_2_1516199_0_0_18/snow+and+ice , (Site accessed on June 24, 2006).

48. Checkel, M.D., “Engine Emissions of Alternative Fuelled Vehicles – The City of Edmonton Transportation Master Plan”, Oct 1997.

49. Philpott, S., “MOBILE5C User Guide”, Environment Canada, Hull, Québec, Canada, 60 pp., 1993.

50. Mondt, J.R., “Cleaner Cars – The history and technology of Emission Control Since the 1960’s”, SAE Order No. R-226.

51. *City of Edmonton vehicle registration data for the year 2005. Forwarded by Lorraine Doblanko of City of Edmonton, Transportation Planning.

CHAPTER 4

DEMONSTRATION OF THE FEATURES INCLUDED IN CALMOB6

Chapter 4 is a demonstration of some of the features that are integrated in CALMOB6. This section is a collection of tests made on the software to check the relevancy of the results. Such features have already been discussed in the previous chapter.

4.0 INTRODUCTION

The aim of this section is to check relevancy of the features that are built-in the program. Such features, discussed in Chapter 3, are for example road grade, traffic pattern, etc. How does the software respond to these features? The answer to this question can be obtained through the demonstration of a collection of tests, performed on CALMOB6. The objective, assumptions and results of each test are discussed and illustrated in the sections below.

4.1 TRAFFIC MOTION

The objective of the traffic motion pattern is to obtain instantaneous vehicle operation data. It provides a speed-time trace, which is representative of the vehicle motion. Such a trace is fundamental to the development of a transportation emissions and fuel-consumption (E&FC) inventory. As described in Chapter 3, there are four main classes of traffic motion altogether:

- *Class 1 - No delay*: All vehicles drive through at the maximum speed
- *Class 2 - Some stops*: Some vehicles cruise through and some make one stop and possibly idle
- *Class 3 - All stop once*: All vehicles make a complete stop but with an idle time of less than 30 seconds. The free speed is adjusted accordingly.
- *Class 4 - Congested*: The vehicles make more than one stop and the maximum speed is reduced.

This sub-section demonstrates a passenger car cruising at 60 km/hr over a link that is 0.23 km long. The permissible speed on the link is 60km/hr. This motion is represented in Figure 4-1. This plot is obtained from CALMOB6 after it has classified the link according to level of congestion and has generated the speed-time trace. The vehicle takes 13.8 seconds to travel though the link. Subsequently, the average speed is raised to 70 km/hr and is then decreased to lower speeds. In each case, the traffic motion is illustrated.

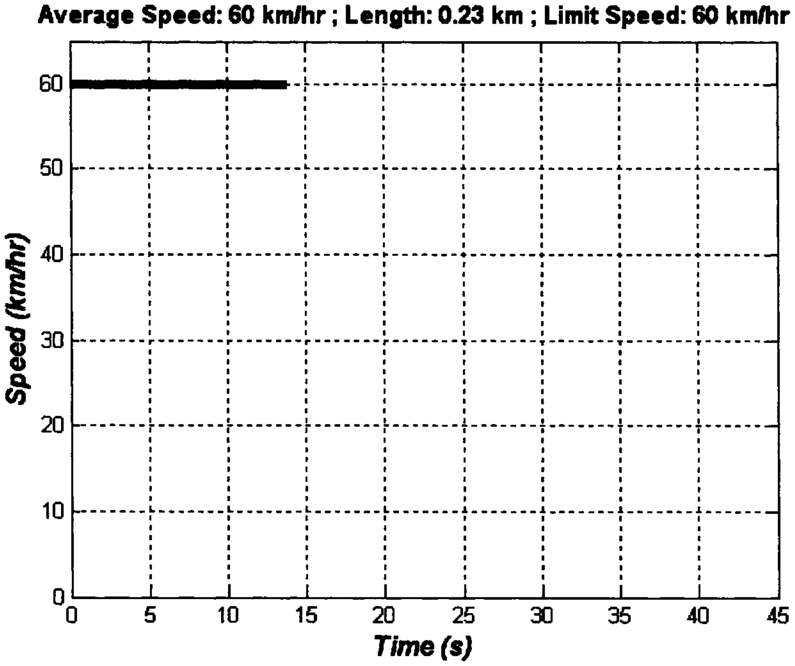


Figure 4-1: Passenger car cruising at 60 km/hr on a 0.23 km long link where limit speed is 60 km/hr. (Class 1)

Figure 4-2 shows the speed-time trace for the vehicle with a specified cruise speed of 70 km/hr instead of 60 km/hr, as above. It is noteworthy that CALMOB6 reads the limit and average speeds from the EMME/2 output file. For any average speed exceeding the limit speed, CALMOB6 sets the average speed to the limit speed. This feature has been set in CALMOB6 as per the requirements of City of Edmonton. As a result, the above motion will result to exactly the same speed trace as one where average speed is 60 km/hr.

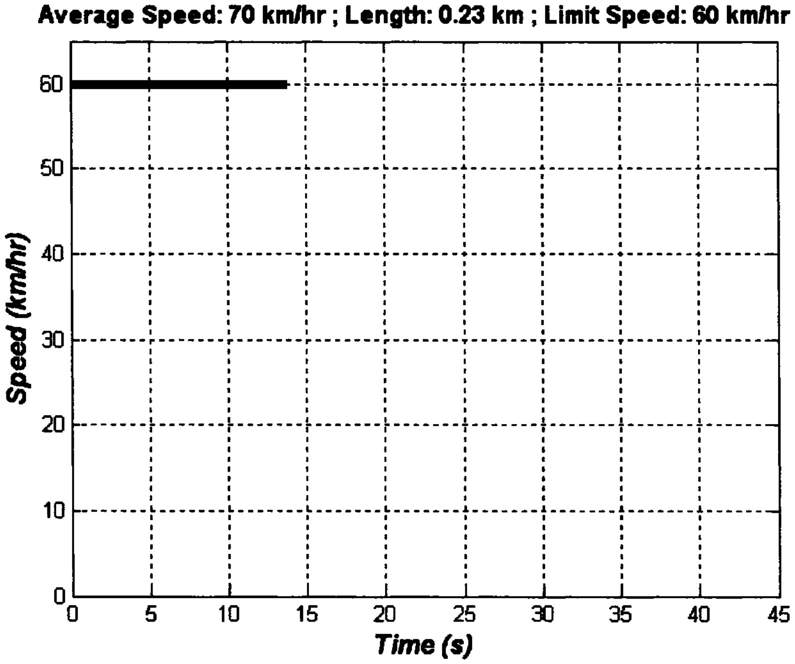


Figure 4-2: CALMOB6 vehicle motion for an EMME/2 average speed of 70 km/hr on the link where limit speed is 60 km/hr. (Class 1)

When the average is reduced to speeds lower than 60 km/hr, the vehicle motion is classified to different driving patterns. Afterwards, CALMOB6 fills out the second-by-second speed data of such cycle.

At 50 km/hr and 40 km/hr, as illustrated in Figures 4-3 and 4-4, the type 2 (or Class 2) vehicle motion is developed. The speed traces for both average speeds are identical. Some vehicles stop and the remaining cruise through. As a result, for the two cases (average speeds of 50 and 40 km/hr), the number of vehicles reaching a complete stop is greater for average speed of 40 km/hr. In this case, adjusting the number of vehicles cruising and stopping affects the average speed of the vehicles over such link.

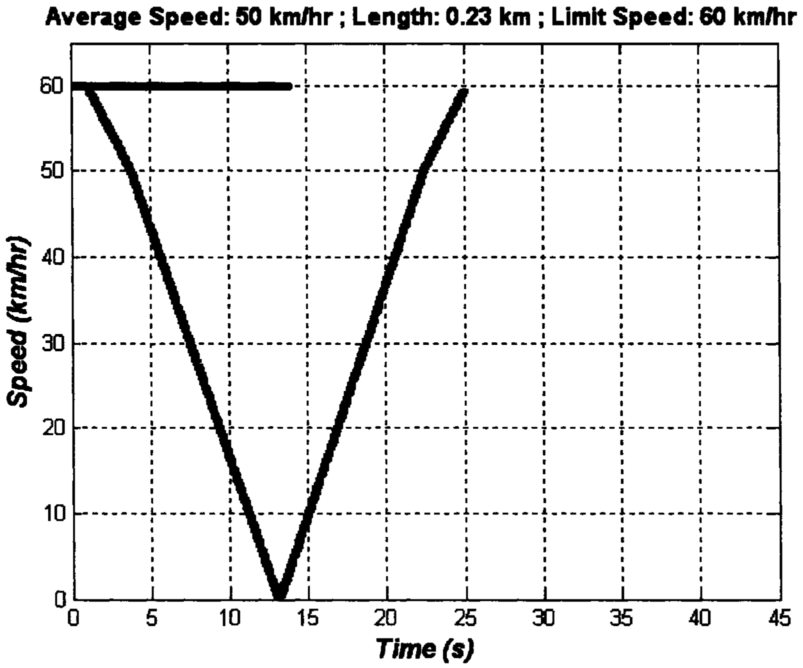


Figure 4-3: Average speed reduced to 50 km/hr. (Class 2) – 24.5% of vehicles stop.

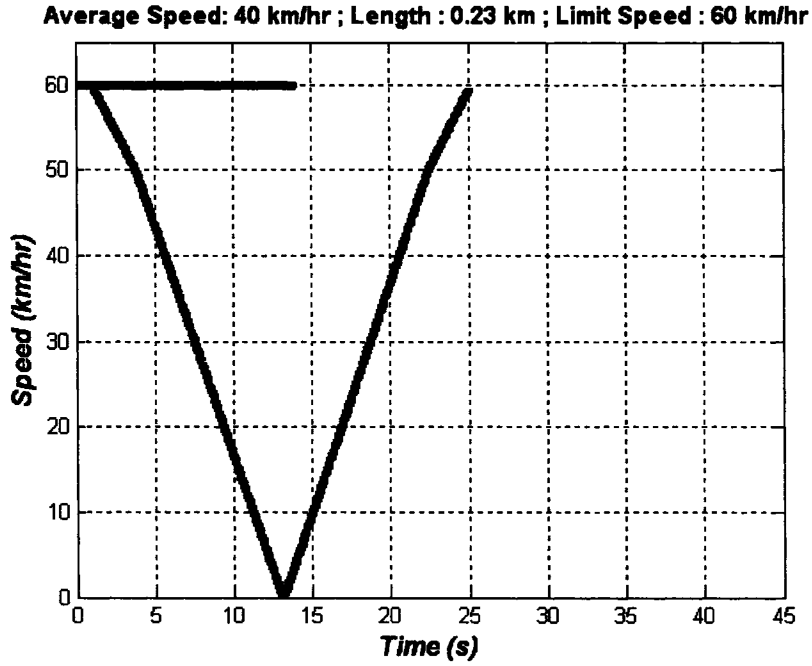


Figure 4-4: Average speed reduced to 40 km/hr. (Class 2) – 61.3% of vehicles stop.

By further reducing the speed to say 30 km/hr, the Class 3 vehicle motion is observed. In this case, CALMOB6 checks if it can accommodate a vehicle complete stop with an idle time of 30 seconds or less. Thus, idle times of 30 seconds or less are included in such cycles.

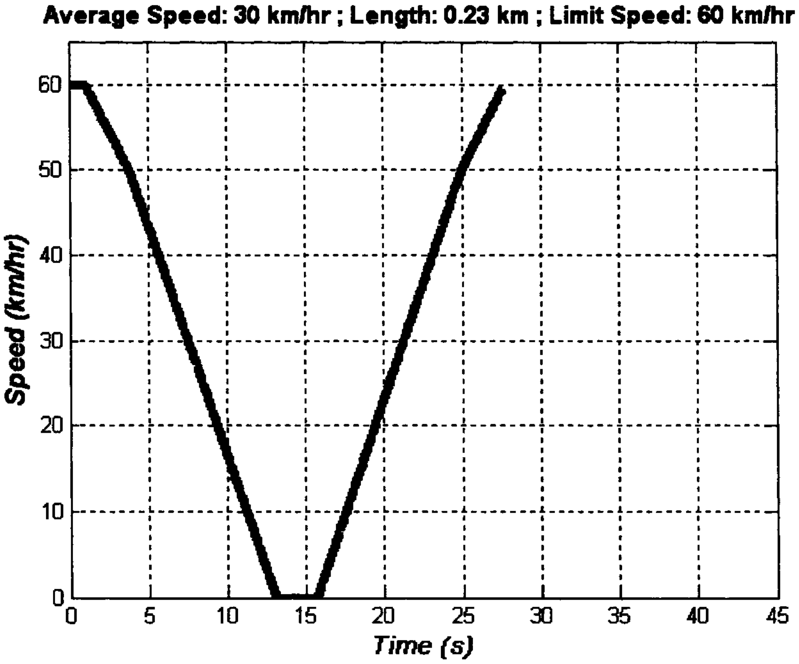


Figure 4-5: Average speed reduced to 30 km/hr. (Class 3) – All vehicles stop.

At an average speed of 20 km/hr, the travel time exceeds the sum of the times for a small cruise period at 60 km/hr, a stop and an idle period over 30 seconds. In this case, CALMOB6 classifies the link as Class 4. However, there is not enough distance over the link to include another stop. Hence, the program assigns such link to a Class 3 one with an idle period longer than thirty seconds.

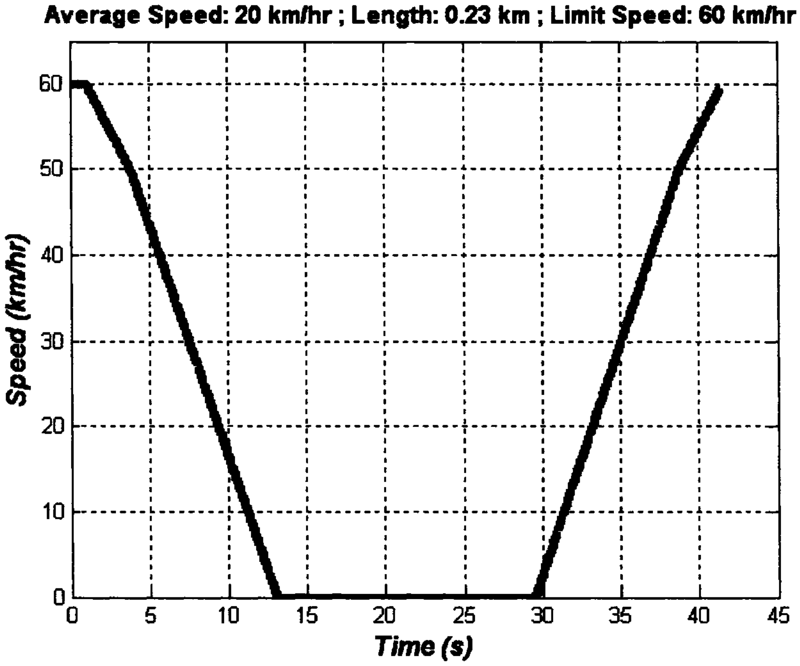


Figure 4-6: Average speed reduced to 20 km/hr. (Class 3) – All vehicles stop.

By further reducing the speed, the Class 4 cycle is expected. This is denoted as the congestion mode. The maximum speed of the vehicle is reduced to two-third of the limit speed (i.e. 2/3rd of 60 km/hr is 40 km/hr). Again, with the available travel time remaining distance, it is impossible to include another stop at the lower speed. Hence, such a link is classified as Class 3.

However, at an average of 5 km/hr, there is longer time of travel. In this case, CALMOB6 has the possibility to include more than one stop. As a result, CALMOB6 reduces the acceleration and deceleration rates by two-third (to 1 m/s^2). The maximum speed of the vehicle motion is also reduced. Hence, the link becomes more congested.

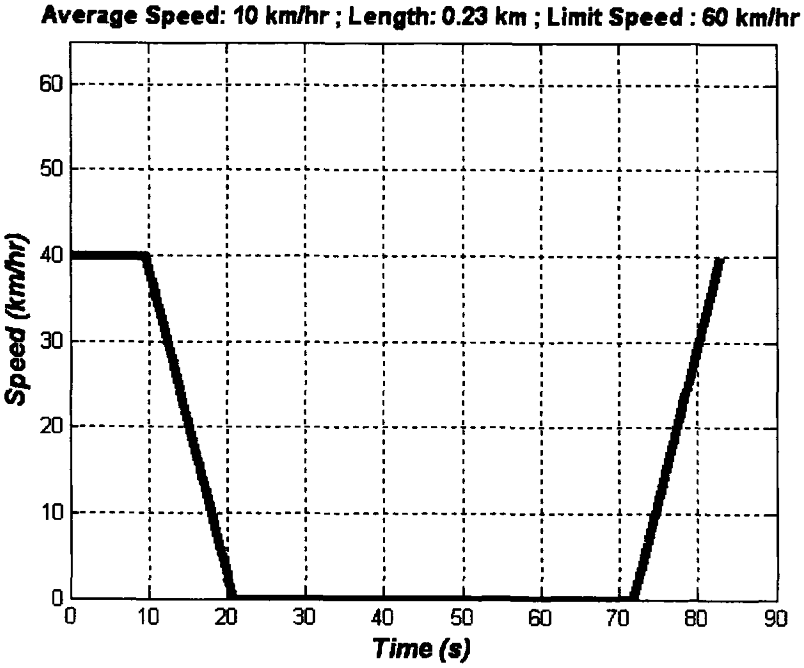


Figure 4-7: Average speed reduced to 10 km/hr. (Class 3) – All follow same path.

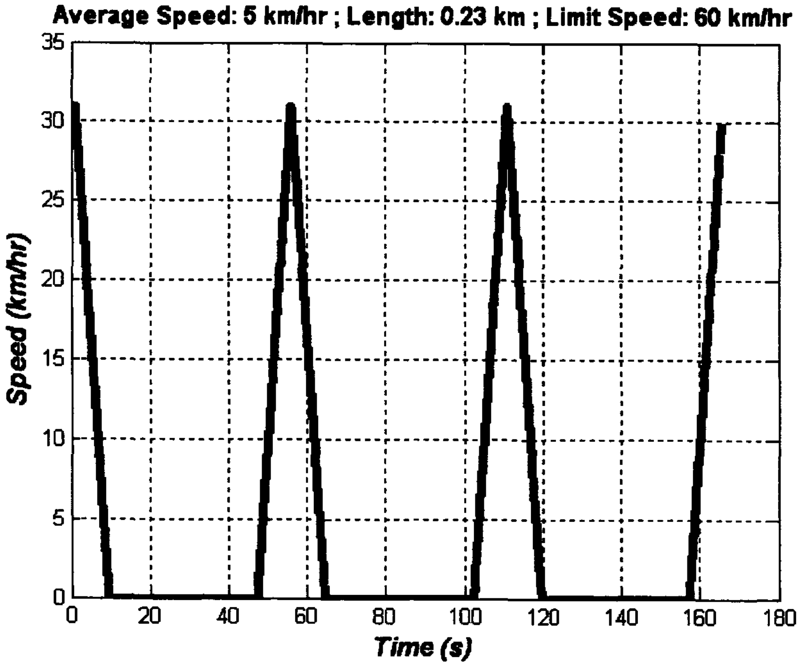


Figure 4-8: Average speed reduced to 5 km/hr. (Class 4) – All follow same path.

4.2 EMISSIONS AND FUEL CONSUMPTION AT DIFFERENT CONGESTION LEVEL

CALMOB6 calculates the emission and fuel consumption rates at each instant over the driving cycle. To perform this math, it uses the emissions and fuel consumption functions as given in Appendix D to calculate all E&FC on a second-by-second basis.

In this case, it is worth seeing how the E&FC amounts vary for different driving cycles stated in section 4.2. As a base case, a gasoline car is assumed to cruise over the link at an average speed of 60 km/hr. The permissible speed on such link is 60 km/hr. The amount of E&FC at this speed is set as reference.

To recall, as speed is increased from the base case, CALMOB6 assumes the vehicle traveling at the maximum speed as per the requirement of the City of Edmonton. For the above link, if EMME/2 stipulates an average speed of 70 km/hr, CALMOB6 sets the average speed to 60 km/hr. Hence, the same amounts of E&FC as for the base case is expected at every EMME/2 average speed exceeding the limit speed.

On the other hand, as average speed is lowered, different scenarios may occur. The level of congestion increases at lower speeds. In this context, there are more stops, more idling times and lower accelerations. As a result, the energy demand of the vehicles is expected to increase. Thus, the E&FC amounts are expected to increase further from the reference amount as the level of congestion increases.

Figure 4-9 illustrates the relative amounts of emissions and fuel consumption (in percentage) from the base case. Relative E&FC at the eight different speeds considered in section 4.1 are graphed on a non-linear scale. The above discussion about the relative E&FC are reflected on the figure below.

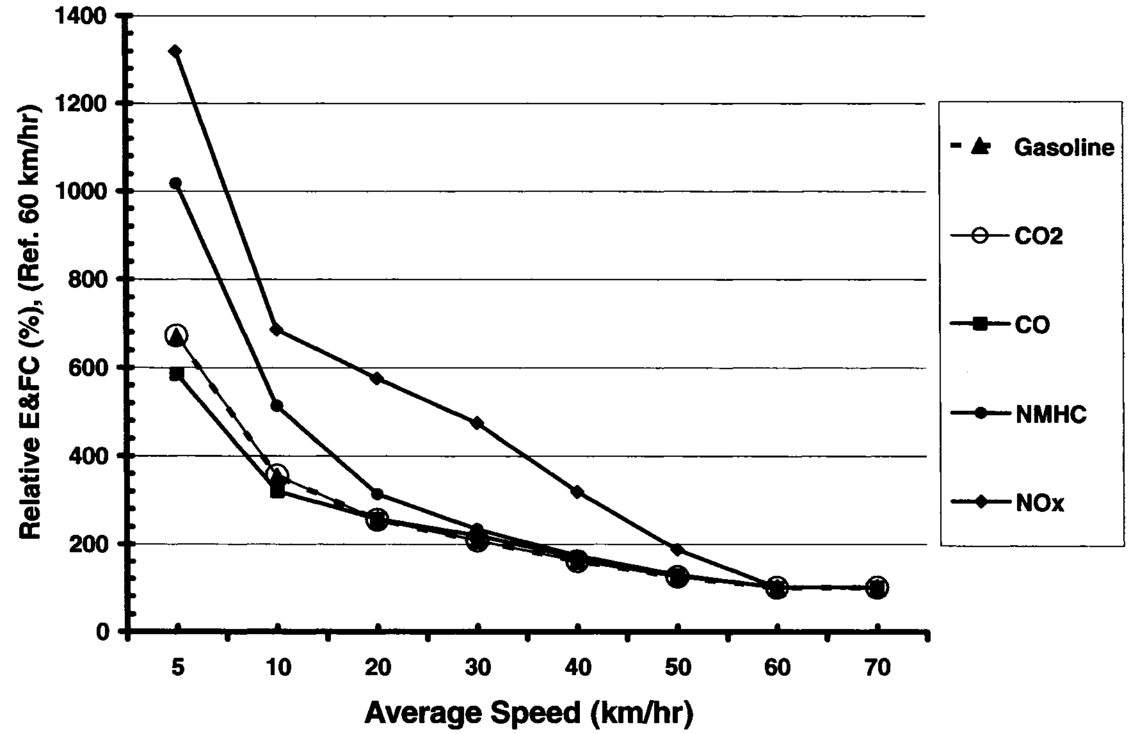


Figure 4-9: Relative emissions and fuel consumption from a gasoline vehicle. Reference for E&FC is set to those at speed of 60 km/hr.

4.3 ROAD SLOPE EFFECT

Road slope is the ratio of average vertical rise of a link to its average length, set as a percentage. Thus,

Slope of road = Rise / Length x 100% ... E.q 4-1

For the City of Edmonton, the road slopes lie in the range from -12% to +12%.

The slope has a substantial effect on the vehicle power requirement. As a result, it strongly affects emissions and fuel consumption. As slope increases, the power demand of the vehicle is expected to increase. Thus, more fuel is consumed and more pollutants are emitted. On the other hand, negative slopes decrease fuel consumption and emissions. These amounts will drop to the threshold emissions and fuel consumption at idle level. At such low slopes, the vehicle drives freely as the slope provides the driving power.

Figure 4-10 shows the effect of the range of positive and negative slopes on CALMOB6 output. The relative power demand at each slope is also plotted as a percentage of the vehicle power requirement on a flat road. Similarly, relative emissions and fuel consumption are also graphed.

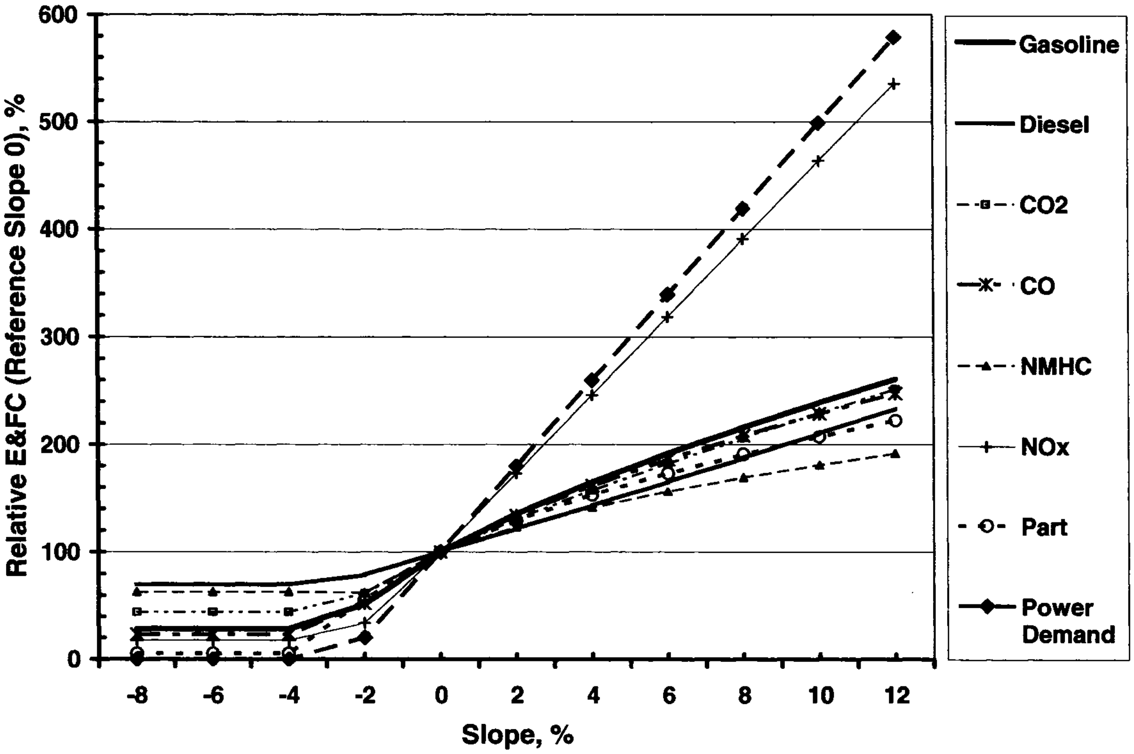


Figure 4-10: Sensitivity of CALMOB6 output values of emissions and fuel consumption to average slope of road.

4.4 ATMOSPHERIC PRESSURE EFFECT

In the calculation of the vehicle tractive energy required to move a vehicle (Appendix C), it is observed that the vehicle must oppose the aerodynamic force. The latter is directly related to the air density (ρ) as demonstrated by the equation below. Cd is the coefficient of drag, A is the frontal area (m^2) of the vehicle and V is the instantaneous vehicle speed (m/s).

$$\textbf{Aerodynamic resistance} = \tfrac{1}{2}.Cd.A.\rho.V^2 \quad \ldots\ldots \quad \textbf{E.q 4-2}$$

The air density is given by:

$$\text{Air Density, } \rho \; (kg/m^3) = \frac{\text{Atmospheric Pressure (Pa)} \times \text{Molar Mass of air (kg/kmol)}}{\text{Universal Gas Constant (J/kmol-K)} \times \text{Ambient Temperature (K)}}$$

Equation 4-3: Equation for air density (kg/m^3)

Equation 4-3 reveals that both atmospheric pressure (Patm) and ambient temperature influence the air density. By keeping the ambient temperature constant, the atmospheric pressure effect on E&FC can be verified by the graph below. Keeping all prevailing conditions constant, a gasoline-fuelled passenger car is made to follow the same speed trace at different assumed atmospheric pressures. Figure 4-11 is obtained by finding the E&FC when atmospheric pressure is 85 kPa. Subsequently, the atmospheric pressure is increased in steps of 5 kPa until pressure is 105 kPa. At each step, the E&FC values are noted and are referenced to by the relative change in E&FC; set as a percentage.

As observed in Figure 4-11, the higher the atmospheric pressures, the greater are the energy demand and the higher the pollutants levels generated.

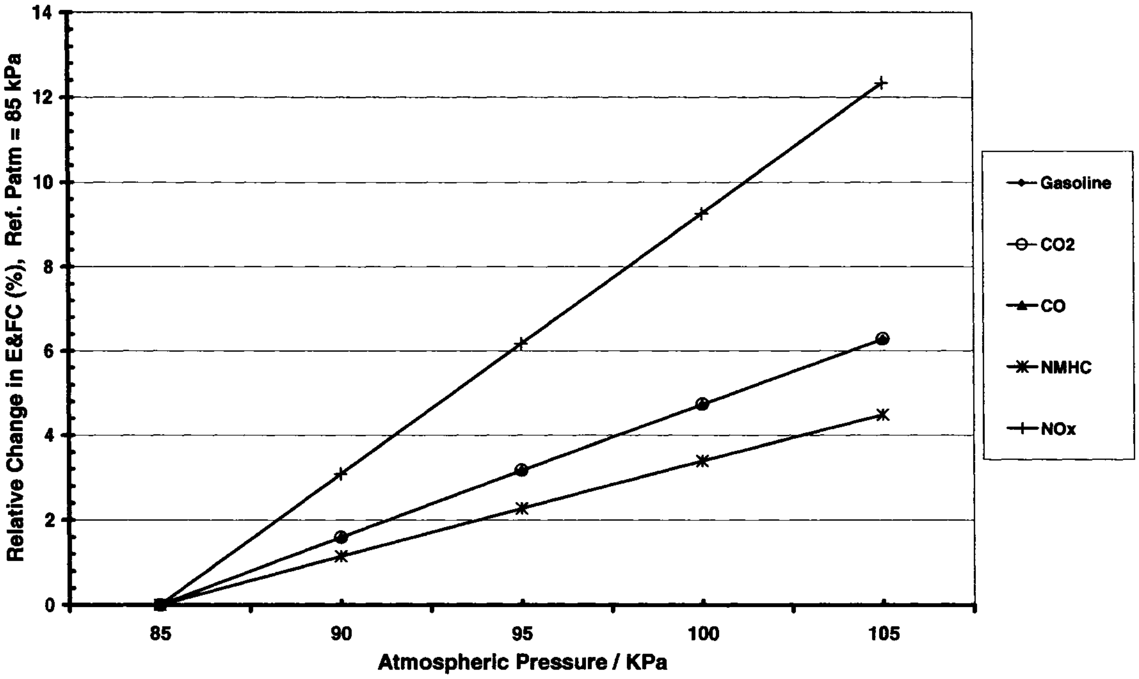


Figure 4-11: Sensitivity of CALMOB6 output values of emissions and fuel consumption to atmospheric pressure.

4.5 AMBIENT TEMPERATURE

The effect of ambient temperature has been partly exposed in section 4.4. However, other factors change E&FC at low temperatures. For instance, the lower the temperature, the longer it takes the catalyst to warm up to its design operating temperature. This results in more emissions when a vehicle is started at these low temperatures. As a result, CALMOB6 calculates its aerodynamic resistance at a unique ambient temperature namely 20^{0}C. Subsequently, relative factors are used to adjust the E&FC amounts. These factors are given in section 3.11.3.

Figure 4-12 gives the amount of E&FC when the ambient temperature is reduced from 25^{0}C to 0^{0}C, then to -25^{0}C. With the lower temperature, E&FC are expected to be higher.

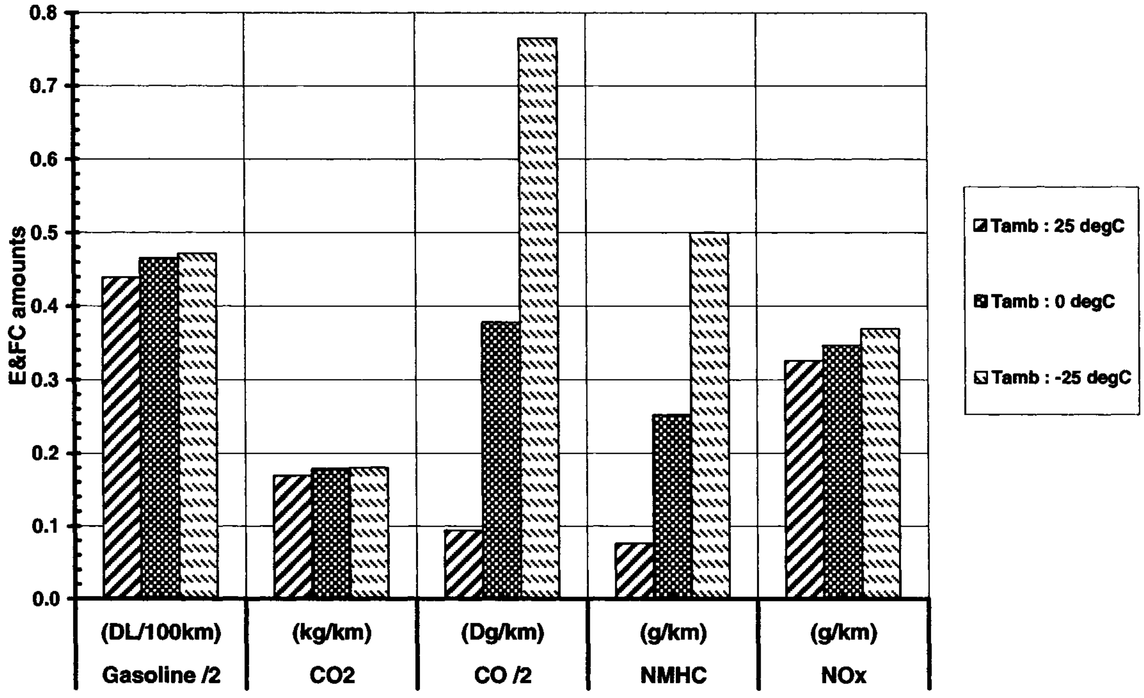


Figure 4-12: E&FC amounts at different ambient temperatures.

4.6 FUTURE E&FC AMOUNTS

The emission rates of future vehicles are obtained using the MOBILE6 database. Similarly, the fuel consumption rates are derived from the US EPA data and the NR Can database. With fleet renewal every year, the composite base emission rates and the consumption rates are expected to decrease in the future.

This section illustrates the trend in E&FC of a light-duty gasoline vehicle (a passenger car). For reference, the emissions and fuel consumption values are calculated for model year 1990 when such vehicle is cruising at 80 km/hr. Thereafter, the future E&FC from such vehicle category is plotted as a percentage of the base case. This is illustrated in Figure 4-13.

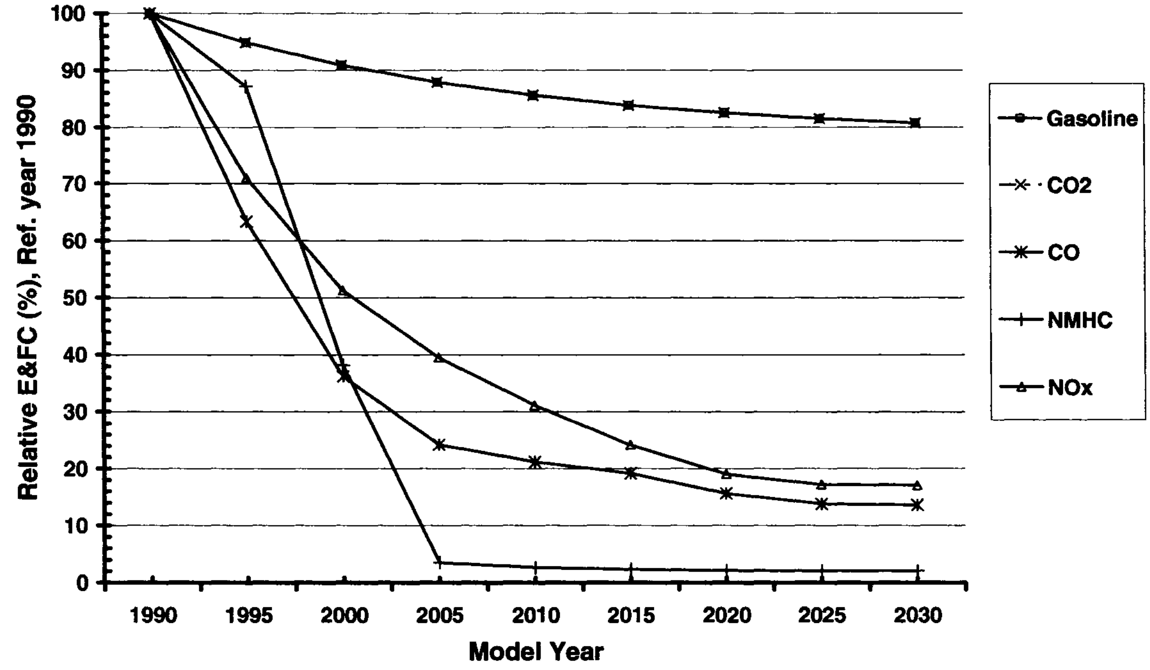


Figure 4-13: E&FC trend from a passenger car over future years.

Figure 4-13 shows the improvement to be expected as new-standard vehicles take over more of the fleet and change fleet emission characteristics. Compared with the base case of year 1990, all the quantities show a net decrease with the most dramatic improvements being in NOx, CO and HC emissions.

The same trends, as in Figure 4-12, will be observed if hundreds of such vehicles are compared in each of the years from 1990 to 2030. Thus, the case illustrates E&FC trends for a 0% traffic growth. However, the vehicle population is actually expected to increase annually. More and newer vehicles come into the fleet each year. The annual traffic growth effect on emissions and fuel consumption are illustrated by the following figures (Figures 4-14 and 4-15).

In Figure 4-14, an *annual* vehicle growth of 1% is assumed. Figure 4-15 demonstrates the trends when the growth is 2%.

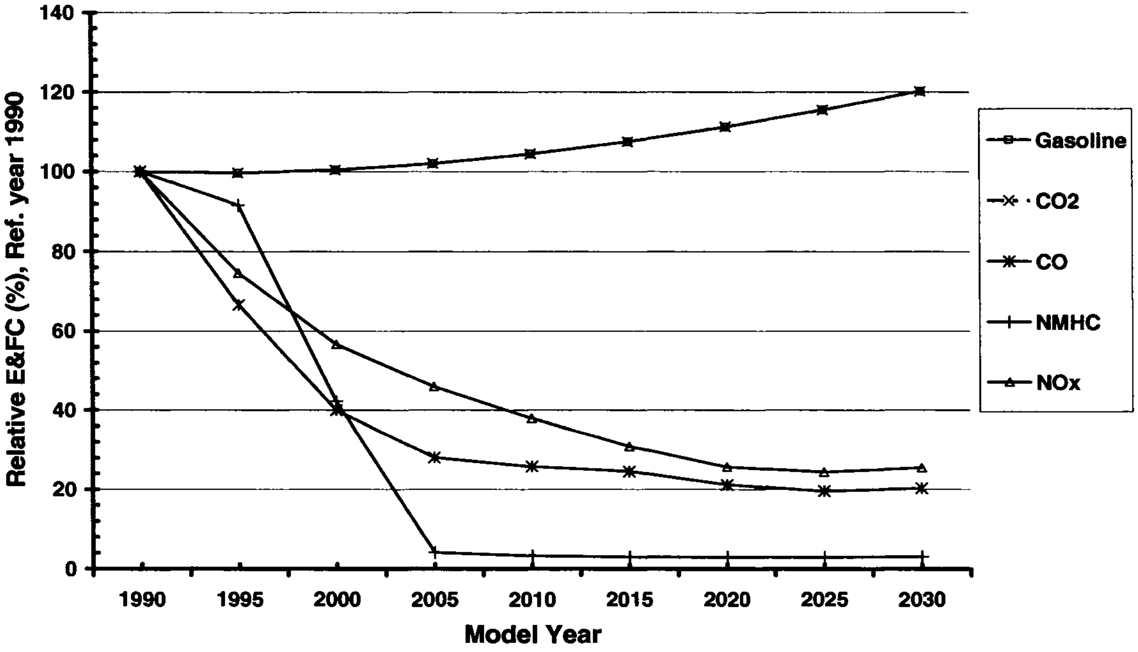


Figure 4-14: E&FC trend from the passenger car fleet growing at an annual rate of 1 %.

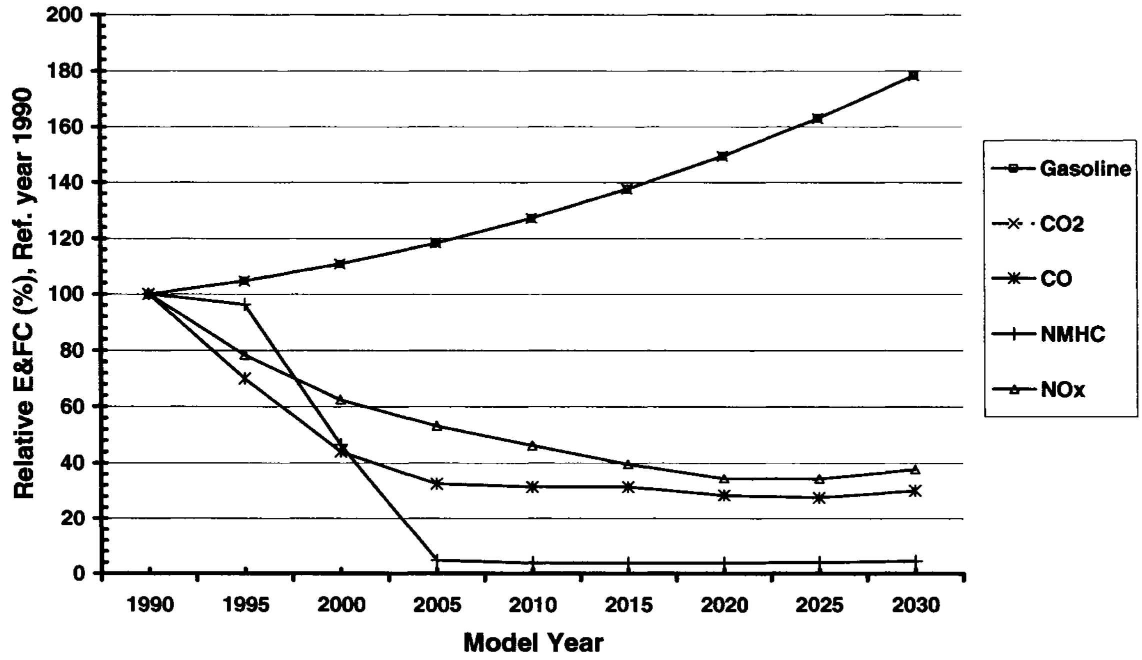


Figure 4-15: E&FC trend from the passenger car fleet growing at an annual rate of 2 %.

These 2 cases (shown in Figures 4-14 and 4-15) reflect that the actual vehicle population is likely to grow. Considering an annual traffic growth rate of 1%, there would be an overall 48.9% increase in traffic by 2030. In this case, the traffic motions and emission rates are considered with 48.9% more traffic than in 1990. As a result, the fuel consumption and green-house gas emissions end up higher than for the 1990 base case but the criteria pollutants still show a net decrease.

The same trends are observed when considering an annual vehicle growth of 2 %. The criteria pollutants level still show the net decrease, even though the level is expected to be more than in the 1% annual vehicle growth case.

Similar trends have been made for the light-duty trucks, the heavy-duty vehicles and the buses. They are illustrated in Appendix M.

4.7 DEMONSTRATION OF FUTURE TIGHT HEAVY DUTY VEHICLE STANDARDS

This section illustrates using CALMOB6 to focus on the effects of fleet evolution and tightening standards on truck emissions in the future. Emissions are here compared between a light-duty car (Economy or mid-size version) and a HDV6 heavy-duty truck. The difference in emissions is plotted in Figure 4-16.

The simulation was built using fleets of light duty vehicles (Passenger car, Economy version) and heavy duty trucks (HDV 6) which followed the same driving schedule as one another. The simulation was repeated for fleet years from 2000 to 2030 at 5 year intervals. The difference in absolute emission levels between the two classes of vehicle was plotted, showing that the emissions of the truck fleet will drop dramatically as the fleet turns over with incoming vehicles meeting planned future emission standards. The tightening truck emission standards have a particularly dramatic effect on NOx and HC emissions with less effect on CO emissions.

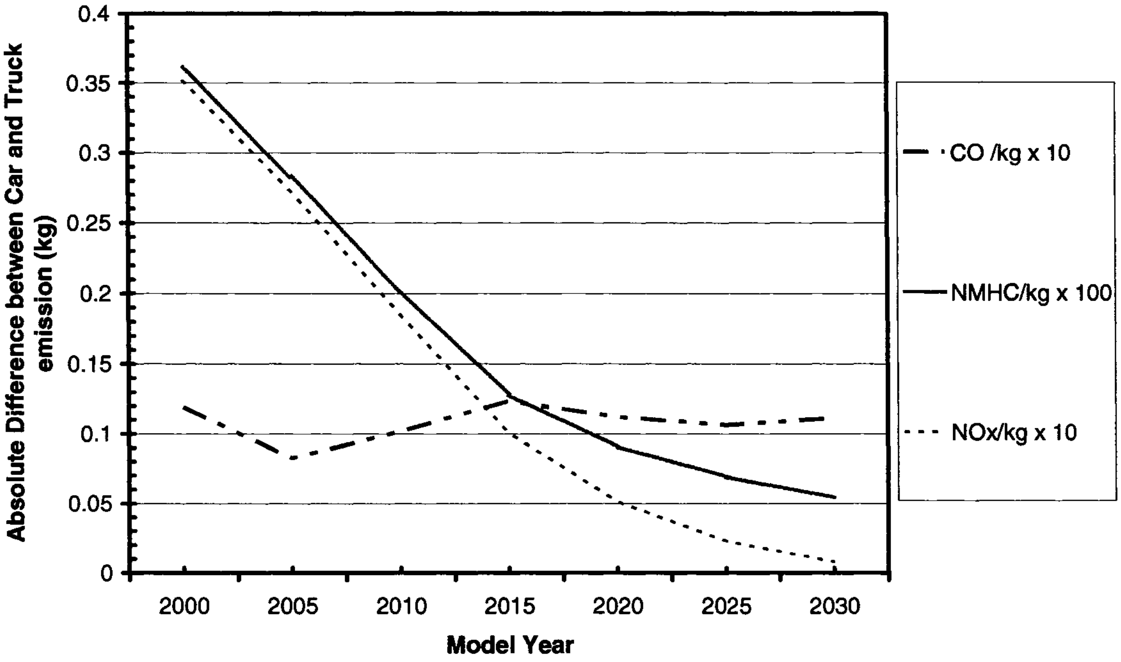


Figure 4-16: Effect of tightening standards for heavy-duty relative to already-tight light-duty values. Quantities plotted are difference in kg between a HDV6 vehicle and an Economy car.

4.8 MODELING AND REAL-LIFE SITUATION

This first illustration in this section compares values calculated by CALMOB6 with values being measured by an on-road fuel consumption and emissions measurement system. This comparison at a single-vehicle level illustrates the basic realism of the CALMOB6 vehicle dynamic models and fuel consumption models at the most direct level.

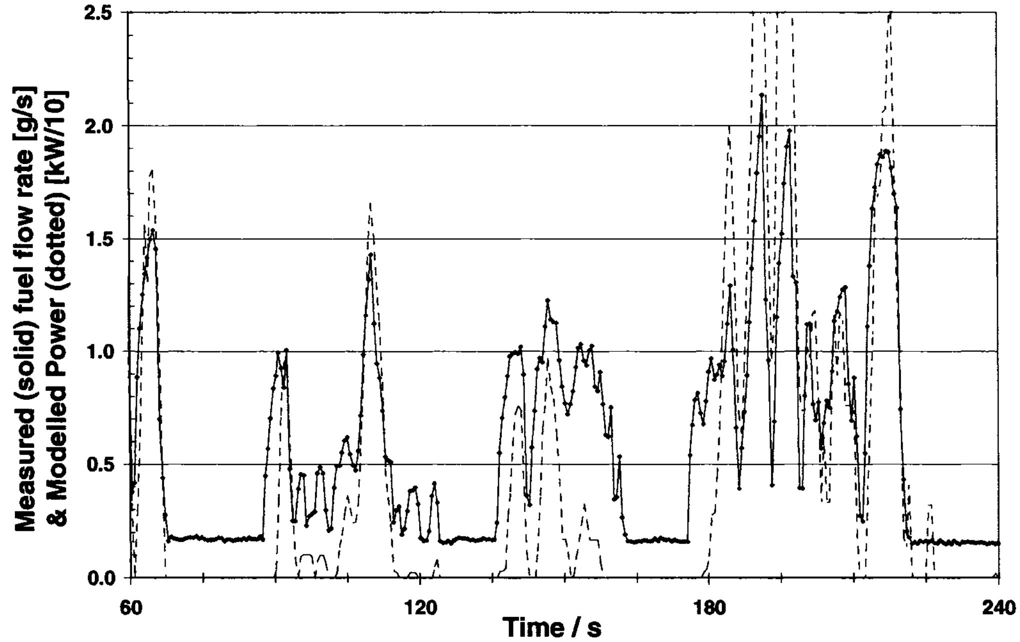


Figure 4-17: Modeled Power (dotted, kW) compared to measured fuel rate (solid, g/s).

Figure 4-17 shows how measured fuel consumption correlates with calculated tractive power based on the measured speed trace for a mid-size car, (Audi A4 1.8T Quattro), driving in urban conditions. The measured fuel consumption correlates well with the tractive power requirements and the importance of modeling idle fuel consumption rate at times of zero or negative tractive power is obvious.

Figure 4-18 provides a more direct comparison of the cumulative fuel consumption measured (heavy) and calculated by CALMOB6 (light) for a large light duty vehicle (GMC 2500 Savannah van, considered LDT 3). The total fuel consumed with time is predicted accurately. It is notable that the only significant discrepancy was in the early stages of the trip where this 2001 model vehicle actually consumed slightly less fuel than predicted by the CALMOB6 model.

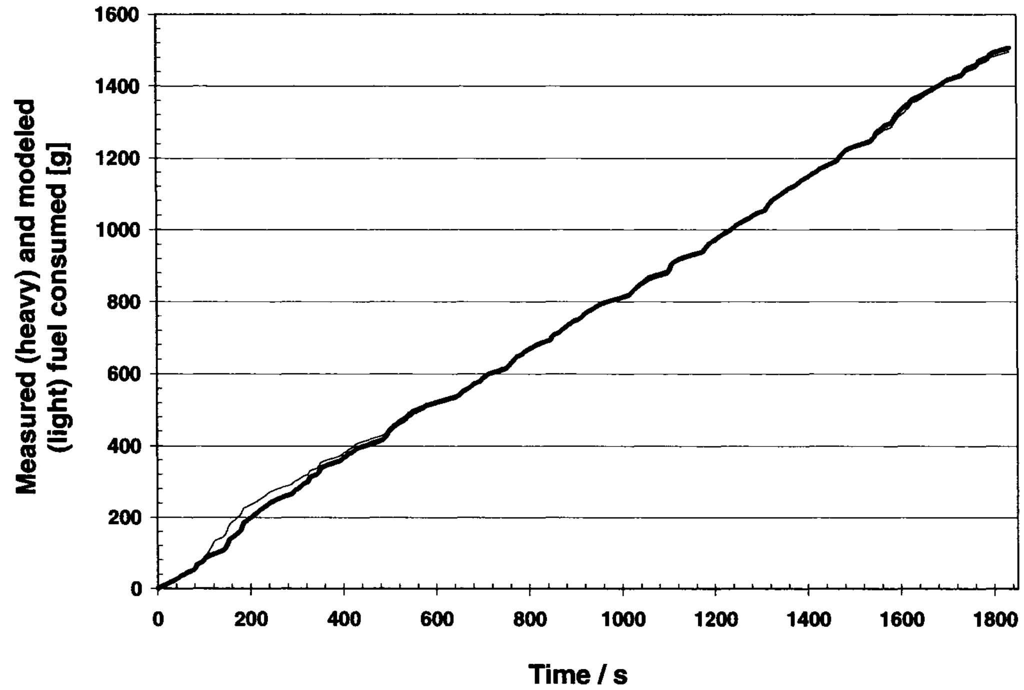


Figure 4-18: Measured fuel consumption (heavy) compared to modeled fuel consumption (light).

4.9 CONCLUSION

This concludes the set of eight basic tests performed on CALMOB6. The response of the program to different conditions has been illustrated. The settings of such software can help policy-makers and traffic planners to better answer some of their questions of interest. CALMOB6 includes a variety of options that can be used when generating an emissions and fuel consumption inventory. Higher accuracy of each option renders better E&FC estimates from CALMOB6.

CHAPTER 5

APPLICATION OF CALMOB6 TO SOME QUESTIONS OF INTEREST TO POLICY-MAKERS

Chapter 5 is a demonstration of the use of CALMOB6 to better illustrate to E&FC effects of traffic control measures. Policy-makers can use CALMOB6 to analyze different possible options in the perspective of energy demand and emissions involved. This way the more reliable option can be chosen.

5.0 INTRODUCTION

Traffic planners use transportation models to determine the effect of certain traffic control measures. Traffic planners need to determine the most efficient solution. Apart from that, they require a tool to justify the reasonable or tolerable amount of resulting emissions from any traffic control measure they apply. Hence, there comes the need for a transportation-emission model.

Three questions of general interest are set. The use of the model will be illustrated to analyze the various possible options to such global questions. The results from CALMOB6 are analyzed and the best alternative is proposed.

It is noteworthy that all the questions are directed towards considering the environment aspect solely. At this stage, the economic aspects of the problems are neglected. Moreover, such problems can be analyzed through greater depths. However, the aim of these problems is to demonstrate use of the model when analyzing the environmental and energy impact of any traffic control measure.

5.1 PROBLEM 1

Statement of problem:

A new residential region is being set-up. Initially, a single two-way road provides access to that region. In five years time, is it wiser to add another lane on each side of the road or allow congestion with average speeds 10 km/hr and 20 km/hr lower than the current average speed?

To better define the problem, the link is assumed 2 km long. The limit speed on the link is set to 80 km/hr. Further, it is assumed that for this reference year there are 100 vehicles traveling over the link during a peak rush hour period. Since the region is new, fast expansion is inevitable. Therefore, a 4% annual increase in traffic population over the link is acceptable. For year 2006 and 2011, the estimated vehicle number of vehicles by type is given in Table 5-1.

	Model Year 2006	Model Year 2011
Light-Duty Vehicles (Cars)	*50*	*61*
Light-Duty Trucks	*30*	*37*
Heavy-Duty Vehicles	*15*	*18*
Buses	*5*	*6*

Table 5-1: Estimated vehicle population by vehicle type over the link during a peak rush hour.

For both years, the calculations are performed for an ambient temperature of 25^0C and for an atmospheric pressure of 94kPa. Similarly, the vehicle fleet composition by type and fuel is assumed the same in future. Also, the maximum speed on the link can remain the same in the future; i.e. 80 km/hr.

Adding a lane on each side of the road will render the traffic more fluid. Further, the average speed of the traffic can be maintained at 80 km/hr in 2011 (condition 2 of Table 5-2).

On the other hand, the traffic growth over the five-year period can increase the level of congestion on the road (conditions 3 and 4 of Table 5-2). The greater the congestion level, the greater is the expected level of emissions and energy demand. This fact is demonstrated in section 4.2. However, will the resulting emissions be under the acceptable level when traffic is growing at such a drastic rate – i.e. 4% per year?

For these options, the results are compared with the actual level of traffic. CALMOB6 is employed to generate the amount of E&FC for the following set of conditions:

Condition No.	Model Year	Traffic Population (Table5-1)	Average Speed, km/hr
1	2006	For 2006	80
2	2011	For 2011	80
3	2011	For 2011	70
4	2011	For 2011	60

Table 5-2: Conditions set for analysis using CALMOB6.

The resulting E&FC from conditions 2, 3 and 4 are compared with condition 1. They are presented, in Figure 5-1, in terms of the relative amounts, set as percentages.

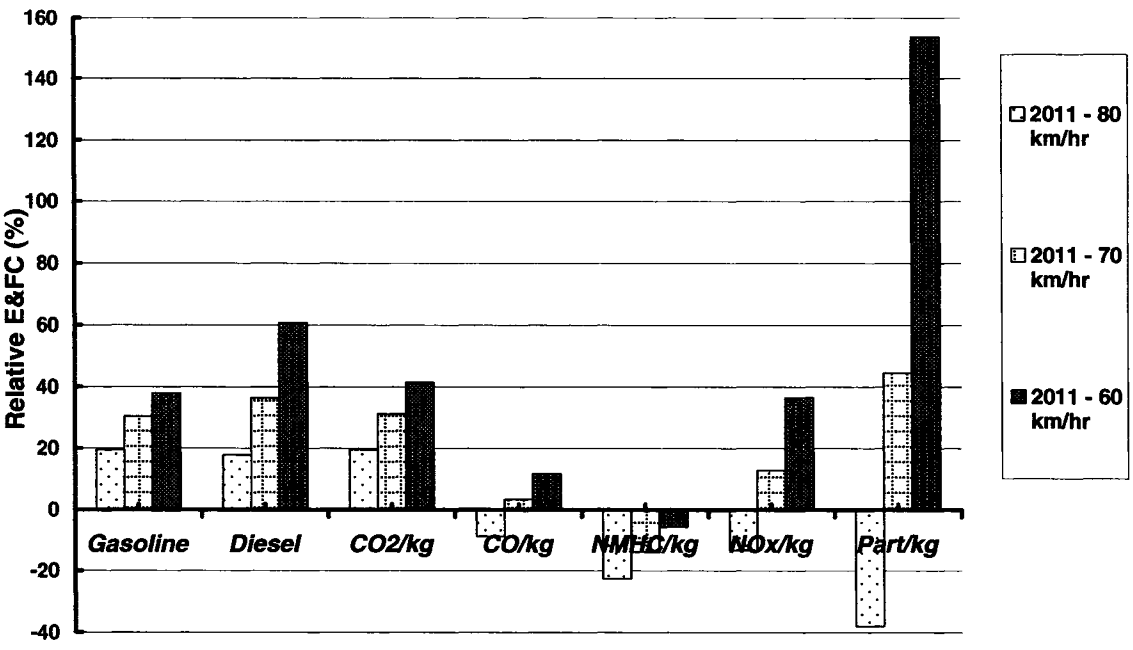


Figure 5-1: Relative emissions and fuel consumption for the conditions 2, 3 and 4.

Figure 5-1 shows that allowing the traffic growth with no development of additional lanes will increase the level of energy demand and of all pollutants except NMHC. The higher the congestion level, the higher is the resulting emission level. The particulates emission is very sensitive to the congestion level.

On the other hand, with the addition of lanes, the same average speed is maintained and lower emissions of criteria pollutants are expected in 2011 even though traffic growth is drastic. Thus, the benefits of vehicle technology improvements will be better enjoyed with the proposed infrastructure development.

5.2 PROBLEM 2

Statement of problem:

The permissible speed on a 2 km long section of a freeway is 80 km/hr. Traffic planners are wondering if it is worth putting a camera to monitor the speed of vehicles. The other option is to permit a greater amount of speeding. From the perspective of resulting E&FC, what is the effect of speeding?

To answer this problem, CALMOB6 is set to process EMME/2 data-files where the average speed equals the limit speed over the link. The limit speed is increased from 80 km/hr to 140 km/hr in steps of 10 km/hr.

All vehicles move at the maximum permissible speed. The higher the permissible speed, the faster the vehicles cruise through and the shorter the travel time over the 2 km section. However, over the same time-scale it is expected that the faster moving vehicles emit more due to higher power requirement.

Figure 5-2 demonstrates the relative E&FC at higher speeds relative to the E&FC at 80 km/hr.

For NMHC and particulates, the effect of lower travel time at higher speeds dominates that of higher power demand. As a result, increasing permissible speed leads to little or no change in resulting E&FC.

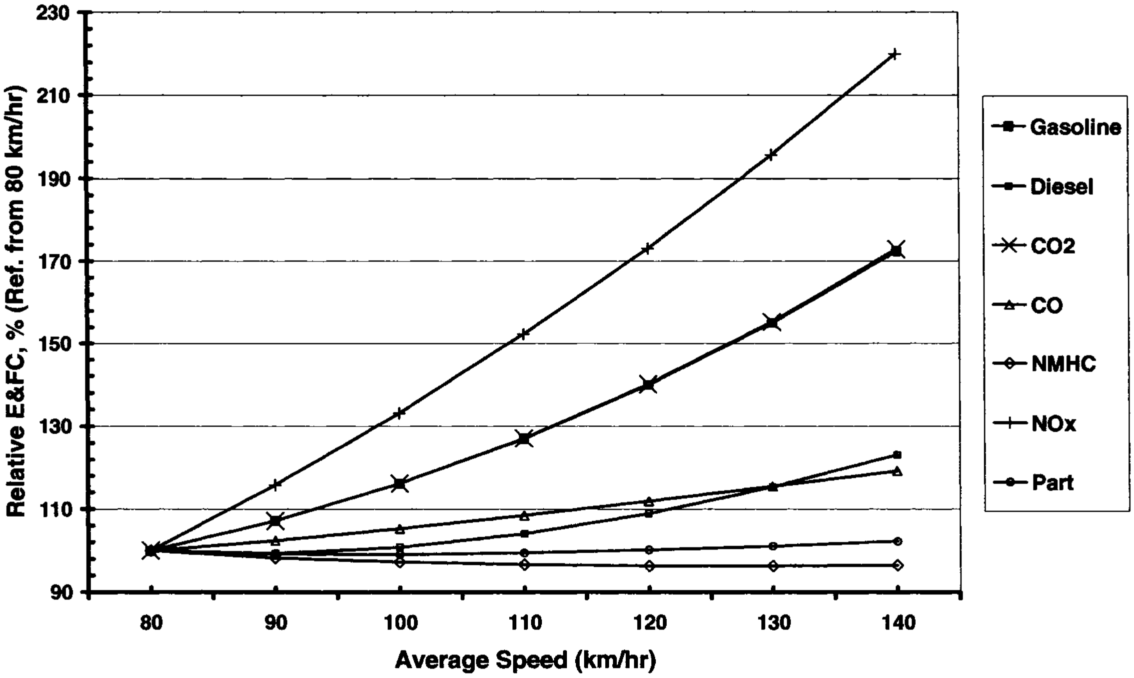


Figure 5-2: Relative emissions and fuel consumption at different average speed.

Carbon monoxide emission and diesel fuel consumption show a moderate increase of around 20% when speed is 140 km/hr. Nitrogen oxides and carbon dioxide emissions, together with gasoline fuel consumption demonstrate radical increases by increasing the average speed of the vehicle.

5.3 PROBLEM 3

Statement of problem:

A new residential community is being set up. A decision on the road infrastructure is underway. Two measures are proposed. Which of the two options are better from the environmental and fuel demand point of view?

I. **Design road infrastructure that can accommodate frequent use of light-duty vehicles (passenger car and light-duty trucks), or**

II. Encourage high bus rider-ship with regular and frequent tours. Consider only the morning rush hour.

The aim of this problem is to compare the amount of emissions when light-duty vehicles travel over such a link compared to buses. For simplicity, a 2 km section of the link is considered for analysis. The speed limit on the link is 60 km/hr. In addition, the vehicle composition by subclass and fuel type is considered representative of Edmonton's fleet. These are given in Tables 3-6 and 3-7.

In case I, it is assumed that 70 passenger cars and 30 light-duty trucks use the link. Reasonable vehicle occupancy is 1.5. As a result, it is expected that 150 people travel by light-duty vehicles. Since the region is a residential one, these privately owned vehicles are assumed to idle for a 30 seconds before accelerating to any cruise speed. Such cycles for zones are better described in section 3.3.2. Moreover, the problem statement is for a morning rush hour. In this case, there is likely to be a percentage of the vehicles that are cold-started.

Case II assumes that each bus-trip move 30 persons out of the region. As a result, to satisfy the 150 people, at least five buses are needed to operate over that peak morning rush hour. It is good to recall that unlike the light-duty vehicles, buses are already 'running hot'. Further, the driving cycles are treated differently with the inclusion of a dwell time on the link.

To compare the emissions and fuel consumptions, different scenarios are developed. For case I, E&FC are considered for vehicles when they are all 'running hot'. Hence, there is no excess emission and fuel consumption due to cold-start. This condition is set as the reference case. Subsequently, the percentage of cold-started vehicles is increased in steps of 25% to finally reach 100% cold starts. Emissions are compared at each step and expressed as a relative output with comparison to the 0% cold start case.

For case II, the minimum number of buses touring the region is five; i.e. every twelve minutes. Again, all the bus emissions are compared with the emissions from the 0% cold-start light-duty vehicles. Sensitivity analysis in this case involves increasing the frequency of the bus tours up to ten buses per hour. A bus tour at every 10 minutes is common in neighborhoods during peak hours leading to a more realistic bus frequency of six buses per hour. The buses may dwell longer on the link. In this case, the average speed of the buses (six per hour) is lowered from 60 km/hr to 30 km/hr in steps of 10km/hr. This second sensitivity analysis makes the bus trip more congested with more stops and more idling times.

Figure 5-3 illustrates the relative amount (in %) of CO_2, CO, NMHC and NOx emissions for the light duty vehicles and the buses. To recall, the base case emissions is from a set of 100 light-duty vehicles running hot. The latter emissions are much lower for the alternative II.

Particulates emissions (PM 10) are common in heavy-duty diesel vehicles (diesel buses). The majority of the buses in case II are assumed diesel-fuelled. More than ninety-nine percent of the light duty fleet is gasoline propelled. Further, MOBILE6 does not state any cold start emission rate for the particulates. Hence, the level of particulates stays the same for the light-duty fleet with increasing cold-start percentages. As a result, contrary to the remaining pollutants, particulates emissions are higher for the buses. Figure 5-4 illustrates the relative emissions of the particulates.

Thus, traffic planners are left with two options: allow more emissions of criteria and global-warming pollutants (CO, NOx, HC and CO_2) through the light-duty vehicles or alternatively permit high emissions of particulates from buses in that neighborhood. It is only after further investigation about the potential health and environmental hazards of the particulates versus the other pollutants that a decision about preferred mode of travel in the neighborhood can be reached.

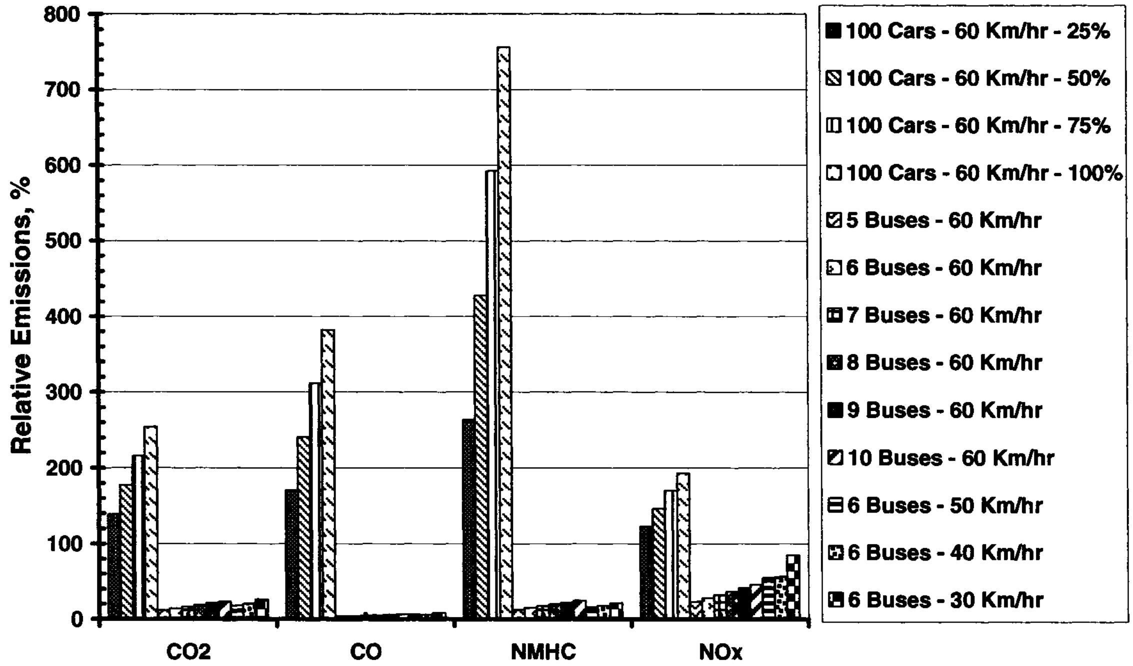


Figure 5-3: CO_2, CO, NMHC & NOx relative emissions (%) for the light-duty fleet and the buses in the neighborhood region during a peak morning rush hour.

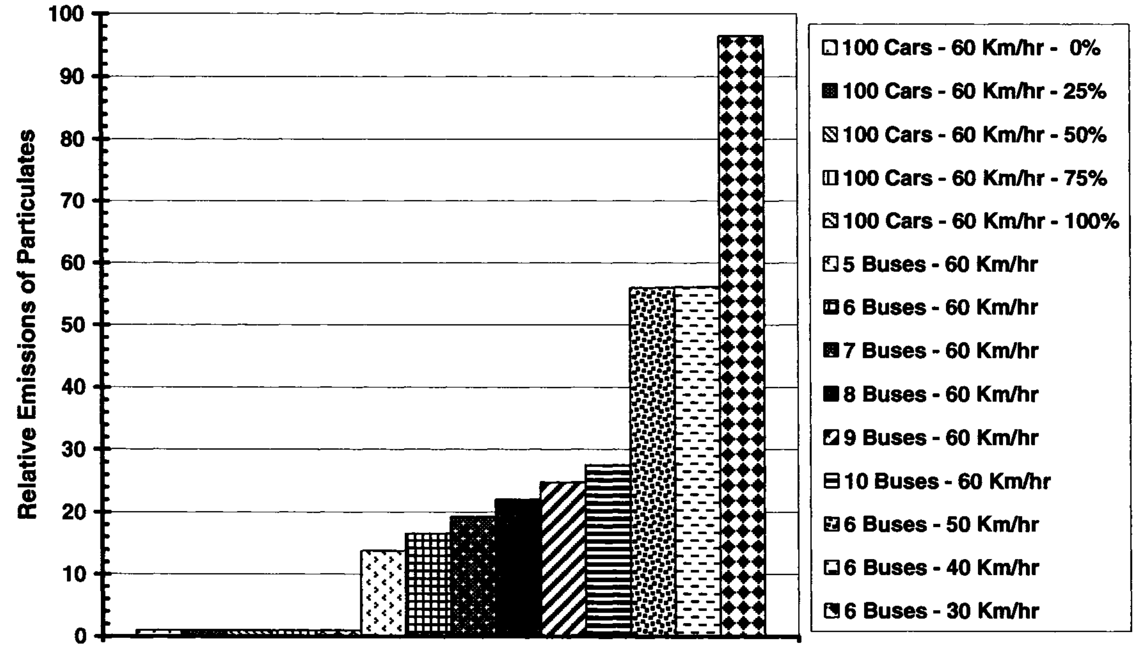


Figure 5-4: Relative emissions of particulates (PM 10) for the light-duty fleet and the buses in the neighborhood region during a peak morning rush hour.

To compare the fuel consumption, the economic value of each fuel is the baseline. This is because different fuels are used – gasoline and diesel. Table 5-3 gives the total amount of fuel consumed for the fourteen different set conditions.

Condition Number	Vehicle Type	No. of Vehicles	Average Speed	% Cold Start	Gasoline /kg	Diesel /kg
1	CARS & LDTs	*100*	*60*	*0*	14.720	0.216
2	CARS & LDTs	*100*	*60*	*25*	20.599	0.218
3	CARS & LDTs	*100*	*60*	*50*	26.478	0.220
4	CARS & LDTs	*100*	*60*	*75*	32.357	0.222
5	CARS & LDTs	*100*	*60*	*100*	38.236	0.224
6	BUSES	*5*	*60*	*0*	0.027	1.377
7	BUSES	*6*	*60*	*0*	0.032	1.653
8	BUSES	*7*	*60*	*0*	0.037	1.928
9	BUSES	*8*	*60*	*0*	0.043	2.203
10	BUSES	*9*	*60*	*0*	0.048	2.479
11	BUSES	*10*	*60*	*0*	0.053	2.754
12	BUSES	*6*	*50*	*0*	0.035	2.121
13	BUSES	*6*	*40*	*0*	0.036	2.403
14	BUSES	*6*	*30*	*0*	0.041	3.160

Table 5-3: Fuel consumption under the 14 different conditions that analyzed.

If price wise the fuels are alike, the addition of the last two columns of Table 5-3 gives an idea of the amount of fuel consumed. In the light-duty vehicle case, the lowest amount fuel is consumed when the vehicle are moving freely; i.e. under condition 1. A total of 14.936 kg of fuel is consumed in this case. The worst scenario that can occur with the buses is under condition 14. Traffic is congested and 3.201 kg of fuel is consumed. Thence, in terms of fuel consumption, the light-duty fleets need at least 4.7 times more fuel than the bus fleet.

5.4 CONCLUSION

This chapter has demonstrated the utility of CALMOB6 as an aid when answering traffic planning related questions. The above three different problems have shown that transportation planners can use such a tool to help justify the traffic control measures they take. Further, this tool can help guide infrastructure development over coming decades though its ability to forecast emissions and fuel consumption data using adequate assumptions.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Chapter 6 states the general conclusions from the work. The model developed has some limitations. This chapter highlights a list of possible future work that will improve the emissions and fuel consumption estimates.

6.0 INTRODUCTION

This thesis has demonstrated the need for continuous on-road vehicle emissions regulations through Chapter 1 which has pointed out the need for an emissions inventory tool to address different transportation issues.

Chapter 2 provides a basic literature review of the need of such an emissions inventory. It lists the different factors that affect emissions and fuel consumption. Besides, it exposes the benefits and limitations of the various emissions and transportation models that are needed when doing an on-road vehicle emissions inventory. In this context, it gathers all the desirable characteristics of an emissions inventory tool and thence sets the requirements of such a model.

Chapter 3 presents the methodology adopted when building the model. It investigates into the types of information that have been retrieved from other emissions/transportation models for use in CALMOB6. Moreover, the optimum use of reliable data obtained from government agencies and private organizations is presented. Finally, other factors available from published technical literatures are built in the model to make it state-of-the-art software.

Chapter 4 is a collection of tests administered to CALMOB6. These tests are made to observe the response of the inventory tool to different prevailing conditions. The purpose of such simulations is, basically, to verify and demonstrate the appropriateness of the main features included in the model. Simulations over real operating conditions to measure the effectiveness of the model against real-time data are also addressed.

Finally, Chapter 5 demonstrates application of the vehicle emissions inventory tool. Three cases of general interest to policy-makers are set. After making practical assumptions, CALMOB6 is used to better address the problems from the environmental perspective. Hence, it has proved its benefits.

6.1 CONCLUSION

A vehicle emissions inventory model has been developed. It has been named CALMOB6; short for CALibrated to MOBile6. It has been translated into state-of-art software that operates on the Matlab platform. It includes twenty-seven of the twenty-eight MOBILE6 vehicle classes. Moreover, it estimates emission levels of carbon dioxide, hydrocarbon, nitrogen oxides, carbon dioxide and particulate matter.

The tool reads traffic data from the EMME/2 transportation analytical tool. It then simulates a model driving-pattern to generate a speed-time trace for each vehicle category. Model vehicles of given mass, frontal area, coefficient of drag and coefficient of rolling resistance are used for this inventory. For each vehicle model, a power trace is generated from the speed traces. Power based emission functions are applied to the vehicle modeled power traces to finally obtain second-by-second emission and fuel consumption (E&FC) rates. By integrating the E&FC rates over a time-scale, the cumulative amounts are obtained.

Further, the tool employs the US EPA's MOBILE6 set of base emission rates to estimate past and current emission rates. This database already accounts for the different emission technologies. Future base emission rates are also predicted using MOBILE6 emissions model. Hence, all the CALMOB6 emission functions are calibrated against the US EPA on-road vehicle model data. Both 'cold-running' and 'hot-running' emissions are computed. Similarly, the light-duty fuel consumption function is calibrated against the Natural Resources Canada database.

Adjustment factors are used to estimate E&FC at different temperatures, for super-emitters and finally, for alternative fuelled vehicles. Apart from the standard gasoline and diesel fuels, the alternative fuels considered are natural gas, propane, methanol and ethanol. Emissions and fuel consumption are estimated for each fuel type on mass and/or volume rate basis. For electric vehicles, emissions of CO_2 and NOx are estimated at power plants.

Unlike the MOBILE6 vehicle emissions model where emissions are estimated on a distance-travelled basis, CALMOB6 is sensitive to the prevailing driving pattern and road grade. As a result, the effects of start/stop, idle, cruise, acceleration and deceleration are accounted for by CALMOB6. These features give an edge to CALMOB6 when it comes to generating emissions and fuel consumption inventories. With this tool, E&FC can be estimated over a metropolitan region or localized down to a particular community, down to a single road and down to a section of the street.

CALMOB6 has been designed for use by traffic/transportation planners. They can use the tool to measure the effects of a variety of options they are faced with, before applying the traffic control measures. Likewise, the effects of travel mode choices, travel infrastructures and traffic patterns on E&FC can be estimated. In this context, CALMOB6 can help to justify certain traffic control actions. Further, the effects of regional fleet composition by age, type, fuel type, high-emitters and cold start percentage can be accounted for. Besides, built in the software, are the effects of fleet renewal on emissions and fuel consumption.

6.2 RECOMMENDATION FOR FUTURE WORK

This work provides a solid foundation with a powerful vehicle emissions inventory tool. Extensive studies are still plausible to improve the software flexibility, adaptability and use in multiple circumstances by including further emissions-related features. This section points out certain limitations of the program. With these restrictions, recommendations for further work are listed.

CALMOB6 actually obtains macroscopic vehicle operation parameters from the EMME/2 macro-analytical regional transportation model. Using suitable assumptions, it then develops a traffic motion model for every link such that the model time matches the actual travel time on every link. Subsequently, it estimates the second-by-second vehicle E&FC. However, the microscopic transportation models (Figure 2-2) already provide instantaneous vehicle operation data. With such microscopic data, E&FC estimations will be more accurate. As a result, if transportation planners are able to generate the second-by second speed information with the more refined transportation model, the speed trace can be the baseline of CALMOB6.

Moreover, there is a lack of proper emission and fuel consumption functions. With the objective to improving E&FC functions for light-duty vehicles, an on-road vehicle E&FC measurement project is underway. Passenger cars and light-duty trucks, all gasoline-fuelled, were run over various speed traces, closely matching standard FTP cycles. However, the E&FC functions from the latter project are not available yet [1]. Once these functions become available, they need to be calibrated against the MOBILE6 data before their application in CALMOB6. As for the heavy-duty vehicles, it is concluded that no better E&FC functions are available than those already employed by EMITPP06 and CALMOB6.

The fuel consumption rate in 2030 is estimated to improve anywhere between 10% and 25% over the 1990 rates for light-duty vehicles (Figure F-19). These estimations were made using the Natural Resources Canada database of fuel consumption rates. It would be beneficial to justify the trends obtained against technical literature should that become available.

The adjustment factors to account for different ambient temperatures must be reviewed. Right now, adjustment factors are available at only two to three points over a wide gap of temperature possibility (range of 50 ^{0}C; from -25 ^{0}C to +25

^{0}C). For instance, to estimate CO emissions at -20 ^{0}C, an adjustment factor of 8 is used to modify the CO emission rates at 20 ^{0}C. Better estimations are possible if adjustment factors are obtainable for every 5 ^{0}C gap. Moreover, air-conditioning in vehicles produces significant effects on E&FC. Air-conditioning provides high load on the engine especially during summer. Accounting for these effects should render the E&FC estimates more accurate.

Moreover, classification of high-emitters has been made according to MOBILE6 assumptions. For instance, vehicles releasing 3 fold the estimated amount of CO are considered as high emitters. Such information is not available for PM and CO_2 emissions nor for the fuel consumption. On the other hand, it is worth pointing out that MOBILE6 has already accounted for the effects of high emitters in its base emission rates. However, to give traffic planners more flexibility, CALMOB6 provides the ability to set a fraction of the high-emitting vehicles. In this way, the effect of high-emitting vehicles may be accounted for twice.

Finally, the adjustment factors for E&FC rates from the alternative fuelled vehicles are derived from averages of the collection of emission rates. These rates were obtained from the technical literature. In most of this literature, the published emission rates are likely to have been achieved on test vehicles. Over the past one or two decades, significant improvement in emission control has made such vehicles less polluting. In this context, it is worth refining the adjustment factors by choosing E&FC rates from properly functioning alternative-fuelled vehicles.

REFERENCES

1. Gao, Y., "In-Use Vehicle Fuel Consumption and Emissions Functions Measurement", University of Alberta, M.Sc Thesis, Aug 2006.

APPENDIX A

On-Road Vehicle Classification

Appendix A shows how the MOBILE6 vehicle classification has been adapted to CALMOB6. This section lists the additional vehicle subclasses that have been included in CALMOB6 to better represent the on-road vehicles characteristics. Finally, all the vehicle characteristics, as used in CALMOB6, have been tabulated.

A.1 INTRODUCTION

It is important to know the vehicle classification before venturing in the transportation/emission model. In addition, it is good to recall that the classification should be similar and comparative to that of a well-accepted vehicle emissions model. MOBILE6 database is common.

In this aspect, the MOBILE6 vehicle classification has been adopted by CALMOB6. However, further refinement in the vehicle classification has been made. This has been done to better represent the vehicle fleet over the metropolitan area. Passenger car, for example, has been subdivided into three major sub-categories – Mini, Economy and Large/Luxury. Each of these subclasses has different vehicle characteristics (mass, frontal area, coefficients of drag and coefficient of rolling resistance. Similarly, the bus fleet has been split. Motorcycles, on the other hand are not considered as they are of negligible quantity in the fleet under study.

It is normal for traffic forecasts to split vehicles into a smaller number of classifications; e.g. Light Duty (cars and light trucks), Medium Duty Vehicle (single body trucks), Heavy Duty Vehicle (large trucks and trailers) and Transit Bus. The CALMOB6 program accommodates this by allowing the user to specify the traffic in terms of these vehicle classes. As a result, the user has the option to choose between two types of vehicle classification schemes.

In this context, Table A-1 introduces the MOBILE6 vehicle classification, while Table A-2 classifies the vehicle fleet to better represent the vehicles operating in a metropolitan region, namely City of Edmonton. Table A-3 highlights the differences between the two CALMOB6 vehicle classification possibilities. In the end, the characteristics of every vehicle considered CALMOB6 are tabulated. Appropriate assumptions have been made to justify the CALMOB6 vehicle characteristics.

MOBILE6 Group Number	**MOBILE6 Vehicle Classifications**	
	Abbreviation	*Description*
1	LDGV	Light-Duty Gasoline Vehicles (Passenger Cars)
2	LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000lbs. GVWR, 0-3,750lbs. LVW)
3	LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000lbs. GVWR, 3,751-5,750lbs. LVW)
4	LDGT3	Light-Duty Gasoline Trucks 3 (6,001-8,500lbs. GVWR, 0-5,750lbs. ALVW)
5	LDGT4	Light-Duty Gasoline Trucks 4 (6,001-8,500lbs. GVWR, > 5,751 lbs. ALVW)
6	HDGV2b	Class 2b Heavy-Duty Gasoline Vehicles (8,501-10,000 lbs. GVWR)
7	HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)
8	HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)
9	HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)
10	HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)
11	HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)
12	HDGV8a	Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)
13	HDGV8b	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
14	LDDV	Light-Duty Diesel Vehicles (Passenger Cars)
15	LDDT12	Light-Duty Diesel Trucks 1 and 2 (0-6,000lbs. GVWR)
16	HDDV2b	Class 2b Heavy-Duty Diesel Vehicles (8,501-10,000 lbs. GVWR)
17	HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)
18	HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)
19	HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)
20	HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)
21	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
22	HDDV8a	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
23	HDDV8b	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
24	MC	**Motorcycles (Gasoline) = Not currently implemented in CALMOB6**
25	HDGB	Gasoline Buses (School, Transit and Urban)
26	HDDBT	Diesel Transit and Urban Buses
27	HDDBS	Diesel School Buses
28	LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001-8,500lbs. GVWR)

Table A-1: MOBILE6 Vehicle Classifications [1].

Note:

1. All the vehicles classes, listed above, are employed by CALMOB6 with the exception of Motorcycle. Table A-2 shows further subdivisions of certain classes.

CALMOB6 Vehicle Classifications			
S/N	***Abbreviation***	***Description***	
1	LDV - MINI	Passenger car Mini	Mini
2	LDV - ECONOMY	Passenger car Economy	Economy
3	LDV - LARGE	Passenger car Large	Large
4	LDT 1	Trucks (Light duty)	0-6000 lbs. GVWR, 0-3750 lbs.LVW
5	LDT 2	Trucks (Light duty)	0-6000 lbs. GVWR, 3751-5750 lbs.LVW
6	LDT 3	Trucks (Light duty)	6001-8500 lbs. GVWR, 0-5750 lbs.ALVW
7	LDT 4	Trucks (Light duty)	6001-8500 lbs. GVWR, >5751 lbs.ALVW
8	HDV2b / MDV2b	Trucks (Heavy/Medium duty)	8501-10000 lbs. GVWR
9	HDV3 / MDV3	Trucks (Heavy/Medium duty)	10001-14000 lbs. GVWR
10	HDV4 / MDV4	Trucks (Heavy/Medium duty)	14001-16000 lbs. GVWR
11	HDV5 / MDV5	Trucks (Heavy/Medium duty)	16001-19500 lbs. GVWR
12	HDV6	Trucks (Heavy duty)	19501-26000 lbs. GVWR
13	HDV7	Trucks (Heavy duty)	26001-33000 lbs. GVWR
14	HDV8a	Trucks (Heavy duty)	33001-60000 lbs. GVWR
15	HDV8b	Trucks (Heavy duty)	>60000 lbs. GVWR
16	TL: Transit Long	Transit & Urban Bus	60ft, low-floor, New-Flyer
17	TN: Transit New	Transit & Urban Bus	40ft, low-floor, New-Flyer
18	TO: Transit Old	Transit & Urban Bus	2-stroke, GM buses
19	TS: Transit Short	Transit & Urban Bus	Small Ford Transit Buses
20	SL: School Long	School Bus	Long
21	SS: School Short	School Bus	Short

Table A-2: CALMOB6 Vehicle Classifications.

Note:

1. Table A-2 gives a basic description of the MOBILE vehicle classes involved in CALMOB6. Further subdivisions of some vehicle categories have been made; e.g. passenger car has been split into Mini, Economy and Large versions.

2. CALMOB6 allows the user to choose the vehicle classification method. The first method resembles more the MOBILE6 fleet characterization. The alternative classification, as customized for City of Edmonton, offers another particular grouping. Table A-3 depicts the differences between the two CALMOB6 vehicle classification schemes.

CALMOB6 Vehicle Classifications				MOBILE6 Group No.
S/N	***Abbreviation***	***Classification 1***	***Classification 2***	
1	LDV - MINI	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
2	LDV - ECONOMY	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
3	LDV - LARGE	LIGHT-DUTY VEHICLE	LIGHT-DUTY VEHICLE	1,14
4	LDT 1	LIGHT-DUTY TRUCK	LIGHT-DUTY VEHICLE	2,15
5	LDT 2	LIGHT-DUTY TRUCK	LIGHT-DUTY VEHICLE	3,15
6	LDT 3	LIGHT-DUTY TRUCK	LIGHT-DUTY TRUCK	4,28
7	LDT 4	LIGHT-DUTY TRUCK	LIGHT-DUTY TRUCK	5,28
8	HDV2b / MDV2b	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	6,16
9	HDV3 / MDV3	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	7,17
10	HDV4 / MDV4	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	8,18
11	HDV5 / MDV5	HEAVY-DUTY VEHICLE	MEDIUM-DUTY VEHICLE	9,19
12	HDV6	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	10,20
13	HDV7	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	11,21
14	HDV8a	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	12,22
15	HDV8b	HEAVY-DUTY VEHICLE	HEAVY-DUTY VEHICLE	13,23
16	TL: Transit Long	BUS	BUS	25,26
17	TN: Transit New	BUS	BUS	25,26
18	TO: Transit Old	BUS	BUS	25,26
19	TS: Transit Short	BUS	BUS	25,26
20	SL: School Long	BUS	BUS	25,27
21	SS: School Short	BUS	BUS	25,27

Table A-3: Different vehicle groupings under the two CALMOB6 vehicle classification schemes and corresponding MOBILE6 group number.

Note:

1. CALMOB6 offers the option to choose between two main vehicle classification schemes – Classification1 and Classification2.
2. Classification 1 closely represents MOBILE6 vehicle classification.
3. Classification 2 results from the customization request of the City of Edmonton. LDT1 & LDT2 have been grouped with the passenger cars. The heavy-duty vehicle has been divided into 2 components: Medium- and Heavy-Duty Vehicle.

CALMOB6 Vehicle Characteristics						
S/N	***Abbreviation***	***Mass / kg***	***Frontal Area / m^2***	***Coefficient of Drag***	***Coefficient of Rolling resistance***	***Applicable Power Limit / kW***
1	LDV - MINI	1005	1.900	0.300	0.013	n/a
2	LDV - ECONOMY	1295	1.951	0.327	0.013	n/a
3	LDV - LARGE	1735	2.118	0.313	0.013	n/a
4	LDT 1	1606	2.346	0.360	0.013	n/a
5	LDT 2	2120	2.633	0.368	0.013	n/a
6	LDT 3	2676	3.122	0.390	0.013	n/a
7	LDT 4	3025	3.126	0.410	0.013	n/a
8	HDV2b / MDV2b	3260	3.655	0.410	0.010	100
9	HDV3 / MDV3	3655	3.800	0.500	0.010	125
10	HDV4 / MDV4	4175	3.900	0.600	0.010	155
11	HDV5 / MDV5	5025	4.000	0.700	0.010	180
12	HDV6	6490	4.200	0.800	0.010	235
13	HDV7	8210	4.500	0.900	0.010	300
14	HDV8a	18100	4.960	0.900	0.010	425
15	HDV8b	23800	5.160	0.900	0.010	450
16	TL: Transit Long	19945	6.370	0.550	0.010	430
17	TN: Transit New	13595	6.370	0.550	0.010	360
18	TO: Transit Old	10955	5.993	0.550	0.010	300
19	TS: Transit Short	3750	4.520	0.550	0.010	130
20	SL: School Long	11000	5.712	0.550	0.010	325
21	SS: School Short	3600	4.718	0.550	0.010	125

Table A-4: CALMOB6 Vehicle Characteristics.

Note:

1. Frontal area (assumed) = Width of vehicle x Height x 0.8
2. For all the vehicles in Table A-4, the vehicle characteristics were obtained from vehicle manufacturer's website. Subsequently, these were averaged for same vehicle group.
3. For the passenger cars, LDT1 and LDT2, a vehicle-occupancy of 1.5 persons was assumed whereas occupancy of 1.8 was assumed for LDT3 and LDT4.
4. A bus rider-ship of 30% was assumed at all times. Thus,

   Mass of Bus = Curb Weight + 0.3 x (GVWR of Bus – Curb Weight)

5. GVWR of the heavy-duty vehicles was assumed an average of the GVWR range for each MOBILE6 HDV class. Assuming 40 % of allowed weight is carried,

   Mass of HDV = Curb Weight + 0.4 x (Ave. GVWR of HDV – Curb Weight)

6. Heavy duty vehicles were power-limited.

REFERENCES

1. US EPA, "User's Guide to MOBILE6.1 and MOBILE6.2 – Mobile Source Emission Factor Model", EPA420-R-03-010, Aug 2003.
2. National Academy of Sciences, "Modeling Mobile-Source Emissions", National Academy Press, 2000.

APPENDIX B

Vehicle Motion Models

The traffic motion model calculates second by second speed-time trace for vehicles. In this context, Appendix B gives an insight of different vehicle motion models that are used by CALMOB6. The latter reads specific information from the transportation modeling software. Subsequently, it internally develops a speed-time trace.

B.1 INTRODUCTION

In order to estimate emissions at a micro-level, second-by second vehicle operation data is required. This is obtained from the transportation simulation and forecasting models. Unfortunately, City of Edmonton is not making optimum use of their transportation micro-simulation model, VISSIM. EMME/2, the travel-forecasting model, is mainly used. Given that the latter is a macro-analytical model, instantaneous vehicle operation data is not provided by such model. However, there is some basic information, which can be provided by EMME/2. These are the travel demand over the streets and the average speed of the traffic, categorized for each vehicle. Together with two other infrastructure properties, namely the maximum speed on the link and the length of the street, CALMOB6 builds a realistic mini-cycle to represent the traffic motion on each. This mini-cycle includes combination of acceleration, deceleration, cruise periods and idle periods. The street is classified as to how congested it is and then a model speed-time trace is determined. This appendix gives further examples of traffic motion.

There are four main classes of traffic motion altogether:

- *Class 1 - No delay*: All vehicles drive through at the maximum speed
- *Class 2 - Some stops*: Some vehicles cruise through and some make one stop and possibly idle
- *Class 3 - All stop once*: All vehicles make a complete stop but with an idle time of less than 30 seconds. The free speed is adjusted accordingly.
- *Class 4 - Congested*: The vehicles make more than one stop and the maximum speed is reduced

EMME/2 distinguishes between traffic on major streets, referred to as *links*, and on surrounding neighborhoods. These are referred to as *zones*. Moreover, traffic motion for the light-duty vehicles differs from that of the heavy-duty vehicles.

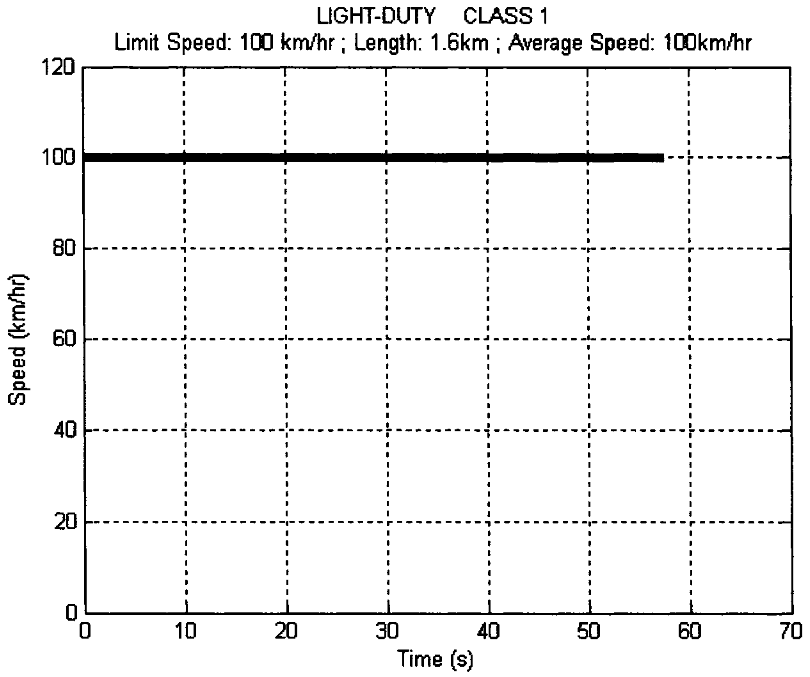


Figure B-1: Model Speed-Time trace for a *Class 1 link* (applicable for both the *Light-duty* and the *Heavy-Duty* Vehicles).

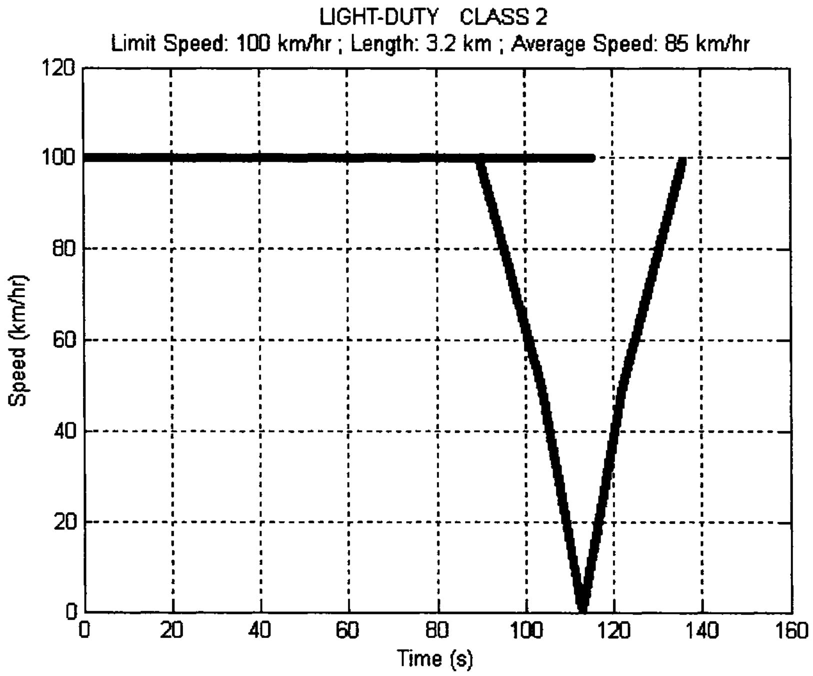


Figure B-2: Model Speed-Time trace for a *Class 2 link* (applicable to *Light-Duty* Vehicles only).

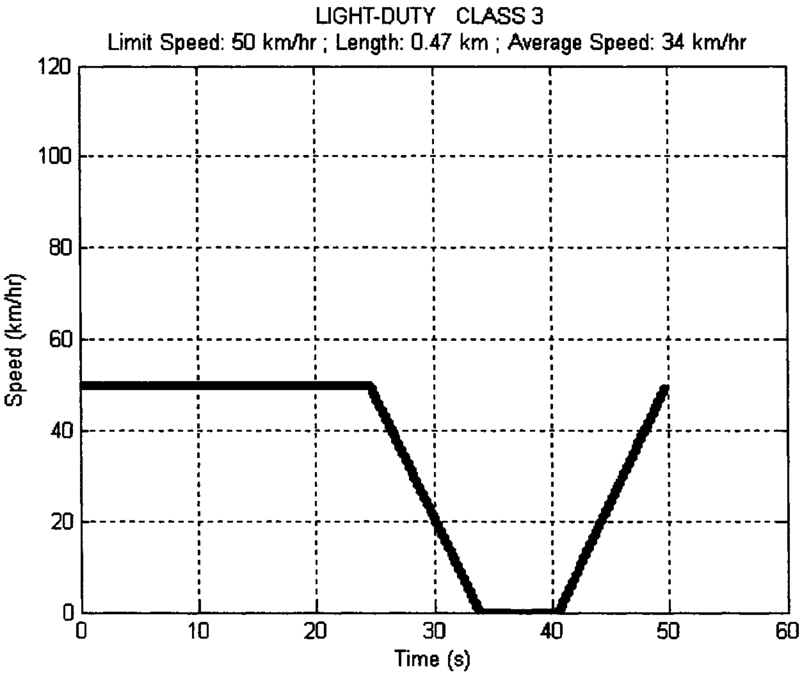


Figure B-3: Model Speed-Time trace for a *Class 3 link* (applicable to *Light-Duty* Vehicles only).

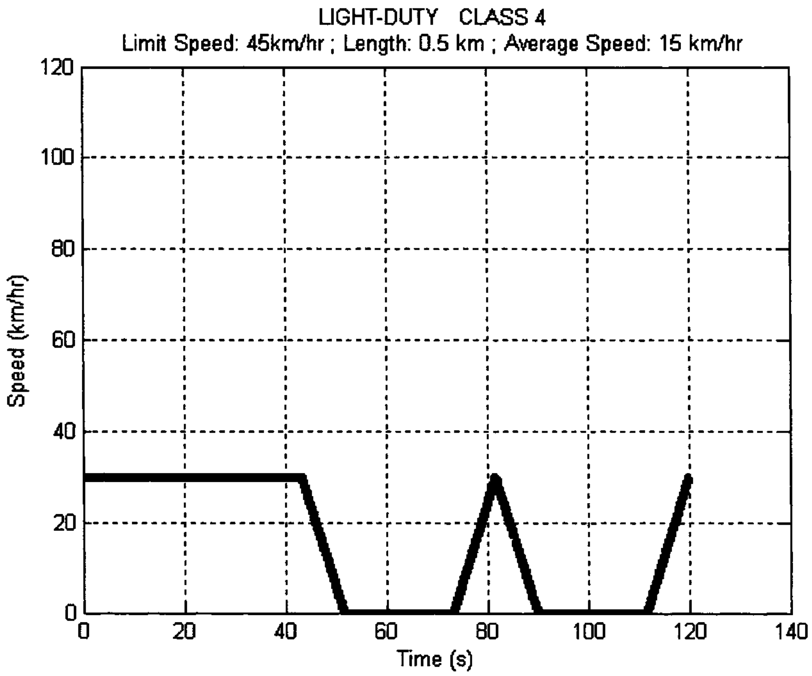


Figure B-4: Model Speed-Time trace for a *Class 4 link* (applicable to *Light -Duty* Vehicles only).

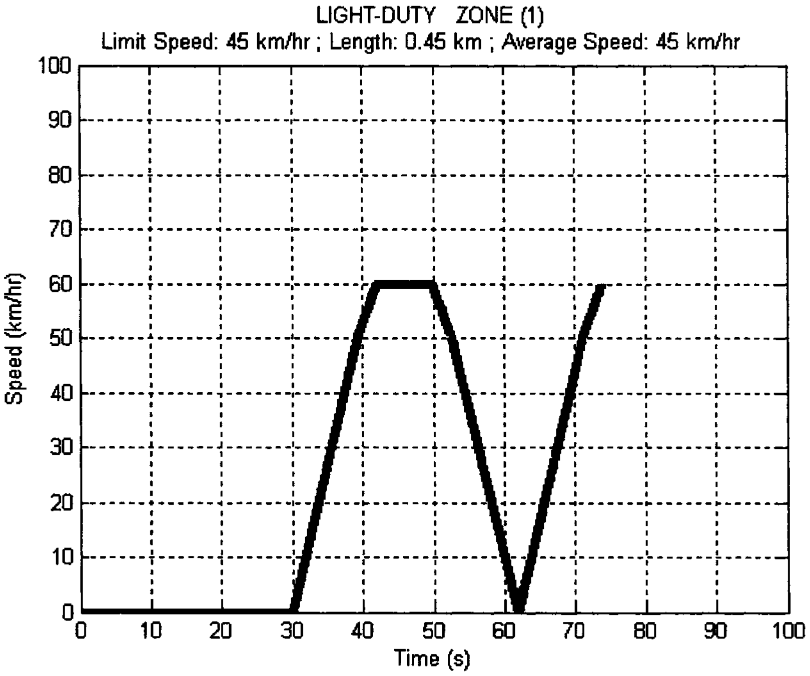


Figure B-5: Model Speed-Time trace for *Zone* with a cruise and a stop with no idle (applicable to *Light-Duty* Vehicles only).

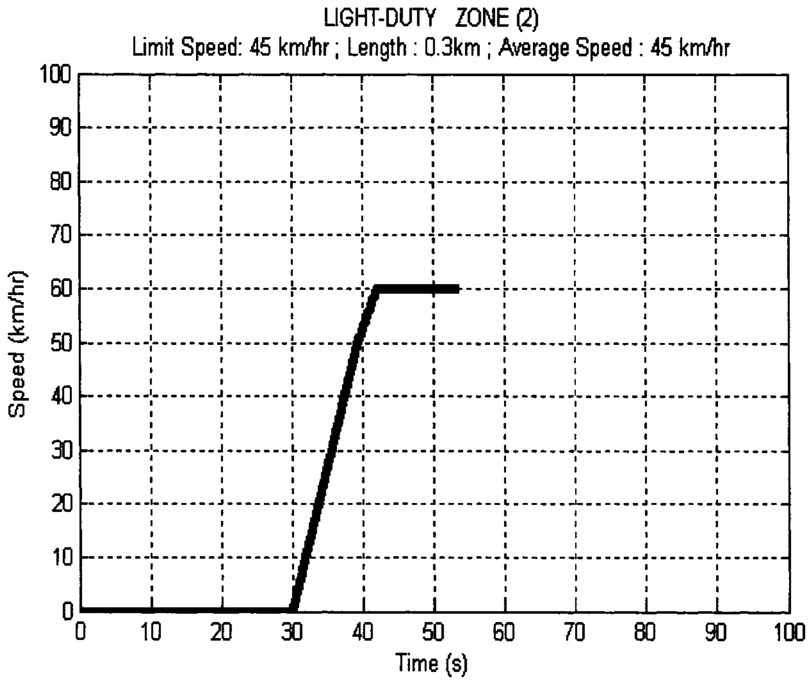


Figure B-6: Model Speed-Time trace for a short *Zone* with only one acceleration (applicable to *Light-Duty* Vehicles only).

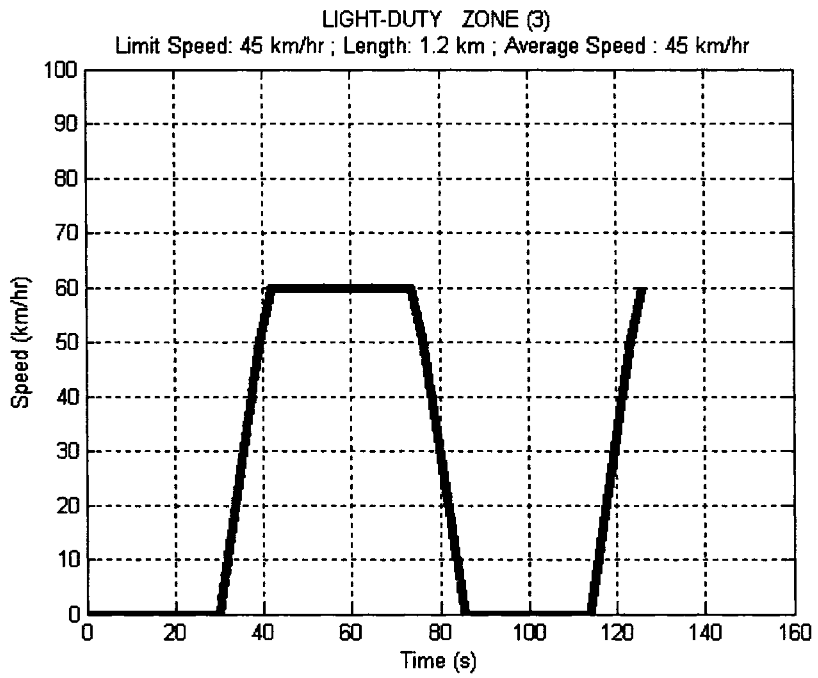


Figure B-7: Model Speed-Time trace for a *Zone* with a cruise period and a stop with idling (applicable to *Light-Duty* Vehicles only).

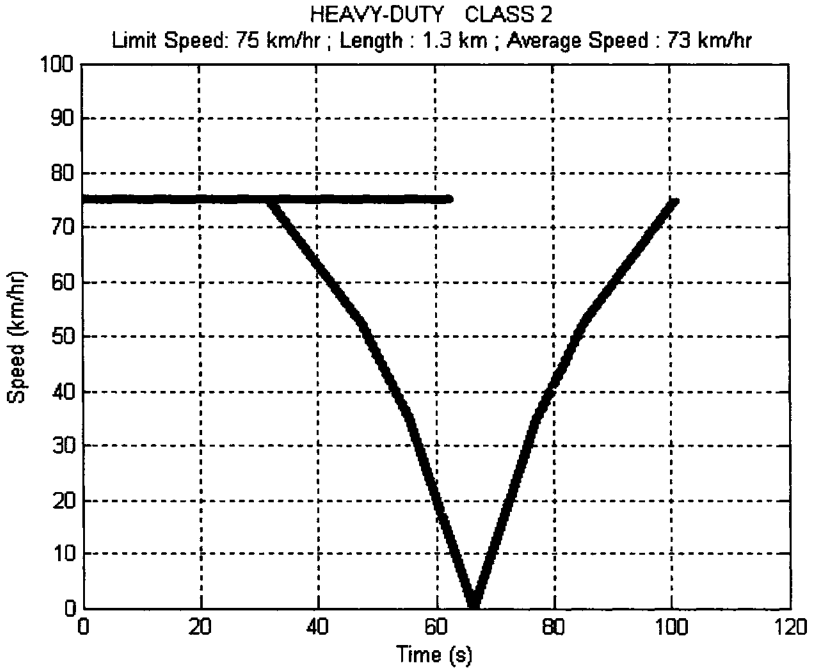


Figure B-8: Model Speed-Time trace for a *Class 2 link* (applicable to *Heavy-Duty* Vehicles only).

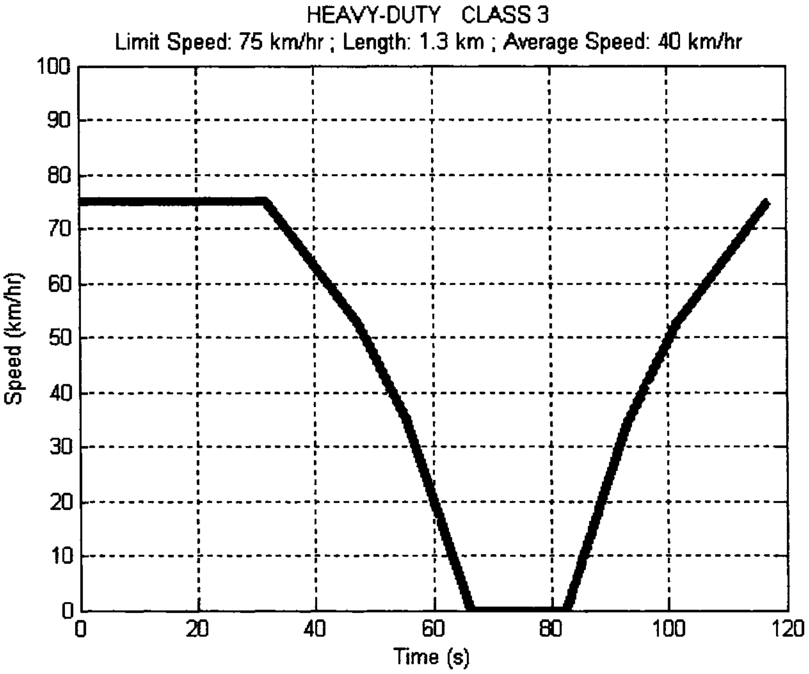


Figure B-9: Model Speed-Time trace for a *Class 3 link* (applicable to *Heavy-Duty* Vehicles only).

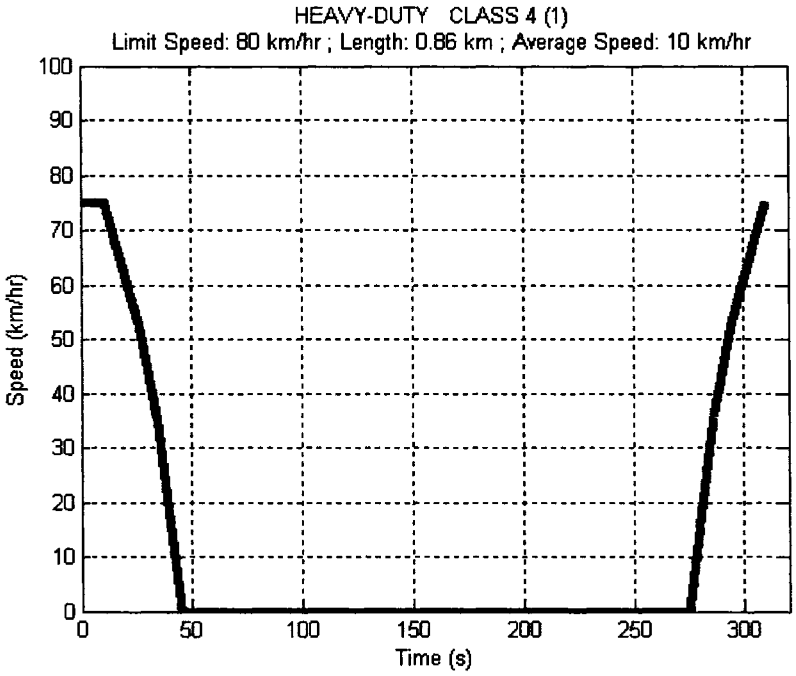


Figure B-10: Model Speed-Time trace for a *Class 4 link* – Heavy congestion (applicable to *Heavy-Duty* Vehicles only).

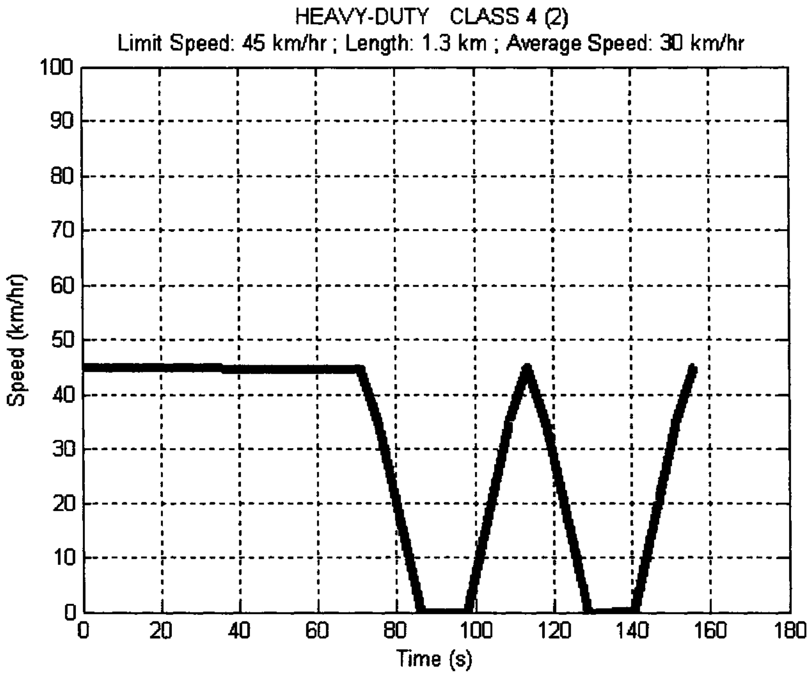


Figure B-11: Model Speed-Time trace for a *Class 4 link* – Congestion with more stops and idling times. (applicable to *Heavy-Duty* Vehicles only).

REFERENCES

1. Checkel, M.D., "Vehicle Emissions Project – The City of Edmonton Transportation Master Plan", Mar 1996.
2. Checkel, M.D., "Truck and Bus Engine Emissions – The City of Edmonton Transportation Master Plan", Nov 1996.

APPENDIX C

Modeling Vehicle Tractive Power

Appendix C illustrates the basic forces that an on-road vehicle is faced. Subsequently, a model equation relating relationship between all the related forces is demonstrated.

C.1 INTRODUCTION

Figure C-1 illustrates the representative forces influencing vehicle motion. The vehicle is faced with three main opposing forces. These are the rolling resistance, the slope resistance and the aerodynamic resistance. The engine of the vehicle has to provide a tractive force to overcome the motion-resisting forces.

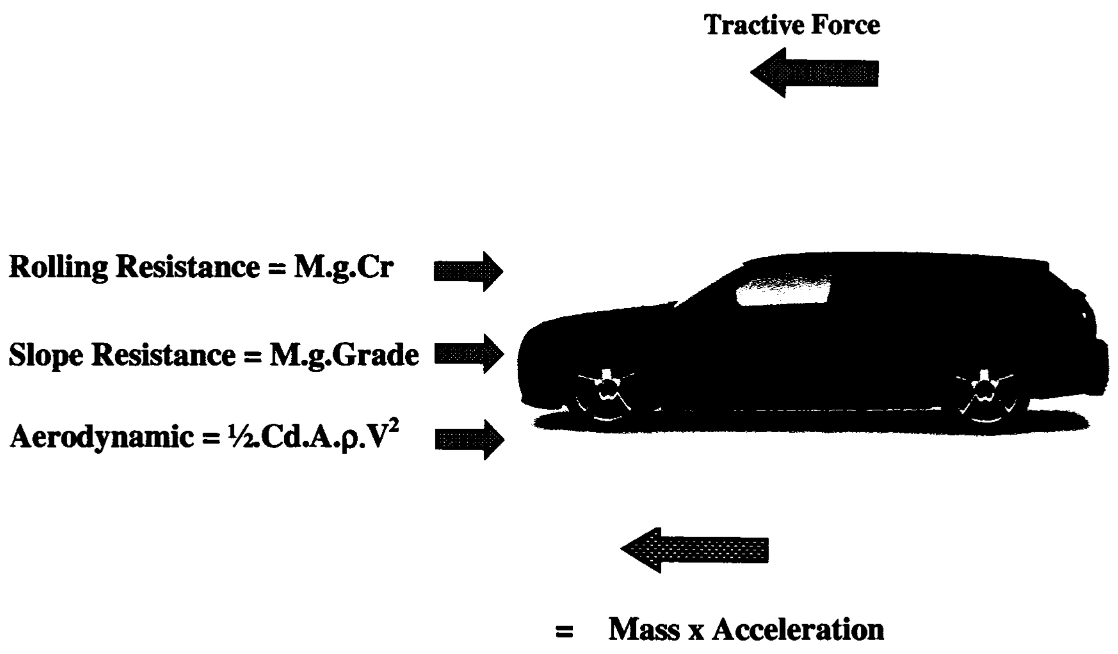


Figure C-1: Representative forces influencing vehicle motion.

Net Force = Tractive – Rolling Resistance – Slope Resistance – Aerodynamic

= Mass x Acceleration

Equation C-1: The dynamic forces that influence vehicle motion.

$$\textbf{Tractive Force} = (M.a) + (M.g.Cr) + (M.g.Grade) + (\tfrac{1}{2}.Cd.A.\rho.V^2)$$

Equation C-2: Re-arrangement of the dynamic forces that influence vehicle

$$\textbf{Tractive Power} = \textbf{Tractive Force} \times \textbf{Vehicle Speed, V}$$

Equation C-3: Instantaneous tractive power (in kW) is known if instantaneous vehicle speed (in m/s) is obtained.

where,

M:	Vehicle mass (kg)
a:	Acceleration (m/s^2)
g:	Gravitational acceleration (m/s^2)
Cr:	Coefficient of rolling resistance
Grade:	Slope of road (rise/horizontal)
Cd:	Coefficient of drag
A:	Vehicle frontal area (m^2)
ρ:	Density of air (kg/m^3)
V:	Vehicle speed (km/hr)

APPENDIX D

Emission and Fuel Consumption Functions used in CALMOB6

Appendix D gives all the emission and fuel consumption functions that have been employed by CALMOB6. These are power-based functions and are given for the gasoline and diesel fuelled vehicles.

D.1 INTRODUCTION

The emissions and fuel consumption functions give the fuel consumption and emission rates respectively. These rates are on a gram per second basis or gram per kilowatt-hour basis. E&FC are given as a function of the engine power developed. Fuel consumption functions have been developed for both the gasoline and the diesel fuelled vehicles [1, 2]. Emissions functions have been developed for carbon monoxide, hydrocarbon, nitrogen oxides and the particulates. Carbon dioxide emissions, on the other hand, are based on a fuel-emissions mass balance.

All the E&FC functions for gasoline vehicles were obtained by running a laboratory engine dynamometer. As for the diesel-fuelled vehicles, only the fuel consumption function was obtained from a laboratory engine dynamometer. Datasets from a 4-stroke medium-duty diesel truck engine (Isuzu) was used to derive CO and NOx emission functions. Similarly, HC and PM emission functions were obtained by running a 2-stoke Detroit diesel bus engine.

Different sets of equations were derived according to the heavy-duty vehicle instantaneous velocities. For example, if the vehicle is accelerating (with actual velocity higher than the previous instantaneous velocity) then the functions below indicated with A=1 (Max Torque test) were used; else those indicated A=0 (13 Mode test) were considered for cruising, idling and decelerating trucks. Pmax, as denoted in Figures D-4 – D-7, is the maximum power that these engines could develop. These are the power limits, assumed for the heavy-duty vehicles. They are tabulated in Table A-4.

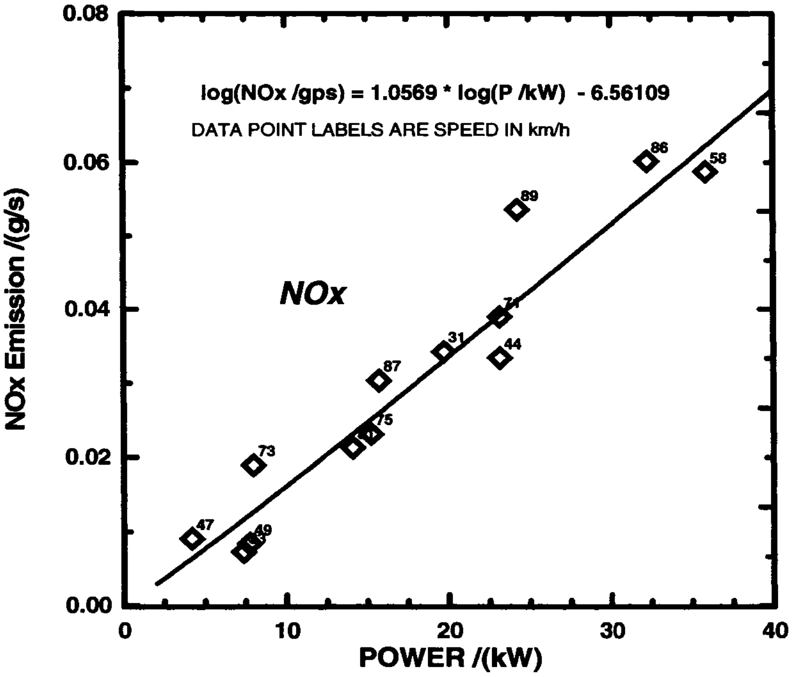


Figure D-1: Power based emission functions of NOx for a GASOLINE-fuelled vehicle [1].

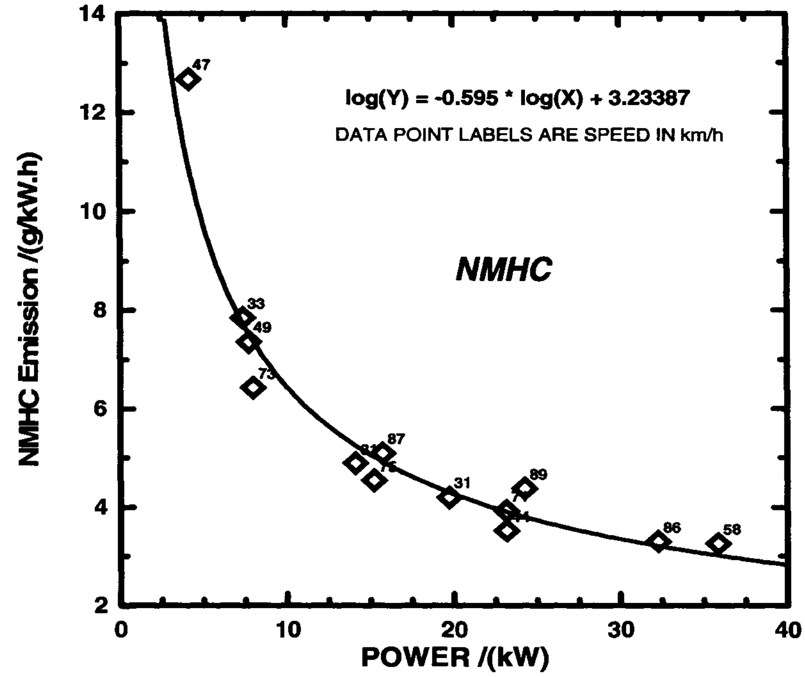


Figure D-2: Power based emission functions of NMHC for a GASOLINE-fuelled vehicle [1].

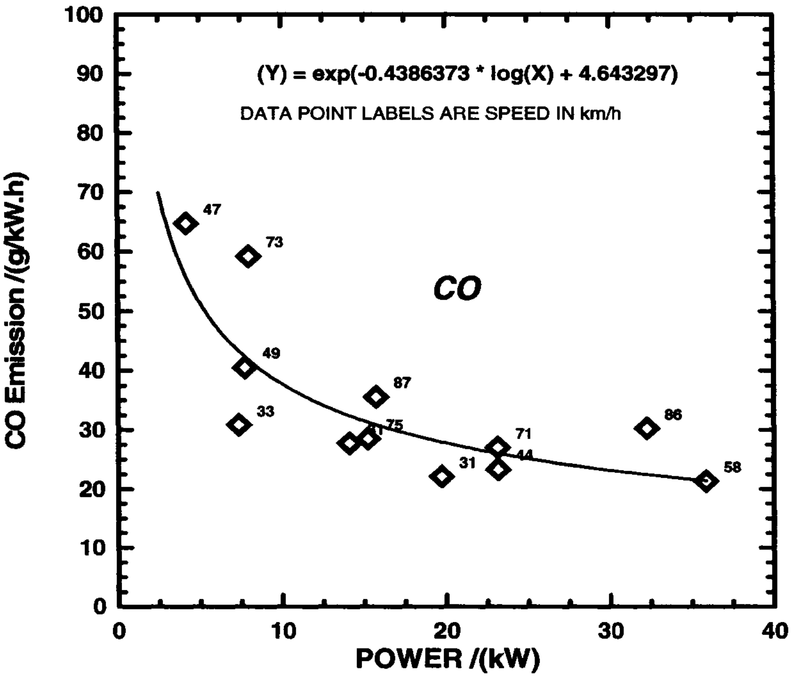


Figure D-3: Power based emission functions of CO for a GASOLINE-fuelled vehicle [1].

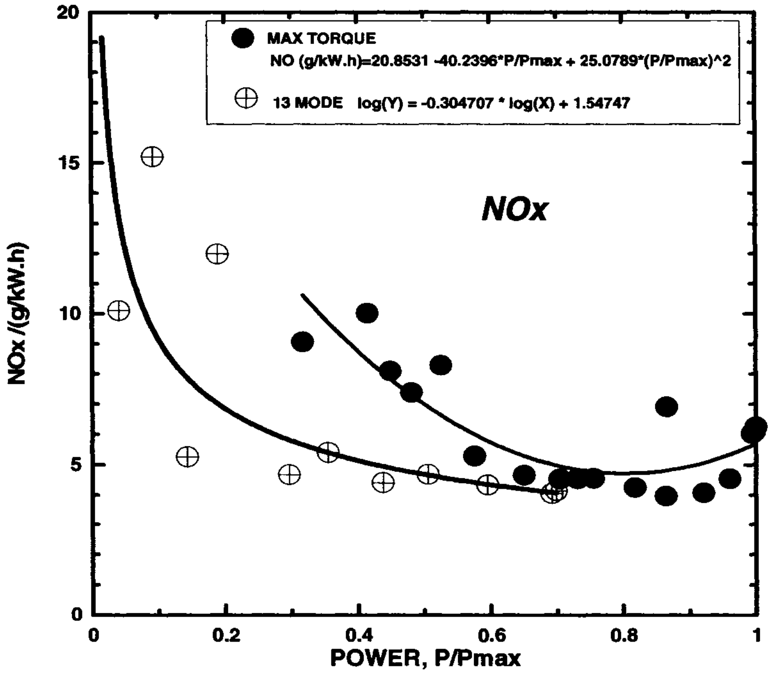


Figure D-4: Power based emissions functions of NOx for a DIESEL-fuelled vehicle [4].

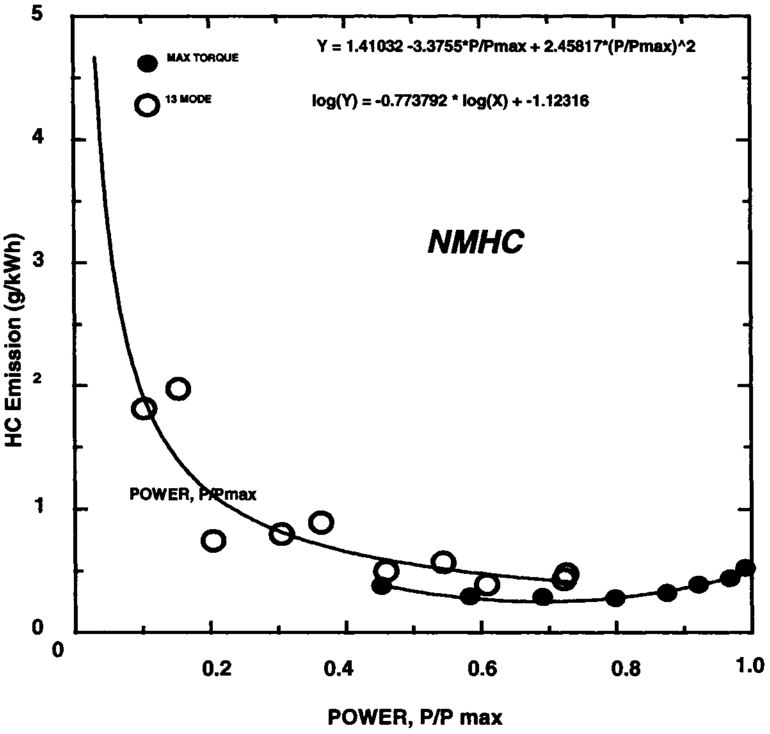


Figure D-5: Power based emissions functions of NMHC for a DIESEL-fuelled vehicle [4].

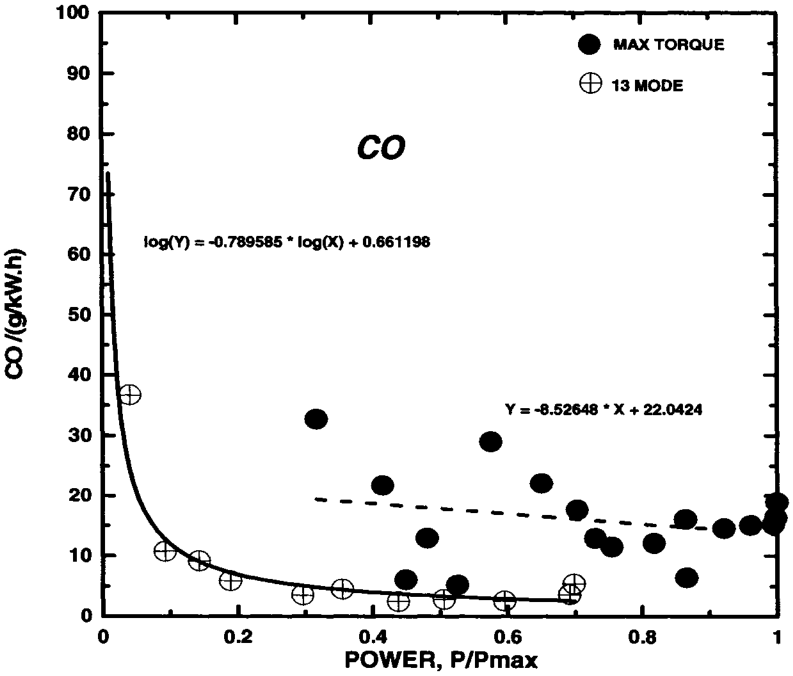


Figure D-6: Power based emissions functions of CO for a DIESEL-fuelled vehicle [4].

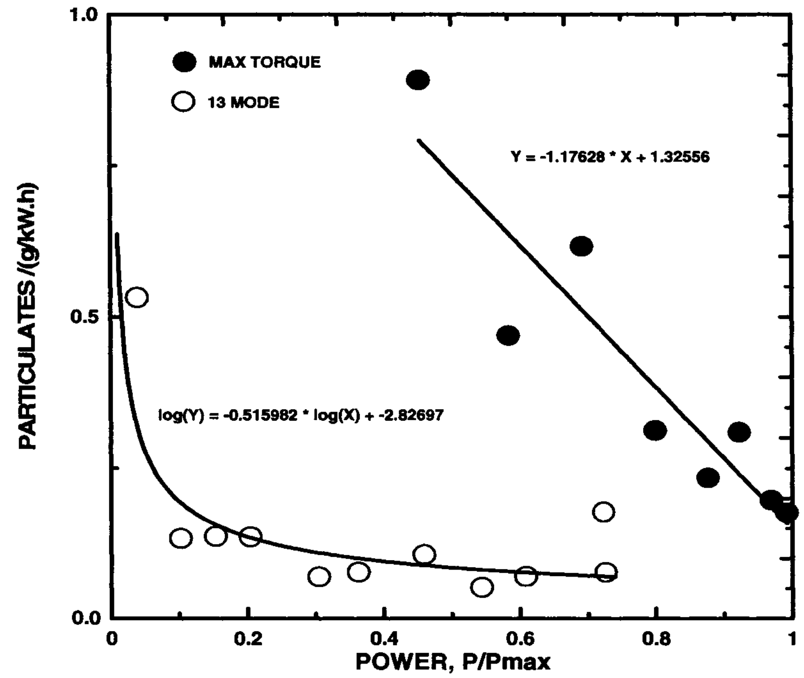


Figure D-7: Power based emissions functions of PM for a DIESEL-fuelled vehicle [4].

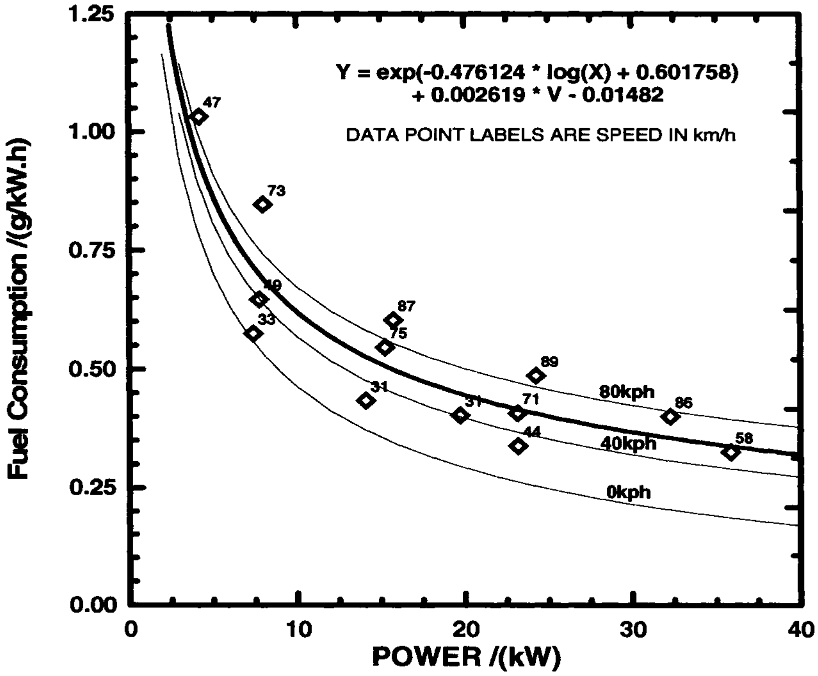


Figure D-8: Power based fuel consumption functions for GASOLINE vehicles [1].

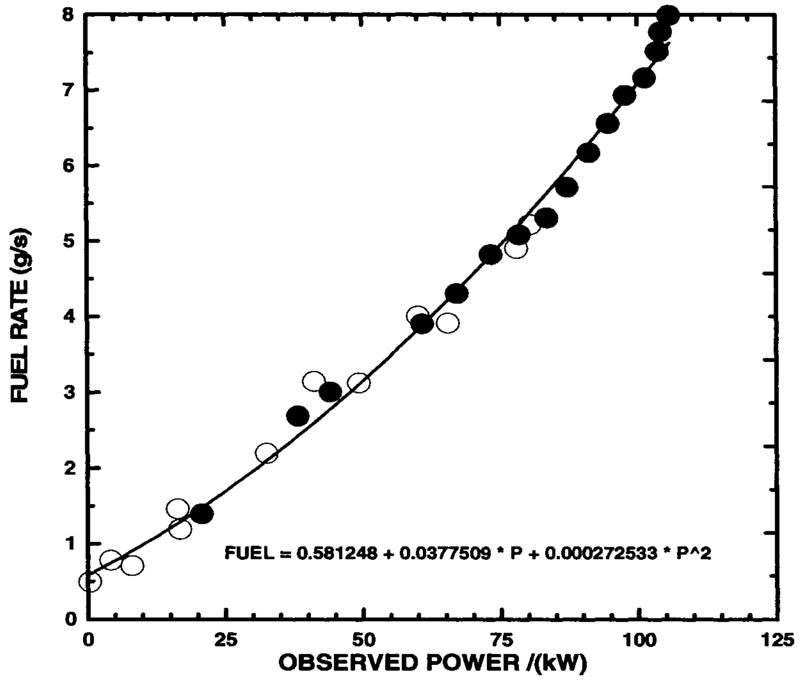


Figure D-9: Power based fuel consumption function for DIESEL vehicles [4].

REFERENCES

1. Checkel, M.D., "Vehicle Emissions Project – The City of Edmonton Transportation Master Plan", Mar 1996.
2. Checkel, M.D., "Truck and Bus Engine Emissions – The City of Edmonton Transportation Master Plan", Nov 1996.

APPENDIX E

Report of the Literature-Obtained Emission and Fuel Consumption Functions for the Heavy-Duty Diesel Vehicles

Appendix E gives a literature review of the heavy-duty diesel emission and fuel consumption functions. Emission functions were obtained from different technical literatures reviews. Diesel fuel consumption data were obtained from a new engine certification test. This dataset has been plotted to retrieve the relationship between the fuel consumption rates with the instantaneous power developed. Finally, the emissions and fuel consumption functions obtained from technical literatures are compared with those previously obtained for EMITPP06.

E.1 EMISSION FUNCTIONS FOR THE HEAVY DUTY DIESEL VEHICLES AND BUSES

Oxides of nitrogen (NOx) and particulate matter (PM) are mainly contributed by the diesel engines whereas gasoline engines contribute significant carbon monoxide (CO) and hydrocarbons (HC) emissions.

West Virginia University (WVU) [1] has developed an extensive database of continuous transient gaseous emissions levels from a particular transit bus (Model year: 1989, GVW: 36,900lb, Test Weight: 19249lb) and a tractor truck (Model Year: 1992, GVW: 80,000lb, Test Weight: 41,953lb). Each of the vehicles is powered by a Detroit Diesel 6V-92 engine having horsepower 253hp (188kW) and 300hp (223kW) respectively. The workers have tried correlating emissions with the real world activity in terms of the instantaneous power delivered by the vehicle. Axle power was lone measured variable in the study. The transient cycles used to generate the continuous data were the Central Business District cycle (CBD), 5-peak WVU test cycle, WVU 5-mile route and the New York Composite cycle (NYComp). It was found that CO emissions could not be modeled reliably based on axle power. Only CO_2 and NOx emissions have shown reliable relationship with that parameter. (P: Instantaneous axle power, in kW)

For the transit bus, the following emission functions were obtained using the CBD (with, $R^2 = 0.9744$ for CO_2 and $R^2 = 0.9014$ for NOx) and NYComp cycles (with, $R^2 = 0.9561$ for CO_2 and $R^2 = 0.9098$ for NOx):

i. **E-CO_2 (g/s) = $-0.001P^2 + 0.3234P + 3.0112$** ....*Eq E-1*

ii. **E-*NOx* (g/s) = $-2E\text{-}5P^2 + 0.0031P + 0.0405$,** ....*Eq E-2*

Using the 5-peak WVU ($R^2 = 0.8581$) and the CBD cycles ($R^2 = 0.3567$), the following emission functions were obtained for the tractor truck:

i. **E-*NOx* (g/s) = $-3E\text{-}6P^2 + 0.0031P + 0.0315$,** using ... *Eq E-3*

Jarett *et al* [2] obtained continuous PM data using a Tapered Element Oscillating Microbalance (TEOM). Reasonable correlation was found between TEOM data integrated over the cycle and conventional PM filter data. Accurate prediction of particulate matter formation is complicated by the nature PM. It consists of elemental carbon, organic carbon (from unburnt fuel and lubricating oils), metals from fuel and engine wear and sulfates. The TEOM unit measures PM mass, mass rate and mass concentration from diluted engine emissions. Similar to Ramamurthy *et al* [1], instantaneous power and TEOM data were time aligned to match peaks or compensate for the exhaust-gas transport delay; power is otherwise dispersed in time artificially to match the real dispersion of the species being measured.

PM data were collected from four chassis tests of a refuse truck powered by a 1999 Cummins M11-300 engine exercised through a double CBD cycle. An improvement in the relation between continuous engine parameters and continuous measured emissions, when instantaneous power is dispersed, is demonstrated in the following equations:

i. **E-*PM* (mg/s) = $\mathbf{0.0505P_h - 0.745}$**, $R^2 = 0.7046$, (instantaneous power)..*Eq E-4*

ii. **E-*PM* (mg/s) = $\mathbf{0.0722P_h - 1.5089}$**, $R^2 = 0.82$, (dispersed axle power)...*Eq E-5*

(where, P_h: axle power, in hp & 1hp =0.7457kW [5])

For the emission inventory case, it is clear that the above TEOM data would impose difficulties due to the negative values. This can happen during deceleration and near-steady state operation when power is less than 20.9 hp in Equation E-5.

Recently, Xu *et al* [5] compared the Tapered Element Oscillating Microbalance (TEOM), used to characterize PM from the dilute exhaust of trucks, with the traditional particulate filter weighing. Different test cycles were used in the study:

Idle, UDDS, Creep, Transient, Cruise and HHDDT_S. On average, TEOM results were approximately 6% lower. Equation E-6 demonstrates a good correlation that was obtained when twenty-two trucks were exercised through the Transient cycle.

$$\boldsymbol{PM_{\text{TEOM}} = 0.9387 \times PM_{\text{Filter}} - 0.0519}, \quad R^2 = 0.9924 \;\ldots\ldots\ldots\ldots \textit{Eq E-6}$$

Substituting the PM_{TEOM} in *Eq E.6* with E-*PM* in *Eq E.5*, yields:

$$\boldsymbol{PM_{\text{Filter}} = 0.0769 \times Ph - 1.5522} \;\ldots\ldots\ldots\ldots \textit{Eq E-7}$$

Clark *et al* [4] argued that in absence of any better information, when instantaneous power was needed, the total PM could be distributed in time over the test in proportion to the CO measurement at that time. This apportioning of PM along continuous CO may provide a more realistic model for the PM inventory calculation to thereby avoid negative E-*PM* values.

$$\textbf{E-}\boldsymbol{PM}\textbf{pr (mg/s)} = \boldsymbol{0.4312\,(\text{E-}PM^{*}) + 0.9884}, \quad R^2 = 0.517 \;\ldots\ldots\ldots\ldots \textit{Eq E-8}$$

where,

E-*PM*pr is the predicted PM mass rate (mg/s), and

E-*PM** is the moisture-corrected PM mass rate (mg/s).

Assuming that the PM rate in *Eq E.5* is moisture corrected, E-*PM** in *Eq E.8* can be substituted with PM_{Filter} in *Eq E.7* to yield:

$$\textbf{E-}\boldsymbol{PM}\textbf{pr (mg/s)} = \boldsymbol{0.0311Ph + 0.3191} \;\ldots\ldots\ldots\ldots\ldots\ldots \textit{Eq E-9}$$

Rearranging *Eq E.9* such that power is in kW yields:

$$\textbf{E-PM (mg/s)} = \boldsymbol{0.0247P + 0.3191} \;\ldots\ldots\ldots\ldots\ldots\ldots \textit{Eq E-10}$$

Moreover, Xu et al [5] confirmed that there was no overall relationship between CO and PM integrated over the test schedule. This applied to the fleet of twenty-three trucks analyzed. The PM/CO ratio varied significantly from engine to engine and ranged from 0.06 to 0.83.

However, a strong relationship between the PM and the CO can be found when reviewing the emissions data obtained for a single truck. A reliable correlation was obtained when a 2004 Freightliner truck powered by a Detroit Diesel Company (DDC) Series 60 engine, operated over the following conditions: idle, UDDS, Creep, Transient, Cruise and HHDDT_S modes at 30,000lb, 56,000lb and 66,000lb test weight. Equations *E-11* and *E-12* describe the relationship.

PM (g/cycle) = 0.2692 x CO (g/cycle) – 2.983, $R^2 = 0.9938$ ....*Eq E-11*

PM (g/cycle) = 0.2405 x CO (g/cycle), $R^2 = 0.9715$ ...... *Eq E-12*

Assuming the change of CO over time for a particular cycle varies exactly the same way that PM does, we can combine *Eq E.10* with either *Eqs E.11* or *E.12* to have a relationship between CO and the instantaneous power (in kW).

E-CO (g/s) = 11. 0822 + (9.1753 E-5) P, (comb. Eqs E.10 and E.11)........*Eq E-13*

E-CO (g/s) = 1.3268 E-3 + (1.0270 E-4) P, (comb. Eqs E.10 and E.12)...*Eq E-14*

Obviously, *Eq E.13* demonstrates an unrealistic assumption with an approximate CO emission rate of over 11 g/s at no power. This is incredibly high. *Eq E.14*, however, gives a better overall picture of the rate of carbon monoxide emissions for the heavy-duty vehicles. The latter equation can be employed.

E.2 FUEL CONSUMPTION FUNCTIONS FOR THE HEAVY DUTY DIESEL VEHICLES

Information regarding the fuel consumption rate was obtained from the detailed results of measurements made on a heavy-duty diesel engine. These results are proprietary to the engine manufacturer. A good correlation relating the

'Corrected' diesel fuel consumption and the developed power was obtained. Plots were made against both the measured power and the net power. The latter is a sum of the measured power, power delivered to auxiliaries, power delivered to fan, and some power correction factors.

E.3 E&FC FUNCTIONS DERIVED FOR HEAVY DUTY DIESEL VEHICLES AND BUSES IN EMMEPP (2001) & EMITPP06 (1996) [6]

For the EMITPP06 and EMMEPP programs, functions were developed for both the 2- and 4-Stroke diesel engines. In the programs, the latter engines were truck based whereas the 2-stroke engines were for the buses; given that majority of the buses were propelled by such engines. It was suggested that functions for the 4-Stroke engines be applied for the buses as of 2005 since it was predicted that a complete turnover of the bus fleet with 4-Stroke engines be effective by this time. Nowadays, only part the Edmonton Transit System fleet (bus) is 2-stroke engine.

Moreover, different sets of equations were according to the vehicle instantaneous velocities. For example, if the vehicle is accelerating (with actual velocity higher than the previous instantaneous velocity) then the functions below indicated with A=1 (Max Torque test) were used; else those indicated A=0 (13 Mode test) were considered for cruising, idling and decelerating trucks.

Emissions and fuel consumption functions were extracted from the resulting data collected from the tests performed on a 2-Stroke Detroit Diesel Bus Engine and a 4-Stroke Isuzu Truck Engine. Pmax, as denoted in the following equations, is the maximum power that these engines could develop. In the post processors, 2-stroke engine functions were used for the buses and the 4-stroke engine functions for the trucks except otherwise stated. CALMOB6 uses functions for the 4-stroke engines, except for particulates where functions are for 2-stroke engine solely.

Fuel Consumption

$\mathrm{Fuel\ (g/s)} = 0.7373 + (5.895\mathrm{E}{-2})\ P + (8.5375\mathrm{E}{-5})\ P^2$, ...*Eq E-15*

CO Emissions

2-Stroke

$\mathrm{CO\ (g/s)} = P * \exp(0.94466 - 0.5645 * \log(P / \mathrm{Pmax})) / 3600$, A=0,...*Eq E-16*

$\mathrm{CO\ (g/s)} = P * (145.389 - 140.702 * P / \mathrm{Pmax}) / 3600$, A=1, ...*Eq E-17*

4-Stroke

$\mathrm{CO\ (g/s)} = P * \exp(0.6612 - 0.78959 * \log(P / \mathrm{Pmax})) / 3600$, A=0, ...*Eq E-18*

$\mathrm{CO\ (g/s)} = P * (22.04 - 8.526 * P / \mathrm{Pmax}) / 3600$, A=1, ... *Eq E-19*

NMHC Emissions

2-Stroke

$\mathrm{HC\ (g/s)} = P * \exp(-1.1232 - 0.7738 * \log(P / \mathrm{Pmax})) / 3600$, A=0, ...*Eq E-20*

$\mathrm{HC\ (g/s)} = P * (1.41 - 3.376 * P / \mathrm{Pmax} + 2.458 * (P / \mathrm{Pmax}) \wedge 2) / 3600$, A=1, ... *Eq E-21*

4-Stroke

$\mathrm{HC\ (g/s)} = P * \exp(-1.8258 - 0.9623 * \log(P / \mathrm{Pmax})) / 3600$, A=0, ...*Eq E-22*

$\mathrm{HC\ (g/s)} = P * (0.7283 - 1.7169 * P / \mathrm{Pmax} + 1.1275 * (P / \mathrm{Pmax}) \wedge 2) / 3600$, A=1, ... *Eq E-23*

In the post processors, only the 2-stroke HC emission functions were applied. This is so because the corresponding functions for the different stroke engine are similar [6].

NOx Emissions

2-Stroke

$\mathrm{NOx\ (g/s)} = P * \exp(2.4285 - 0.397 * \log(P / \mathrm{Pmax})) / 3600$, A= 0, ... *Eq E-24*

NOx (g/s) = P * (14.721 - 25.852 * P / Pmax + 25.397 * (P / Pmax) ^ 2) / 3600, A=1, ... *Eq E-25*

4-Stroke

NOx (g/s) = P * exp(1.5475 - 0.030471 * log(P / Pmax))/ 3600, A=0, ...*Eq E-26*

NOx (g/s) = P* (20.8531 - 40.2396 * P / Pmax + 25.0789 * (P / Pmax) ^ 2) / 3600, A=1, ... *Eq E-27*

Particulate Emissions

2-Stroke

Part (g/s) = P * exp(-2.827 - 0.516 * log(P / Pmax)) / 3600, A= 0, ...*Eq E-28*

Part (g/s) = P * (1.3256 - 1.1763 * P / Pmax)/ 3600, A=1, ...*Eq E-29*

The functional form for the particulates emissions appeared to work well with a range of 2- and 4 stroke engines [6]. Hence, it was used for all diesel engines but with different adjustment factors for different fleets.

CO_2 Emissions

Carbon dioxide emissions are calculated after a mass balance analysis. Mass of fuel consumed and the resulting amount of carbon monoxide emissions are used to estimate such emissions.

The Equations *E-1* – *E-14* were made on 4-stroke engines. Hence, emission functions that were developed for 4-stroke engine only will be compared but the particulates functions.

The following graphs (illustrated in Figures E-1 – E-4) were obtained when a power limit, Pmax, of 300 kW was assumed. *A=0* and *A=1* functions were previously used. *N*-indicated functions are the newly obtained functions from technical literatures.

(i) NOx Emissions

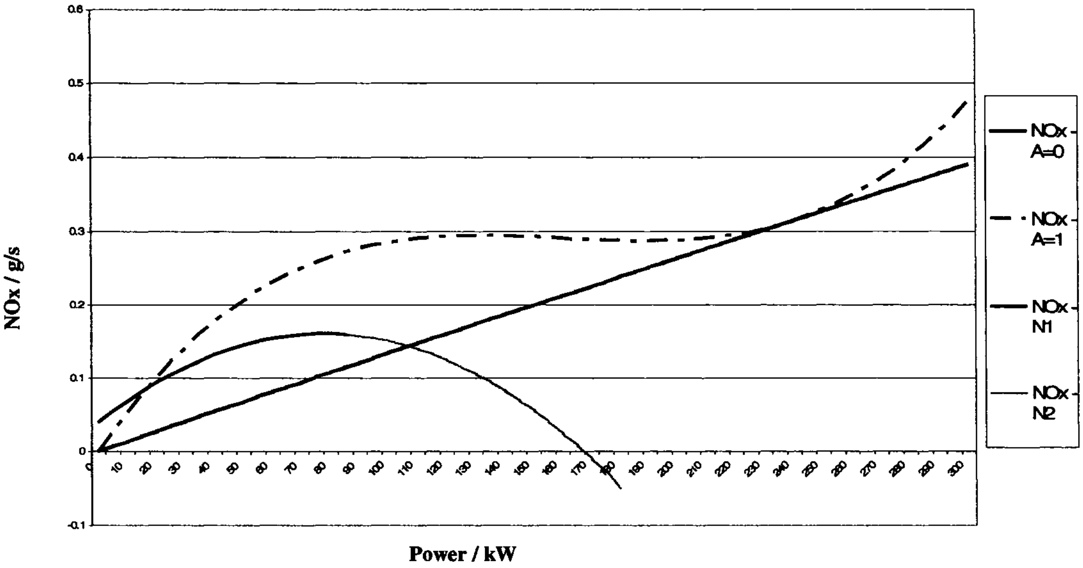


Figure E-1: NOx Emission Rate as a function of Power in kW.

Note:

1. Experimental values obtained by Ramamurthy *et al* [1] is labeled as [NOx-N1] and [NOx-N2]. It is worth pointing out that such data were valid up to a maximum of 80-85 kW, as indicated by [NOx-N1]. Thereafter, negative slope was obtained as described by curve [NOx-N2].
2. Experimental values obtained by Checkel [6] are labeled [NOx-A=1] for the accelerating truck and [NOx-A=0] for the decelerating, idling or cruising ones.
3. Hence, up to a power of 80 kW, both experimental values follow similar trends.

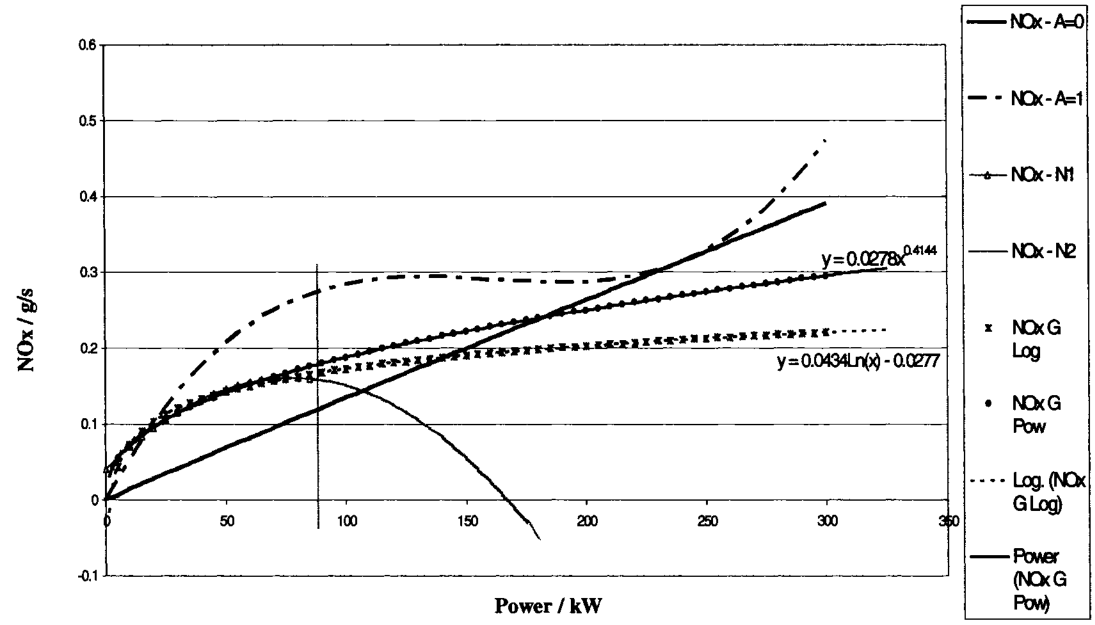


Figure E-2: Estimated trend in NOx Emissions Rate at higher powers (> 80 kW).

Note (Cont):

4. The data obtained by Ramamurthy *et al* [1] were extrapolated to beyond 80 kW. Power and Logarithmic functions were used to observe a possible trend. The coefficients of determination are 0.911 and 0.9732 respectively.

5. It is observed that a better estimate is possible by using the Power law. At low powers (<80 kW), the curve closely match the experimental values. At higher powers, the curve is closer to the experimentally obtained dataset of Checkel [6].

6. Thus, equation $y = 0.0278x^{0.4144}$ can be used in CALMOB6 for estimating emissions of NOx for the heavy-duty diesel engines (HDDV's and buses).

(ii) PM Emissions

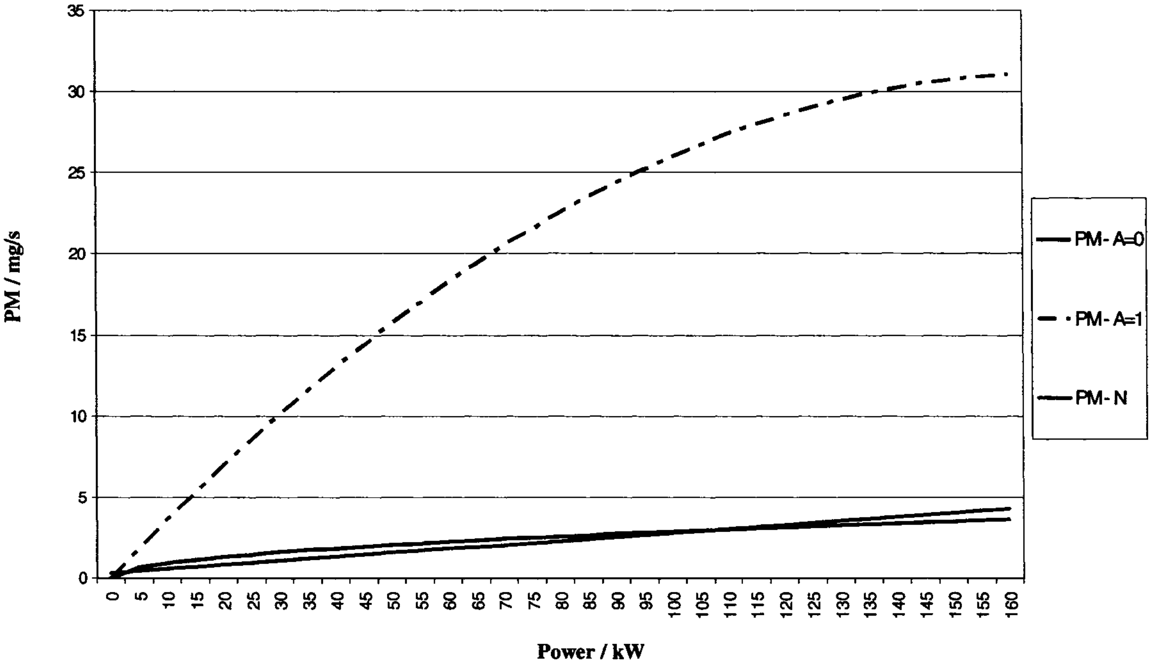


Figure E-3: PM Emission Functions.

Note:

1. The PM emission function [PM-N] obtained by Xu et al [5] was adjusted to the description of Jarett *et al* [2]. The modified function can be used in CALMOB6. It reflects very much the same trend obtained previously; i.e. [PM – A=1].

(iii) CO Emissions

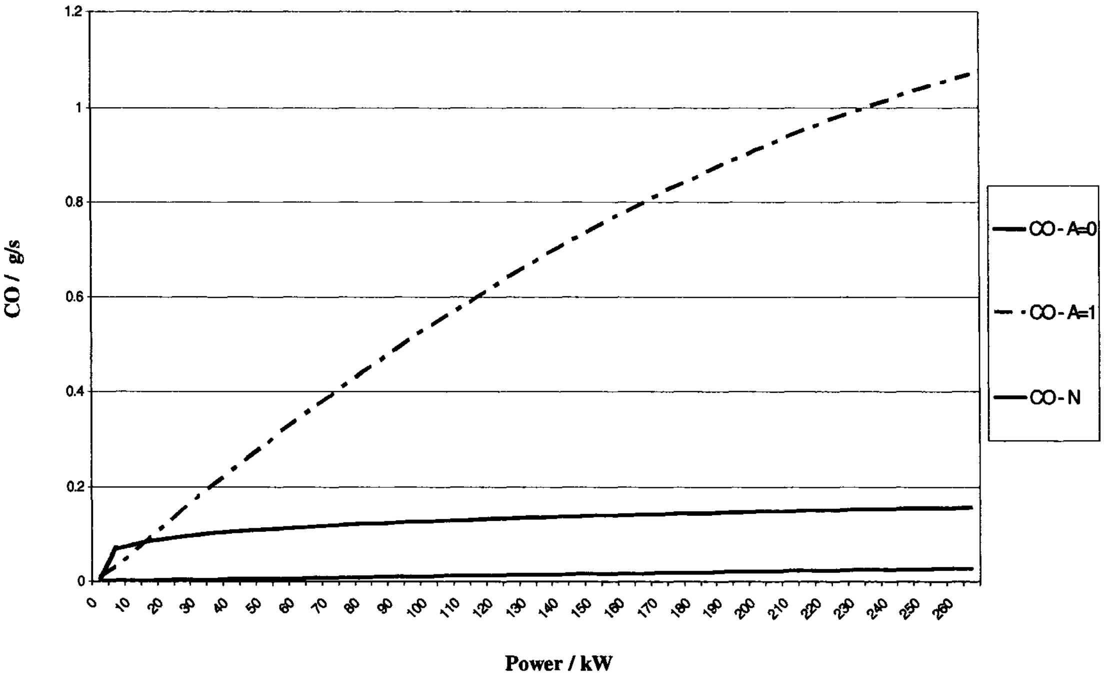


Figure E-4: CO Emission rate in g/s as a function of Power in kW.

Note:

1. The function obtained by Clark *et al* [after combining results from references 3, 4 & 6] [CO-N] is merely a downward shift from that obtained previously by Checkel [6] [CO – A=1]. Hence, it is clear that the new function can be adjusted by the calibration factors set in CALMOB6 and thereafter be used for CO emission estimates.

(iv) HC Emissions

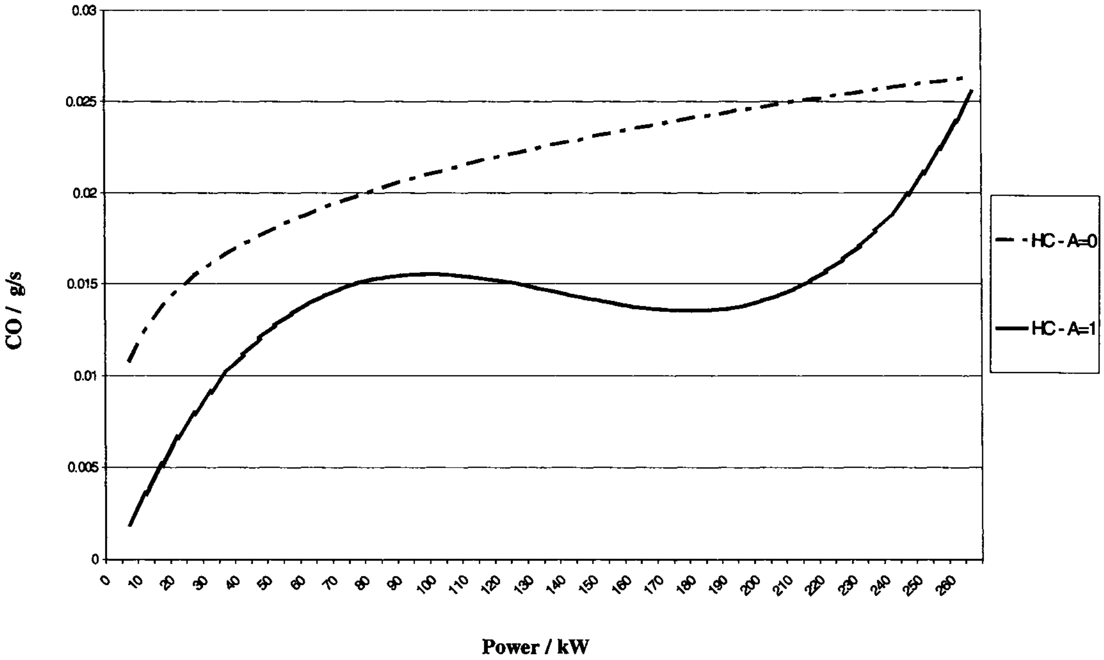


Figure E-5: HC Emission rate in g/s as a function of Power in kW.

Note:

1. No better estimate was obtained as concern the HC Emission and Diesel Fuel Consumption functions for the HDDV's and Buses.

(v) Diesel Fuel Consumption

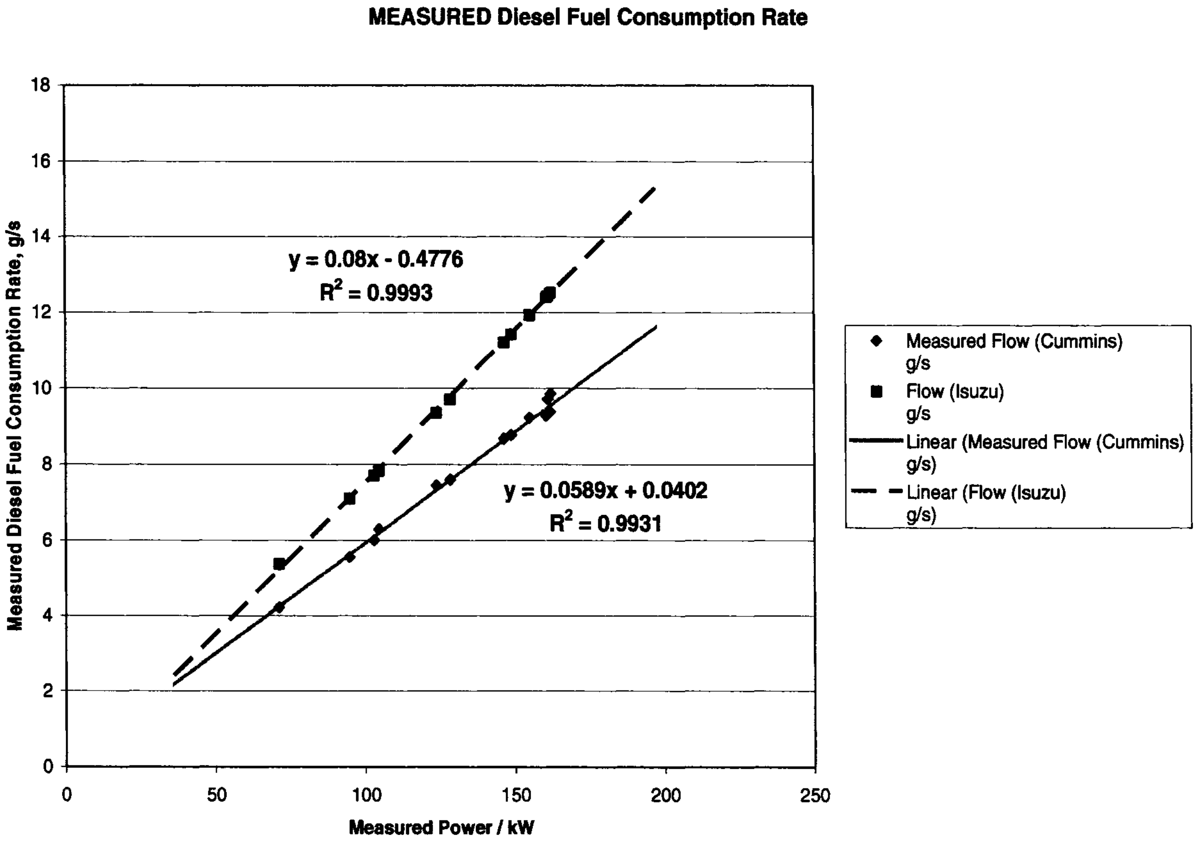


Figure E-6: MEASURED Diesel Fuel Consumption in g/s as a function of MEASURED Power / kW [7].

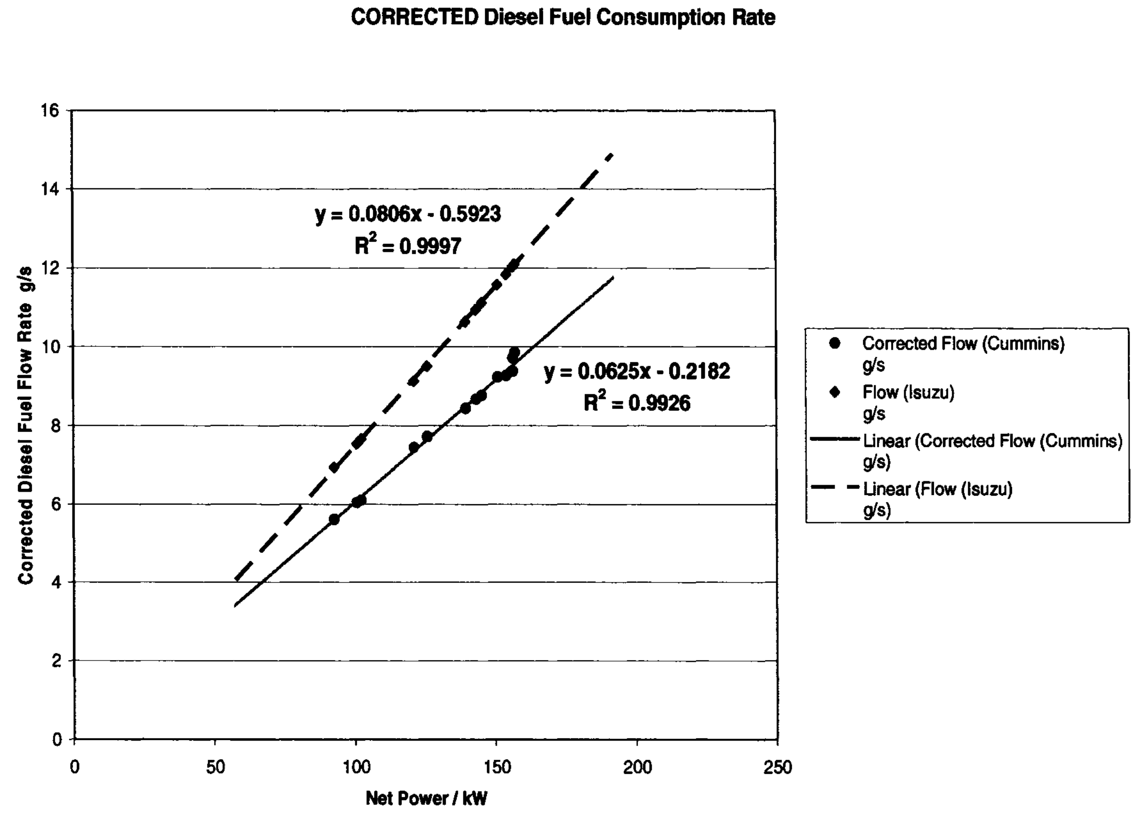


Figure E-7: CORRECTED Diesel Fuel Consumption in g/s as a function of CORRECTED Net Power / kW [7].

The diesel-consumption rate results are very satisfactory. The results obtained for the Corrected diesel fuel flow against Net power for the Cummins can be used in CALMOB6.

REFERENCES

1. Ramamurthy, R.; Clark, N.N.; Atkinson, C.A.; and Lyons, D.W., “Models for Predicting Transient Heavy Duty Vehicle Emissions”, SAE 982652, Oct 1998.
2. Jarett, R.P.; and Clark, N.N., “Evaluation of Methods for Determining Continuous Particulate Matter from Transient Testing of Heavy Duty Diesel Engines”, SAE 2001-01-3575, Sept 2001.
3. http://www.unit-conversion.info/power.html
4. Clark, N.N.; Jarett, R.P.; and Atkinson, C.M., “Field Measurements of Particulate Matter Emissions, Carbon Monoxide, and Exhaust Opacity from Heavy Duty Diesel Vehicles”, Journal of the Air & Waste Management Association, PA 15222,V49, p76, Sept 1999.
5. Xu, S.; Clark, N.N.; Gautam, M.; and Wayne, W.S., “Comparison of Heavy-Duty Truck Diesel Particulate Matter Measurement: TEOM and Traditional Filter”, SAE 2005-01-2153
6. Checkel, M.D, “Truck and Bus Engine Emissions – The City of Edmonton Transportation Master Plan”, Nov 1996.
7. Vehicle Certification Agency – Job No.: P99-00/2842, “Communication Concerning Approval Granted of A Engine Type With Regard To Emissions or Measurement of Power of The Engine only, Pursuant to Regulation No. 24R-03”, Jun 2000.

APPENDIX F

Fuel Consumption Trends

Appendix F presents the trends of fuel consumption rates for each of the light-duty and heavy-duty vehicle subclasses. These are applicable for both the diesel and gasoline fuelled vehicles.

F.1 INTRODUCTION

To calibrate the fuel consumption functions, accurate and reliable databases of fuel consumption is required. These databases can be used to estimate past and present fuels consumption amounts as well as predict them. Information from Natural Resources Canada (NR Can) is used to estimate gasoline passenger cars and light-duty trucks fuel consumption. As for the heavy-duty fleet and the diesel light duty vehicles, the United States Environmental Protection Agency (US EPA) databases are reliable.

F.2 LIGHT-DUTY GASOLINE VEHICLES

Natural Resources Canada [1, 2] has a database of rated fuel consumption values (in L/100km) for light-duty cars and trucks sold in Canada. These values are based on a 55%/45% split of City/Highway driving cycles. The yearly rate considers the annual vehicle sales and dates from 1979, extending to 2001. NR Canada describes the passenger car and light duty truck fleet as shown in Table F-1 which also gives the corresponding CALMOB6 vehicle class

Fuel consumption depends primarily on the vehicle type, mass and technology. It is important to isolate these three main factors to make better estimates of fuel consumption. Further, this will improve E&FC forecasts. To clarify the mass effect, fuel consumption was plotted against vehicle mass for same-type vehicles of a given model year. These are plotted in Figures F-1 – F-10. Subsequently, the mass effect of light duty vehicles has been removed and the resulting fuel consumption trend for gasoline cars are shown in Figures F-11 – F-17. Figure F-18 compares the resulting fuel consumption trends of all light-duty gasoline vehicles – cars and trucks. Finally, Figure F-19 compares the projected fuel consumption (FC) with that of a 1990 vehicle of same model.

NR Canada Class	**Description**	***CALMOB6 Categorization***
Cars		
1	Two Seater	***Mini***
2	Mini Compact	***Mini***
3	Sub Compact	***Mini***
4	Compact	***Mini***
5	Mid Size	***Economy***
6	Large	***Large/Luxury***
7	Small Wagons	***Mini***
8	Mid-Size Wagon	***Economy***
9	Large Wagons	***Large/Luxury***
Trucks		
10	Small Pickups	***LDT 1***
11	Passenger Vans	***LDT 1***
12	Small SUVs	***LDT 2***
13	Large Pickups	***LDT 3***
14	Cargo Vans	***LDT 3***
15	Large SUVs	***LDT 4***

Table F-1: Natural Resources Canada vehicle categories as re-categorized for CALMOB6 [1, 2].

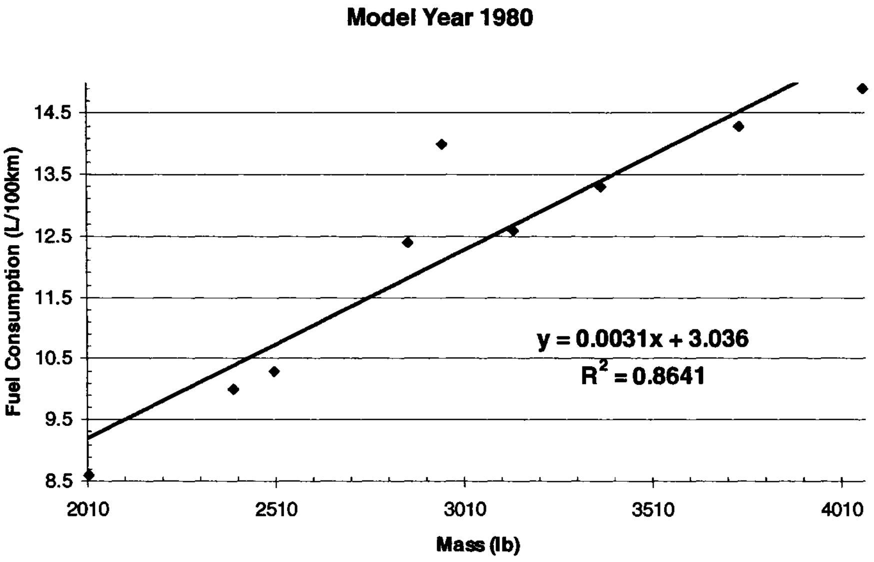


Figure F-1: Mass effect on gasoline fuel consumption for Passenger Cars of model year 1980.

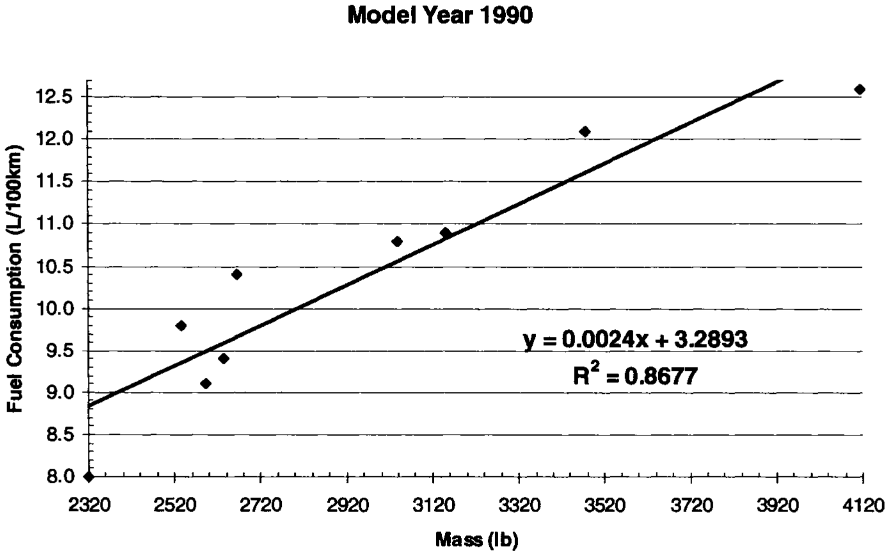


Figure F-2: Mass effect on gasoline fuel consumption for Passenger Cars of model year 1990.

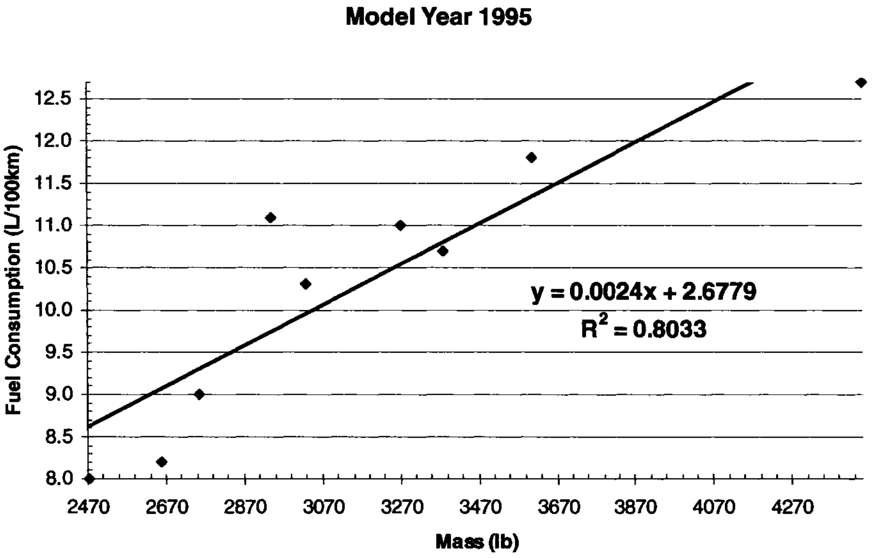


Figure F-3: Mass effect on gasoline fuel consumption for Passenger Cars of model year 1995.

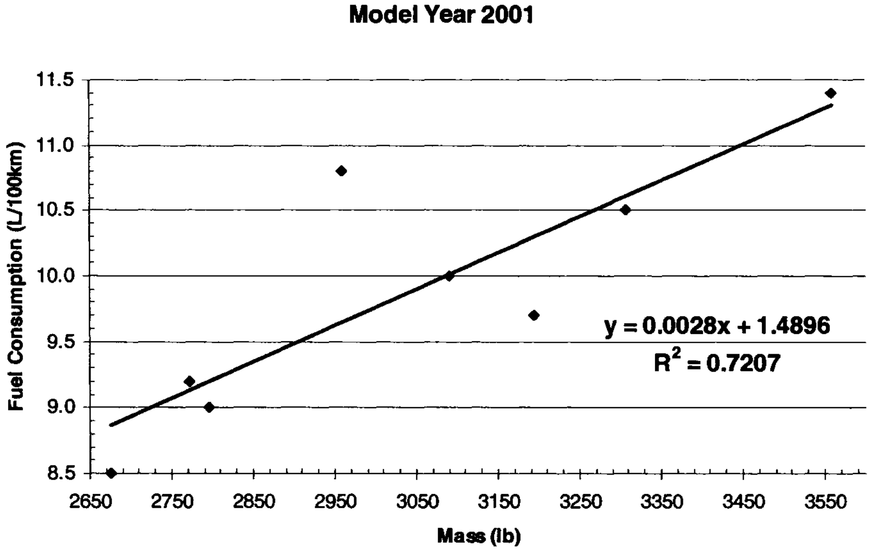


Figure F-4: Mass effect on gasoline fuel consumption for Passenger Cars of model year 1990.

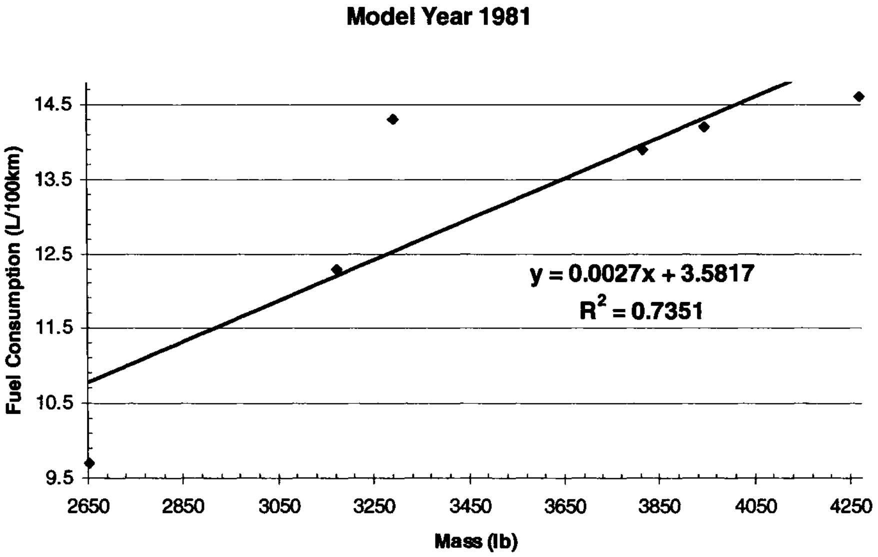


Figure F-5: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 1981.

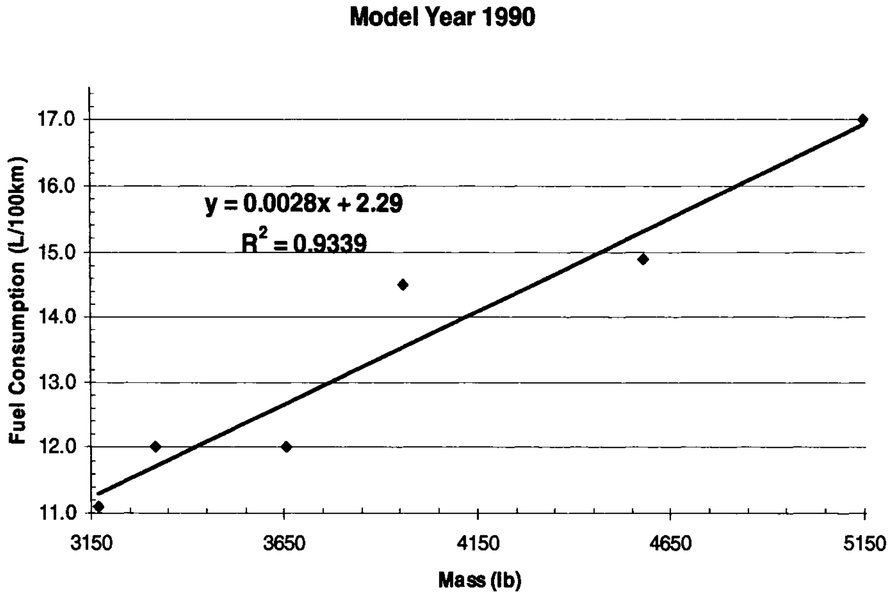


Figure F-6: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 1990.

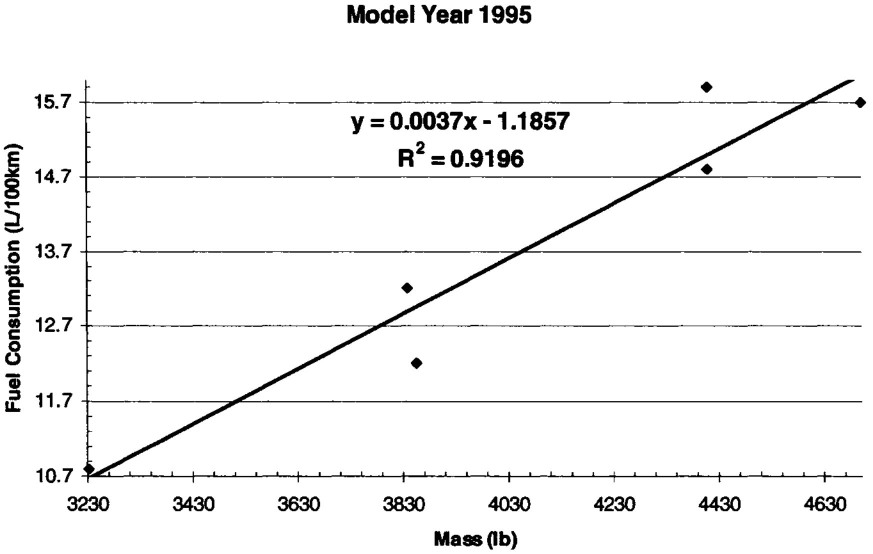


Figure F-7: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 1995.

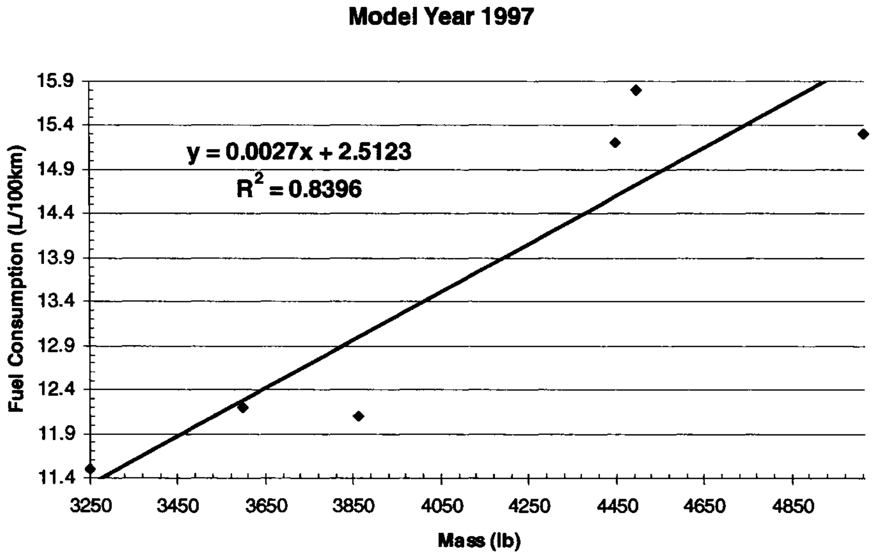


Figure F-8: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 1997.

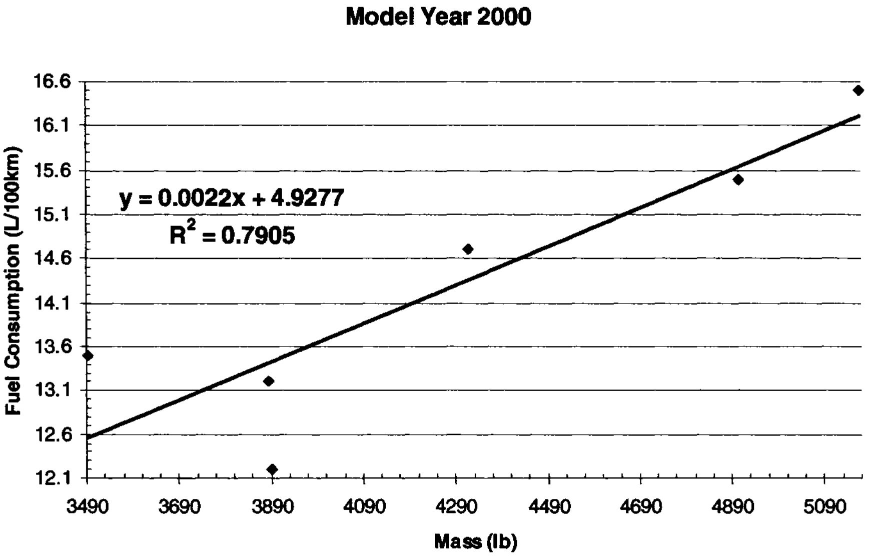


Figure F-9: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 2000.

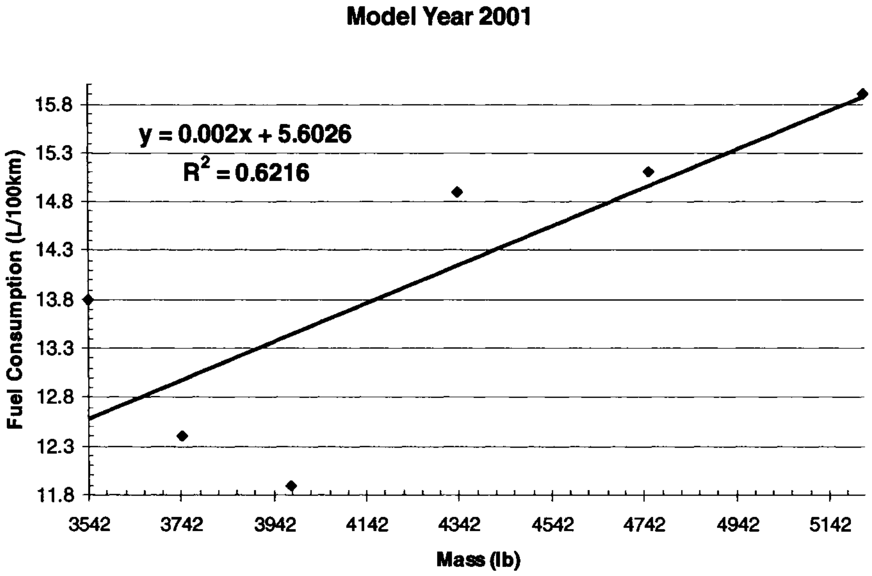


Figure F-10: Mass effect on gasoline fuel consumption for Light-Duty Trucks of model year 2001.

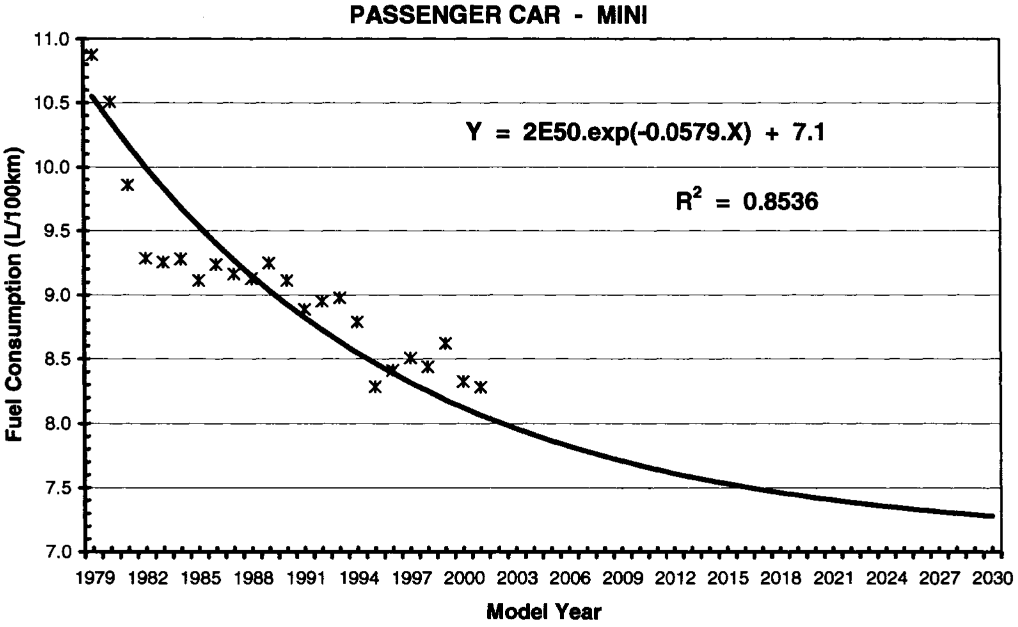


Figure F-13: MINI Car predicted fuel consumption (gasoline) trend extending up to 2030 (based on past values adjusted for fixed mass).

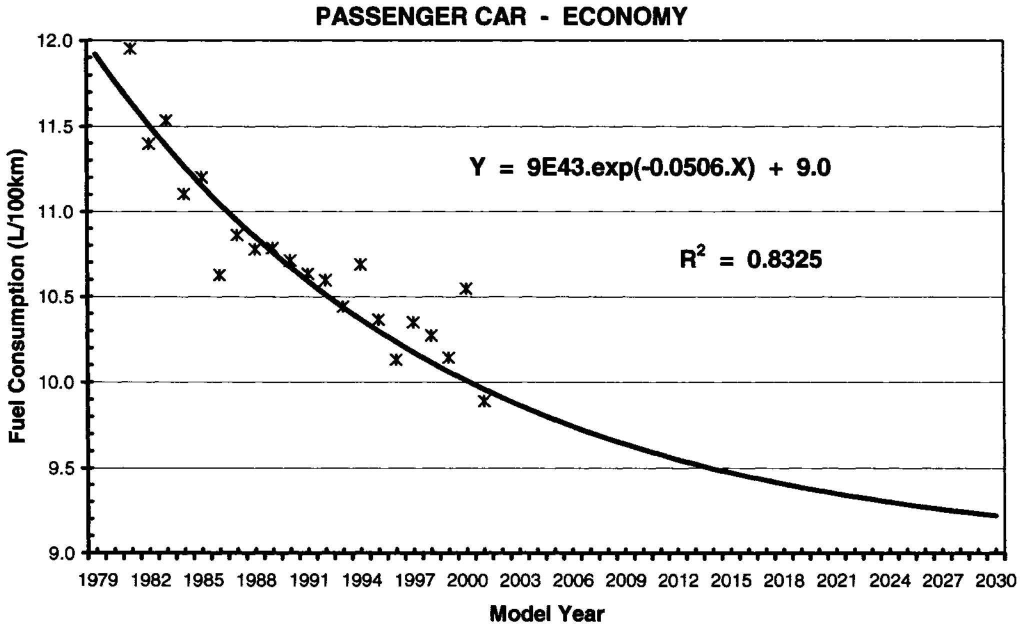


Figure F-12: ECONOMY Car predicted fuel consumption (gasoline) trend extending up to 2030 (based on past values adjusted for fixed mass).

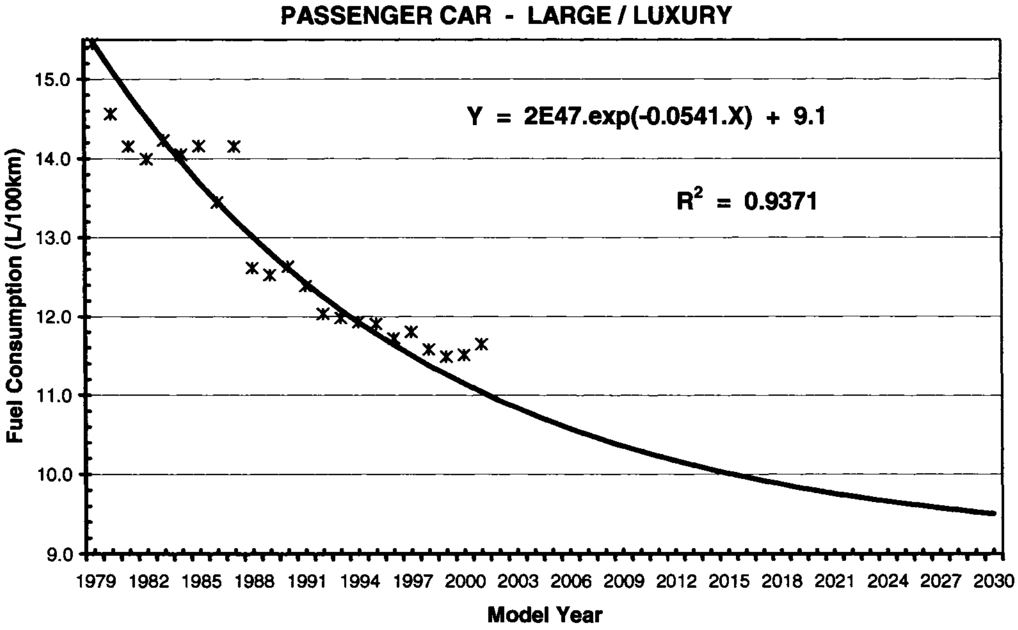


Figure F-13: LARGE / LUXURY Car predicted fuel consumption (gasoline) trend extending up to 2030 (adjusted for fixed mass).

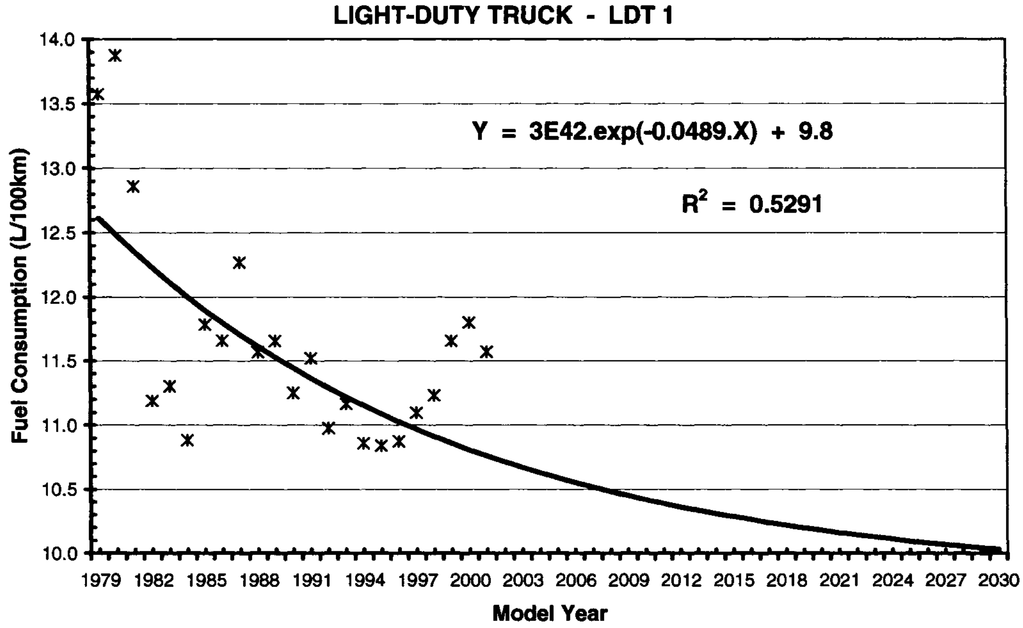


Figure F-14: LDT 1 predicted fuel consumption (gasoline) trend extending up to 2030 (adjusted for fixed mass).

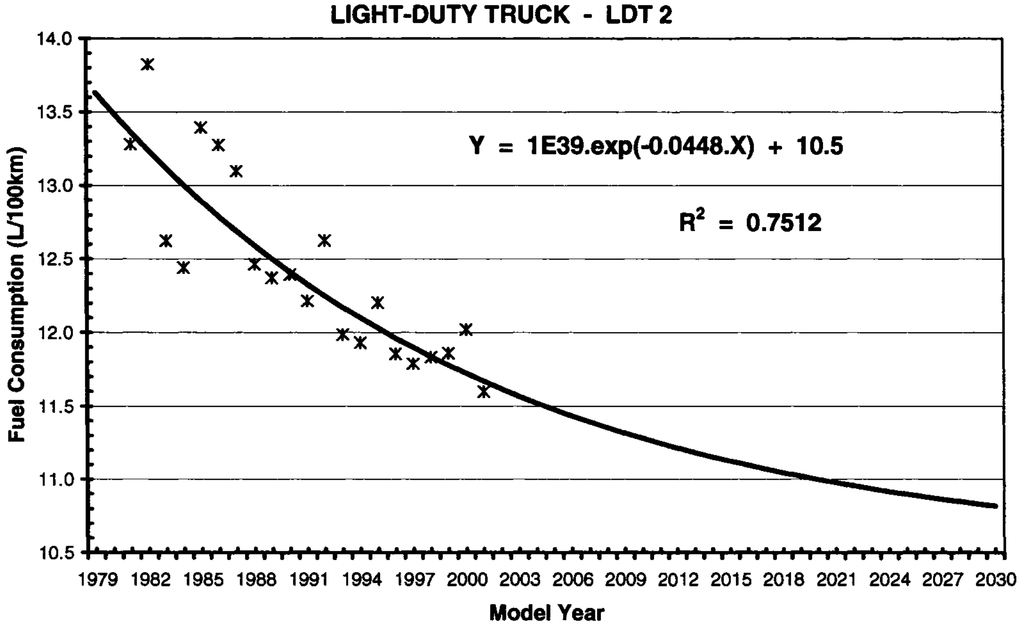


Figure F-15: LDT 2 predicted fuel consumption (gasoline) trend extending up to 2030 (adjusted for fixed mass).

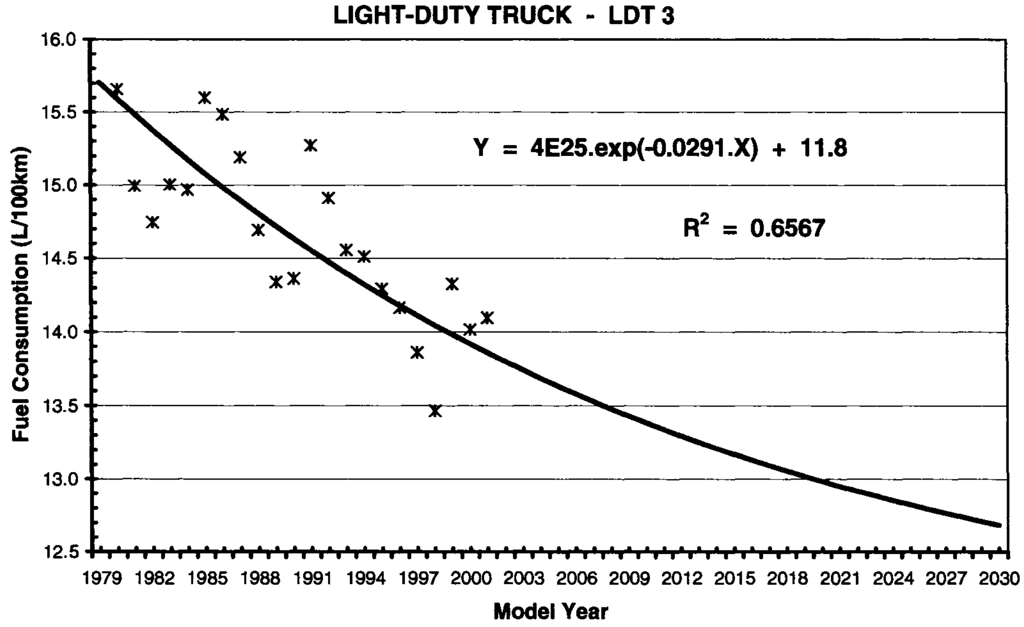


Figure F-16: LDT 3 predicted fuel consumption (gasoline) trend extending up to 2030 (adjusted for fixed mass).

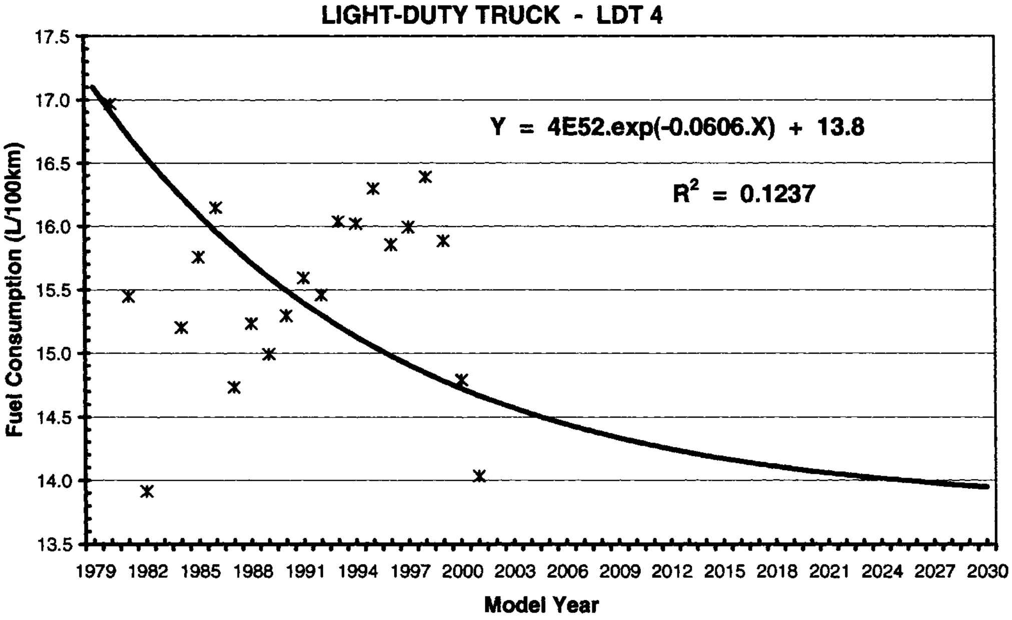


Figure F-17: LDT 4 predicted fuel consumption (gasoline) trend extending up to 2030 (adjusted for fixed mass).

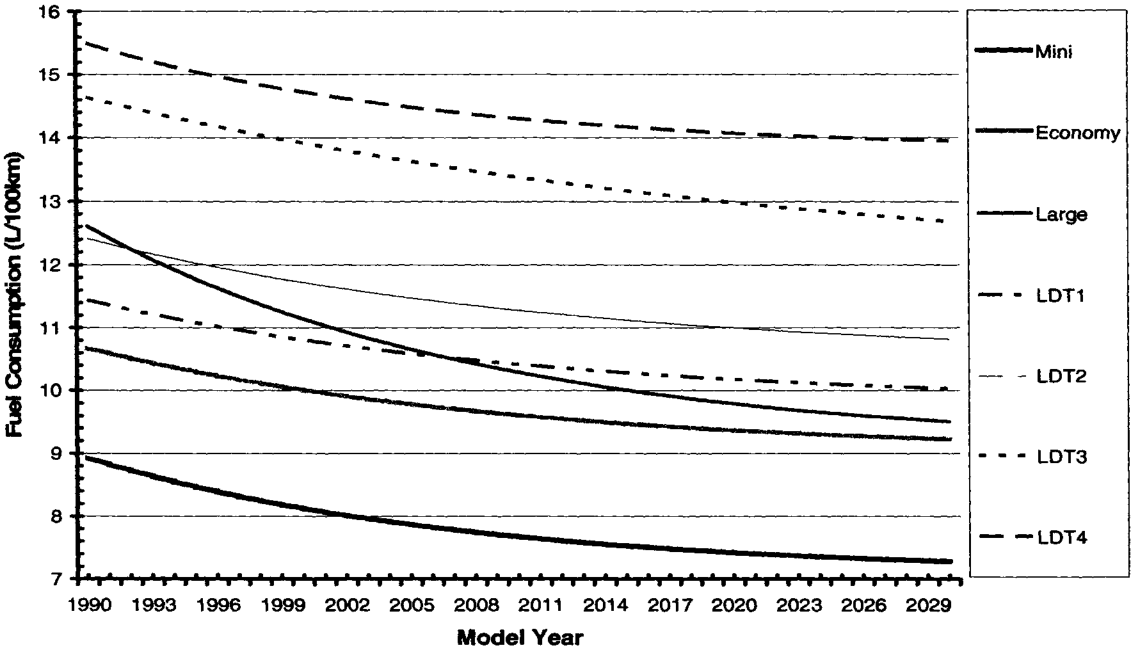


Figure F-18: Comparison of the Light-Duty fleet predicted gasoline fuel consumption.

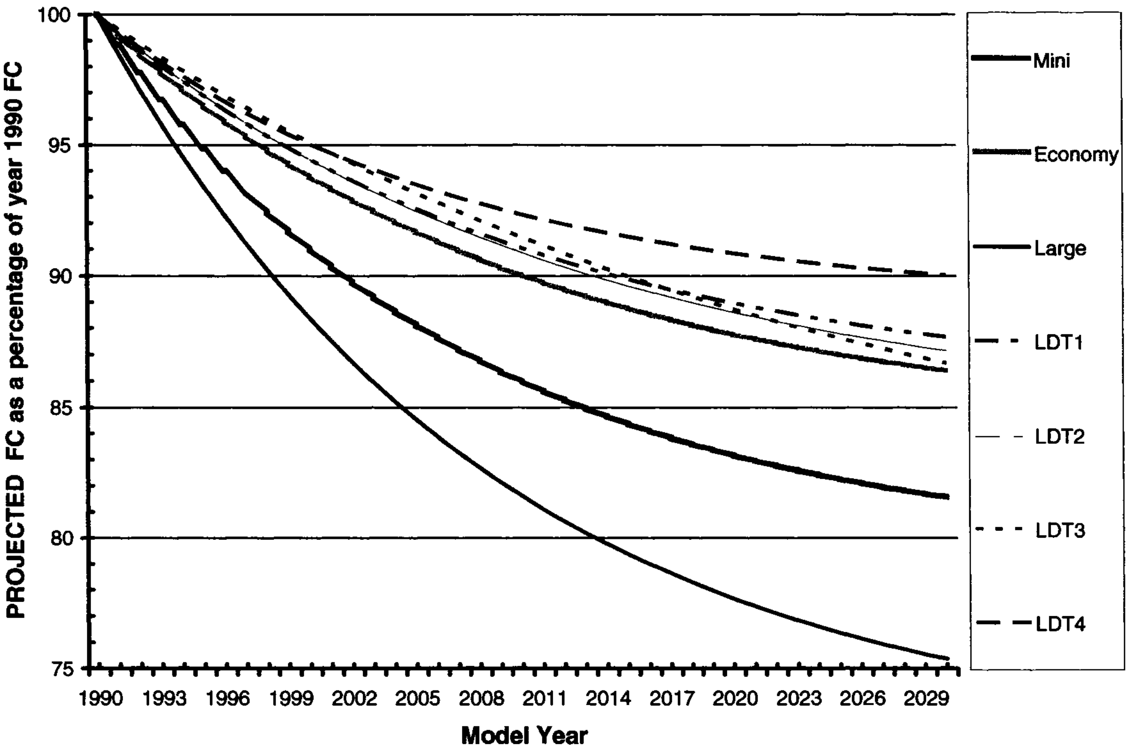


Figure F-19: Projected Fuel Consumption (FC) as a percentage of the FC for a model year 1990 vehicle.

F.3 LIGHT-DUTY DIESEL VEHICLES

US EPA has reported on annual fuel economy for the light-duty diesel vehicles [4]. It is presented in miles per gallon (MPG). They date back from year 1975 till 2001. It is noteworthy that these rates are based on their laboratory data. The data have been plotted below in Figure F-20 and appropriate fuel consumption trends have been obtained.

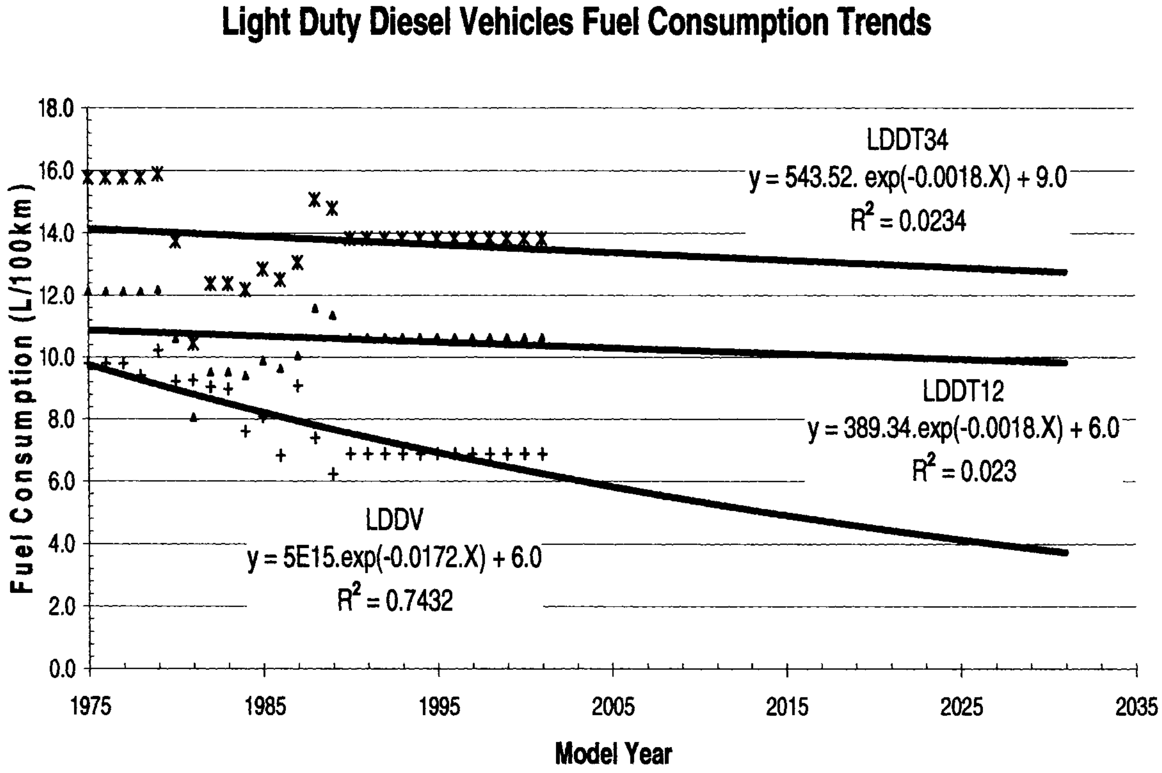


Figure F-20: Comparison of the Light-Duty fleet predicted DIESEL fuel consumption. (based on US EPA available past and estimated data [4]).

F.4 HEAVY-DUTY VEHICLES

To extrapolate the fuel economies beyond 1992 for the trucks, EPA uses a power curve fit of the form $y=ax^b$ [5]. These curves fits are made for every heavy-duty vehicle class fuel economy in mpg. This applies for both the diesel and gasoline trucks. Table F-2 lists the translated data to reflect the evolution of fuel consumption in L/100km.

WEIGHT	GASOLINE	DIESEL
2B	$y = 1887.3\ X^{-0.9624}$	$y = 2194.2\ X^{-1.0506}$
3	$y = 2033.0\ X^{-0.9632}$	$y = 2378.4\ X^{-1.045}$
4	$y = 5751.1\ X^{-1.1902}$	$y = 468.6\ X^{-0.6598}$
5	$y = 532.7\ X^{-0.6348}$	$y = 950.8\ X^{-0.8078}$
6	$y = 6959.2\ X^{-1.2015}$	$y = 440.8\ X^{-0.6117}$
7	$y = 1842.0\ X^{-0.8909}$	$y = 58.5\ X^{-0.1374}$
8A	$y = 3635.6\ X^{-1.0285}$	$y = 1519.0\ X^{-0.8194}$
8B	n/a	$y = 19766.5\ X^{-1.3742}$

Table F-2: Curve fits of Fuel Consumption (L/100km) for heavy-duty vehicles.

Note: X = *Model Year – 1900*
y: *Fuel Consumption (L / 100 km)*

F.5 BUSES

The US EPA has tabulated the estimated bus-fuel economies in mpg. This applies for the transit, intercity and school buses. Data are available for both the diesel and gasoline buses over the range of years 1987 to 1996 [5]. For CALMOB6 purposes, only the transit and the school vehicles are of interest. These data have been plotted and projected. Figures F-21 – F-24 display the bus fuel-consumption trends. The equations on the figures describe the trend.

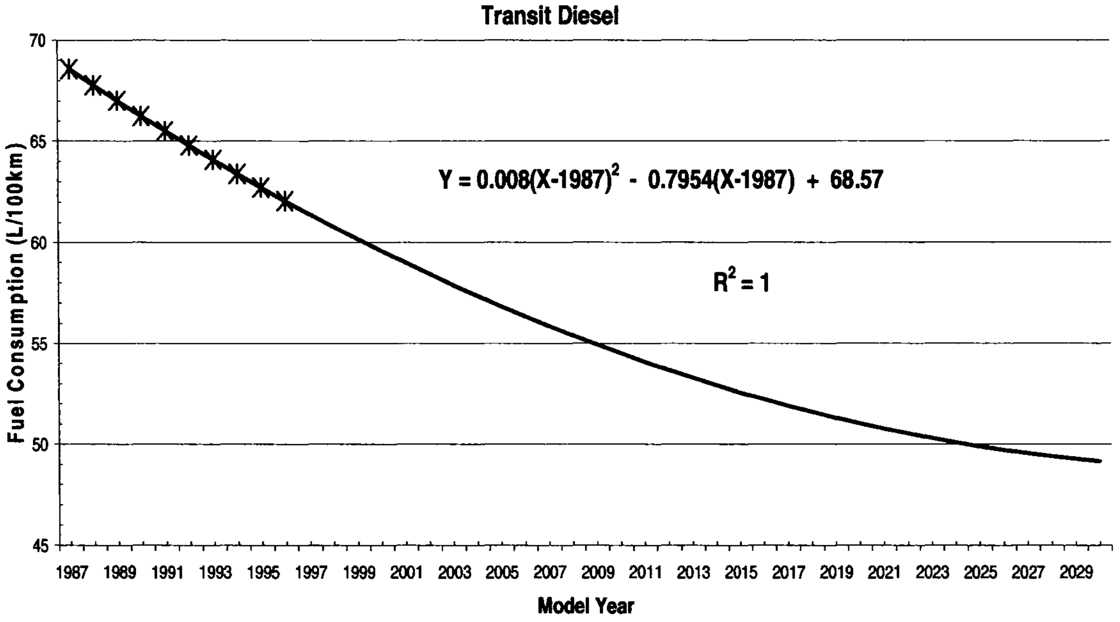


Figure F-21: DIESEL TRANSIT Bus predicted fuel consumption trend extending up to 2030.

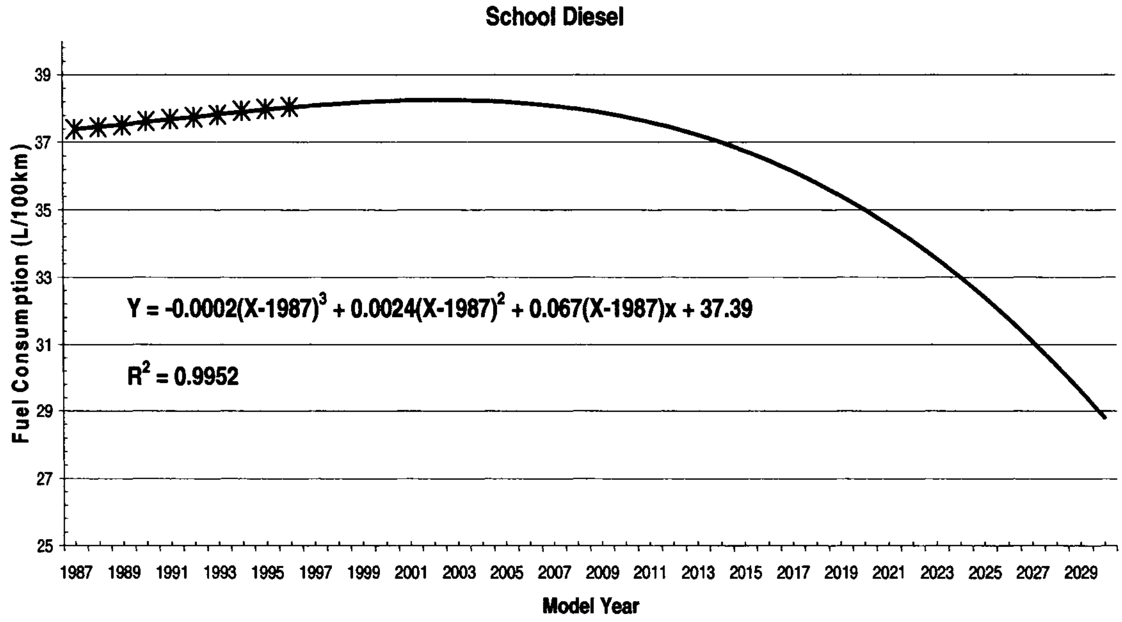


Figure F-22: DIESEL SCHOOL Bus predicted fuel consumption trend extending up to 2030.

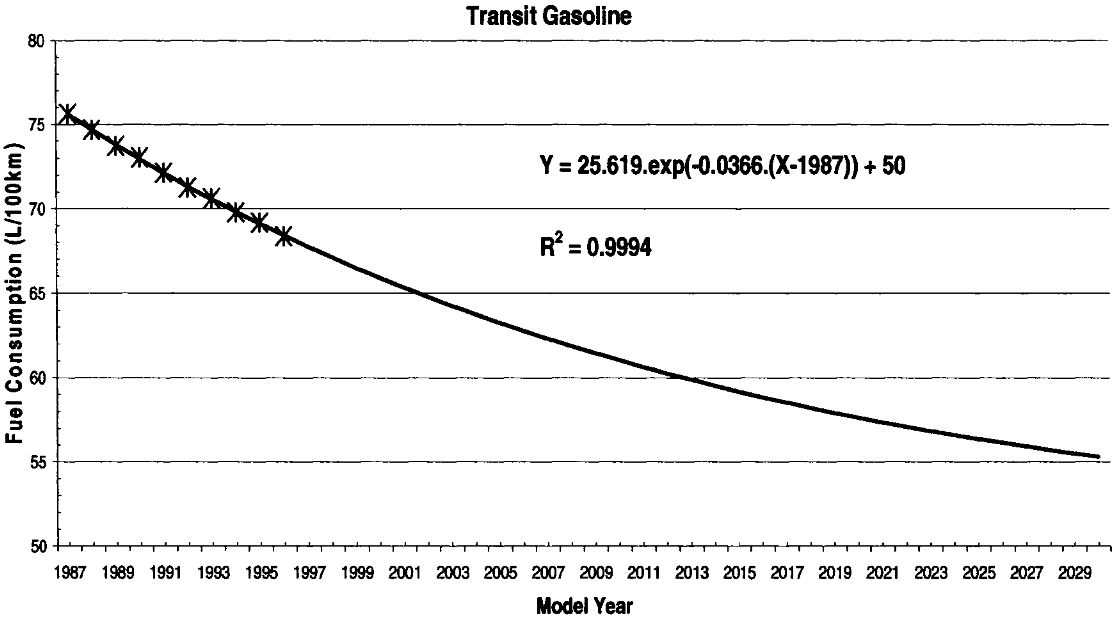


Figure F-23: GASOLINE TRANSIT Bus predicted fuel consumption trend extending up to 2030.

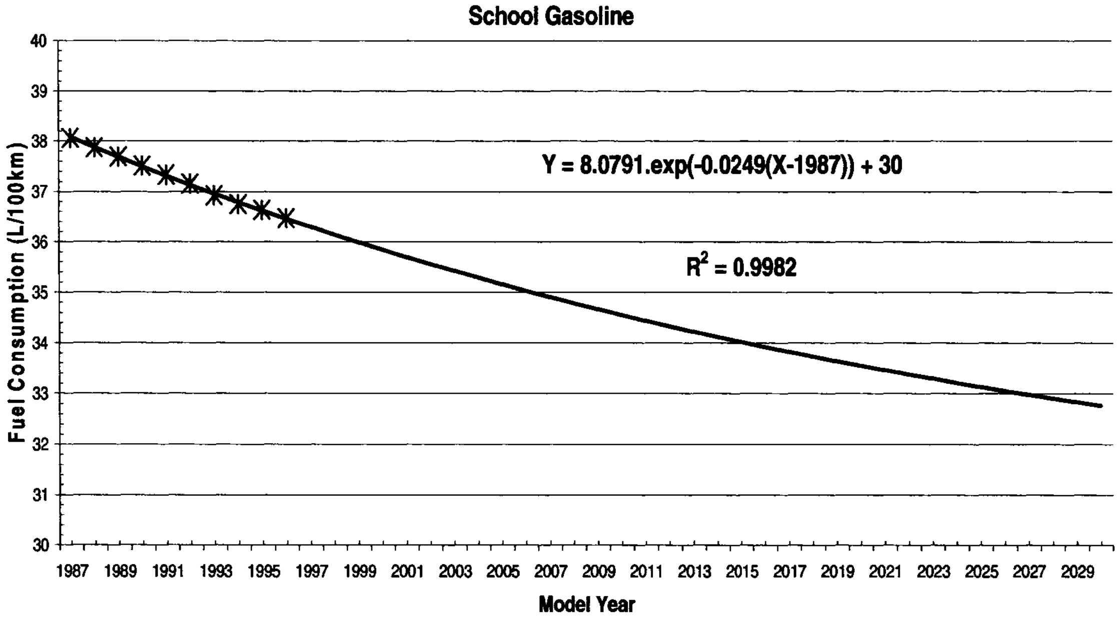


Figure F-24: GASOLINE SCHOOL Bus predicted fuel consumption trend extending up to 2030.

REFERENCES

1. Schingh, M.; Brunet, É.; Gosseling, P., "Canadian New Light Duty Vehicles: Trends in Fuel Consumption and Characteristics (1988-1998)", Transportation Energy Use Division, Office of Energy Efficiency, Natural Resources Canada, July 2000.
2. *Fuel Consumption Database forwarded by Edelweiss d'Andrea from Natural Resources Canada.
3. US EPA, "User's Guide to MOBILE6.1 and MOBILE6.2 – Mobile Source Emission Factor Model", EPA420-R-03-010, Aug 2003.
4. US EPA, "Updating Fuel Economy Estimates in MOBILE6.3 – DRAFT", EPA420-P-02-005, M6.GHG.001, Aug 2002.
5. US EPA, "Update Heavy-Duty Engine Emission conversion factors for MOBILE6 – Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities", EPA420-R-02-006, M6.HDE.002, Jan 2002.

APPENDIX G

MOBILE6 Base Emission Rates

Appendix G illustrates the use of the US EPA database to extract the base emission rates (BERs) for the various vehicle types. Extracting BERs for light-duty vehicles is more complex than for heavy-duty vehicles. This is mainly because of the variety in light-duty vehicle technologies. Further, this section assumes different fractions for the vehicle technologies in view of extracting a composite base emission rate.

G.1 INTRODUCTION

MOBILE6 includes a database of emissions expected when specific classes of vehicles are run over standard FTP (Federal Test Procedure) cycles. The criteria pollutants considered are CO, NOx and HC. Further updates account for the particulates [13]. For light duty vehicles the values are presented in terms of cold start emissions offset and gram/mile values for new vehicles of various model years back to the 1960's. There are also deterioration rates for these parameters to account for progressive increase in the fraction of altered, malfunctioning or worn out components which affect emissions. For heavy duty vehicle classes, emission rates are given on a g/bhp (grams per brake horsepower) basis and there are conversion factors (bhp/mile) to adjust the emission factors to a gram/mile rate for vehicles of varying weight class running standard test programs. This data base provides a useful source of emission rates for past, current and future years for vehicles running standard test cycles.

It is important to point out that the altitude of Edmonton is 2192 feet above mean sea level [8]. MOBILE6 gives separate emission rates for low and high altitude regions. The low attitude range is around 500 ft whereas the high altitude range is around 5,550ft [10]. Since 2192 ft is closer to the lower level, the low altitude emission rates have been extracted.

G.2 LIGHT DUTY BASE EMISSION RATES

The base emission rates for the light-duty vehicles (passenger cars and light-duty trucks) are derived from the Federal Test Procedure test, FTP 75 [1]. Figure G-1 gives the speed-time trace. This trace is used to generate both the start and running emissions for the light-duty vehicles.

FTP 75 is divided into three main segments: Bag 1, Bag2 and Bag 3. Bag 1 emissions are collected after a minimum of 12-hour soak period. It contains an engine start and it is usually referred to as 'cold-start'. Bag 2 emissions are collected continuously after the first 505 seconds. It contains no start and the engine is warm. Bag 3 emissions are collected after a 10-minute soak time. It contains a start, particularly referred to as 'hot start' since the engine is fully warmed. This speed-time trace for the Bag 3 is identical to that of Bag 1 and they both contain start and running emission.

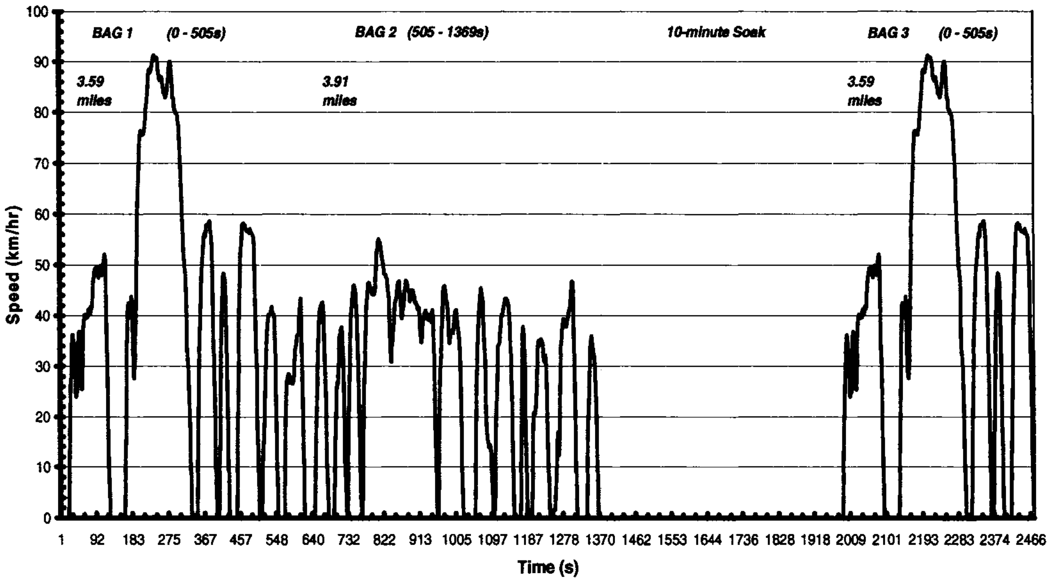


Figure G-1: Speed –Time trace for the FTP Urban cycle (FTP 75).

MOBILE6 uses the LA4 cycle trip. The latter is composed of either the Bag 1 and Bag 2 emissions or the Bag 3 and Bag 2 emissions. However, the EPA has recently introduced the Hot Running 505 (HR 505) cycle [1, 2]. It has identical speed-time trace as Bag 1 and Bag 3 trips. HR 505, however, does not include any engine start.

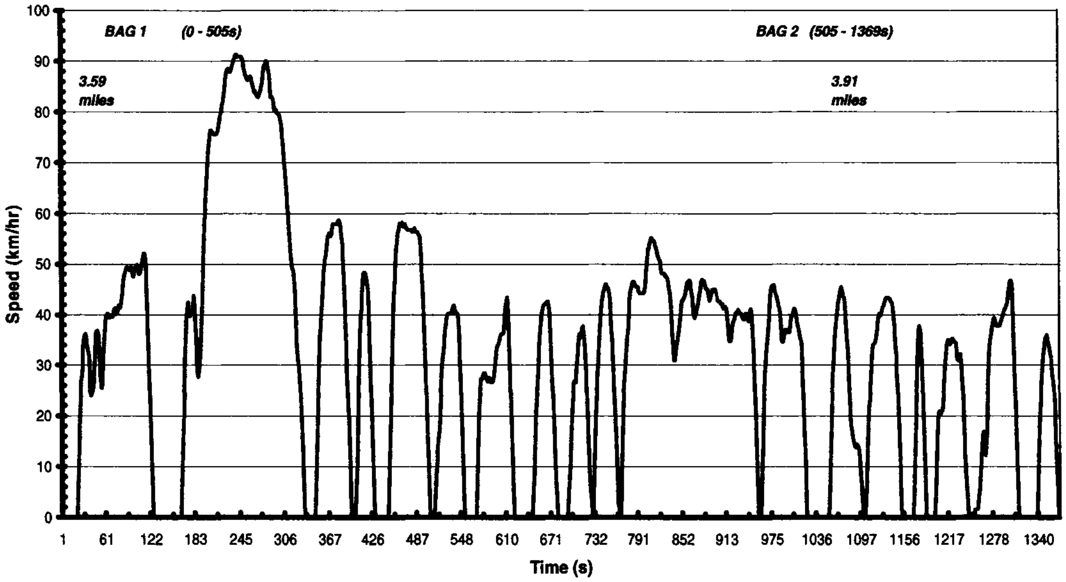


Figure G-2: Speed-Time trace for an LA4 cycle.

G.2.1 MOBILE6 EXHAUST RUNNING EMISSION [1]

To determine the exhaust running emission, MOBILE6 uses the Hot Running LA4 cycle. This cycle is a combination of the HR 505 and Bag 2 emissions solely. As a result, Bag 1 and Bag 3 are replaced by the HR 505, without any engine start. All emissions are measured in gram/mile for the running part. Hence, a suitable weighting for the g/mile collection of each Bag is required. The distance traveled during each segment is used for such purpose. Hence, the exhaust running emissions (ERE) is given by:

$$\text{ERE (g/mile)} = \left[\text{HR 505 (g/mile) x } \frac{3.59}{7.50}\right] + \left[\text{Bag 2 (g/mile) x } \frac{3.91}{7.50}\right]$$

Equation G-1: MOBILE6 exhaust running emission equation [11].

G.2.2 MOBILE6 ENGINE START EMISSION [2]

To observe the effect of engine start on emissions, MOBILE6 uses the new HR 505 and Bag 1 trips. Emissions are given in grams for the start part. This absolute value, basically, refers to the excess amount of emissions if an engine is cold-started. The Basic Start Emission Rate (BSER) is given by the following relation:

$$\text{BSER (grams)} = \left[\text{Bag 1 (g/mile)} - \text{HR 505 (g/mile)} \right] \times 3.59 \text{ miles}$$

Equation G-2: MOBILE6 basic start emission equation [12].

G.2.3 MOBILE6 START AND RUNNING EMISSION FRACTIONS

The FTP composite emission rate is a weighted combination of the three bags [3], designed to represent two trips. The first one consists of a cold start whereas the second has a hot start. EPA concluded from its driving activity study that 43% of all start emissions are due to 'cold start' (i.e. Bag 1), while 57% account for emission due to a 'hot start' (i.e. Bag 3) after a 10-minute soak. As a result, the FTP composite emission rate is given by:

$$\text{FTP} = [\text{Bag 1} \times 0.43 \times (3.59/7.5)] + [\text{Bag 2} \times (3.91/7.5)] + [\text{Bag 3} \times 0.57 \times (3.91/7.5)]$$

Equation G-3: VMT weightings of the 3 bags to generate the composite FTP g/mile [11]

To represent the effect of engine start and running emissions over the total emissions collected during the FTP tests, fractions are used. Hence, there is an engine start emissions fraction and a running emission fraction. These are given by [13]:

$$\boxed{\text{Start Emission Fraction} = \text{ERE (g/mile)} \;/\; [\text{FTP (g/mile)} \times 7.5\ \text{miles}]} \ldots E.q\ G\text{-}4$$

$$\boxed{\text{Running Emission Fraction} = \text{BSER (g/mile)} \;/\; \text{FTP (g/mile)}} \ldots E.q\ G\text{-}5$$

G.2.4 CALCULATING BASE EMISSION RATES

For any given light-duty vehicle there are generally two sets of emission factors: start emissions and running emissions. Start emission factors pertain to the amount of pollutant generated per vehicle start. Running emission factors relate to the rate at which a pollutant is generated during a standardized driving cycle

Each of these two factors is further broken down into a zero-mile-level (ZML) rate and a deterioration rate (DR or DET). ZML refers to the emission factor when the vehicle is brand new and the DET calculates how much the emission factor increases with increasing vehicle mileage. Unless otherwise stated, all DET factors are in units of grams/10,000 miles for start emissions and grams/mile/10,000 miles for running emissions.

The vehicle fleet is composed of multiple technologies. Some examples are Port Fuel Injection, Throttle Body Injection, Fuel Injection and Carbureted. To generate the base emission rates, light-duty vehicles (more particularly the gasoline fuelled ones) have been categorized into three main groups: the open-loop vehicles (Pre-1981) [3], the 1981-1993 range vehicles [1, 2] and the post Tier1 vehicles [4, 5]. Each of these groups accounts for the different vehicle technologies over the different years. The DET and ZML for each group differ. The following methods are used to estimate the base emission rates from each of the three main groups.

G.2.4.1 PRE-1981 LIGHT-DUTY GASOLINE AND PRE-1994 LIGHT-DUTY DIESEL VEHICLES [3]

For these vehicles, deterioration and zero-mile level rates were developed using the fractions illustrated by Equations G-3 and G-4. These fractions were used to adjust MOBILE5 DET and ZML accordingly.

Each vehicle class has four emission factors, regardless of the vehicle technologies. They are start ZML (in grams), start DET (in grams/10k miles), running ZML (in grams/mile) and running DET (in grams/mile/10k miles). This applies for every pollutant – CO, NOx and HC. These rates are available for the following vehicle categories: LDGV, LDDV, LDDT, LDGT12 (<6,000 lbs. GVWR) and LDGT34 (6,001-8,500 lbs. GVW). They are tabulated, year-wise, in the Appendices of ref. 13.

For the gasoline vehicles, the data are available up to year 1980. However, for the light-duty diesel vehicles, EPA leaves the option to using the DET and ZML to beyond the 1980's. In this case, the ZML and DET for the diesel vehicles are used up to year 1993. Thereafter, i.e. post 1994, phasing in of the Tier 0, Tier1, LEV and Tier 2 diesel vehicles has been assumed. It is noteworthy that each vehicle category has a unique deterioration rate for a particular year.

For a given mileage, Mil, the resulting base emission rate (BER) is calculated as follows:

$$\boxed{\mathbf{BER_S = ZML_S + [DET_S \times Mil]}} \text{ , ... } \textit{E.q G-6}$$

$$\boxed{\mathbf{BER_R = ZML_R + [DET_R \times Mil]}} \text{ , ... } \textit{E.q G-7}$$

where,

BER_S = Base Start Emission Rate (grams)

BER_R = Base Running Emission Rate (grams/mile)

Mil = Vehicle accumulated mileage (miles/10,000)

ZML_S = Start Zero-Mile Level (grams)

ZML_R = Running Zero-Mile Level (grams/mile)

DET_S = Start Deterioration (grams/10,000 miles)

DET_R = Running Deterioration (grams/mile/10,000 miles)

To estimate running BER, for example, the accumulated vehicle mileage is, first, divided by 10,000. Subsequently, the ZML_R and DET_R of the appropriate vehicle category, for the desirable pollutant and for the corresponding year of estimate are plugged into Equation E.q G-7.

Superscripts preceding each term denote the term number in the Equations G-6 and G-7; for example, ZML_S is the first term in the equation. The general methodology behind calculating BER_S is similar. Thus, Equations G-6 and G-7 will be used as a basis of comparison for calculating BERs of different vehicles.

G.2.4.2 1981-1993 LIGHT-DUTY GASOLINE VEHICLES AND TRUCKS [1, 2]

Emission factors in this range of years are given for the various vehicle technologies. These are classified in the following main groups: Ported Fuel Injection (PFI), Throttle Body Injection (TBI), Fuel Injection (PFI plus TBI), Carbureted Close Loop and Carbureted Open Loop. This categorization is essential to represent the evolution in the emission standards over the years. In order to estimate the MOBILE6 base emission rate, it is important to know the composition of fleet according to the technology group.

For these vehicles from model year 1981 to 1993, there is more than one running deterioration rate; for example, a vehicle may deteriorate at 0.009 grams/mile for the first 20,000 miles of its life and after 20,000 miles, it may deteriorate at 0.010 grams/mile. The calculation for BER is of the same form as that given in Equations G-6 and G-7. However, there are a few key differences.

For normal emitters, the running deterioration rate, DET_R, is calculated as follows:

$$DET_R(Mil) = \begin{cases} S1 \times Mil & , Mil < C1 \\ S1 \times C1 + S2 \times (Mil - C1) & , C1 < Mil < C2 \\ S1 \times C1 + S2 \times (C2 - C1) + S3 \times (Mil - C3) & , Mil > C2 \end{cases}$$

Equation G-8: Estimating deterioration rates for 1981-1993 light duty gasoline vehicles

where,

Mil = Vehicle mileage (1000 of miles)

DET_R(Mil)=Running Deterioration as a function of mileage (grams/mile)

S1=First Slope (grams/mile/1000 miles)

S2=Second Slope (grams/mile/1000 miles)

S3=Third Slope (grams/mile/1000 miles)

C1=First Corner (1000s of miles)

C2=Second Corner (1000s of miles)

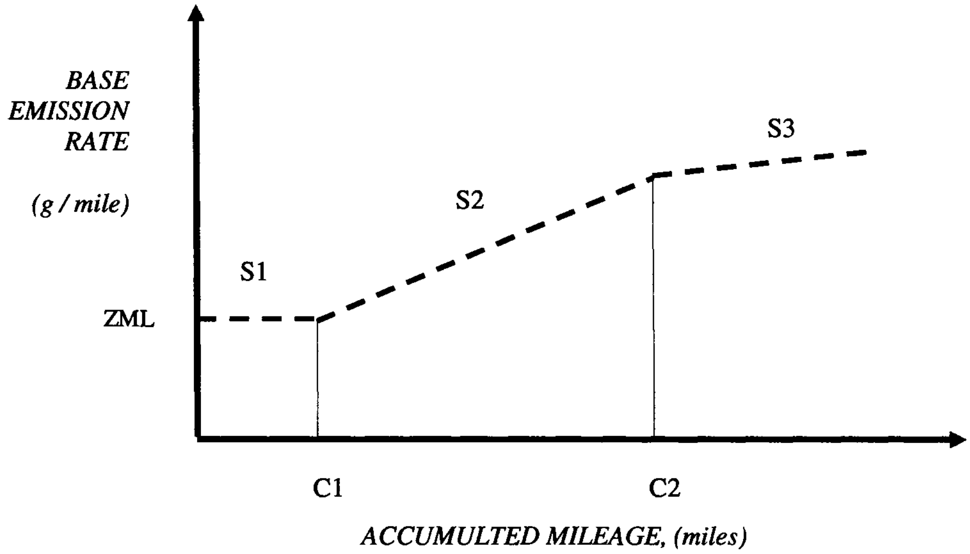


Figure G-3: Illustration of estimating the MOBILE6 base emission rates for 1981-1993 model year vehicles.

Further, for post 1981 vehicles, MOBILE6 has the ability to distinguish between normal and high emitter vehicles. It provides information specific to each of the following: technology group, pollutant, model year and vehicle category (i.e. passenger car and light-duty truck). As a result, the above information on the deterioration rates (slopes and corners) and ZML are available for both types of emitters. Simultaneously, US EPA provides information on the expected fraction of high emitting vehicles in the fleet. This fraction has been decided and listed as a function of accumulated vehicle mileage.

High emitters are calculated in the same manner as normal emitters. However, there is no deterioration rate assumed for the start portion of these high-emitting vehicles. The high emitters have only a mean start ZML emission rate provided. Hence, DET_S in Equation G-6 is always zero.

G.2.4.3 POST TIER 1 LIGHT-DUTY VEHICLES – DIESEL & GASOLINE [4, 5]

Vehicles made after 1994 marked the beginning of the Tier 1 emission standard [5]. A gradual Tier 1 vehicle phase-in is assumed. Starting in 1994, 40% of all passenger vehicles, LDT 1 and LDT 2 sold were required to conform to the Tier 1 / LEV emission standard. This increased to 80% in 1995 and to 100% in 1996. The differences in the percentages for the given years account for Tier 0 vehicles. The latter Tier 0 vehicles are composed of different fraction of PFI and TBI vehicle technologies. Tier 1 and later vehicles group include the following classes: Tier 1, LEV, ULEV, Tier 2, Interim, Interim A and Interim B

The emission factors for the Tier 0 vehicles are hence calculated using the latest zero-mile levels and deterioration rates (i.e. for year 1993) for the PFI and TBI technologies. Subsequently, fraction of the emission factors from these two technologies account for the Tier 0 vehicles. For Tier 1 and later vehicles, data are readily available for the gasoline vehicles. For the diesel vehicles, however, data has to be computed based on MOBILE5 values.

For each of the Tier 1 and later gasoline vehicle technologies, US EPA specifies the ZML, DR and "High" BER for the start and running emissions in grams and gram/mile, respectively. The ZML and DR are used to calculate the base emission rate for normal emitters. Hence, ZML_S, ZML_R, DET_S and DET_R (from Equations G-6 and G-7) are available. The "High" BER gives a unique value the running and start emission rates. Hence, only the zero-mile level is specified for these high-emitting vehicles; both DET_S, DET_R are zero. With appropriate technology and high-emitter fractions, the base emission rates for this vehicle category can be determined.

For diesel vehicles, MOBILE6 did not update all the light-duty diesel emission factors [6]. This is so because the diesel vehicles form a minor population in the whole light duty vehicles fleet. Besides, because of the low sales volume of light-duty diesel trucks, emission standards have been combined. Hence, LDT 2 standards are used to compute emissions for MOBILE6 LDDT 1 and LDDT2. Similarly, LDT 4 standards are used to calculate MOBILE6 LDDT 3 and LDDT 4 vehicle emissions.

For calculating emissions for the light-duty diesel vehicles, MOBILE6 uses MOBILE5-based emission factors for Tier 0 vehicles. These factors have already been separated to represent the start and running parts. These are the ZML_S, ZML_R, DET_S and DET_R for these pre-1994 light duty diesel vehicles. However, MOBILE6 adjust these data to better represent the evolution of emission standards. Hence, to obtain the basic emission rate for start and running emissions for a given vehicle class, emission standard and pollutant, the following equation has been used:

$$\textbf{Tier ``X'' BERs} \quad = \quad \textbf{Tier 0 BER} \quad \textbf{x} \quad \left( \frac{\textbf{Tier ``X'' Standard}}{\textbf{Tier 0 Standard}} \right) \qquad \textbf{....E.q G-9}$$

For instance, to obtain the DET_S of a Tier 2 diesel passenger car for the hydrocarbon, the corresponding DET_S for pre-1994 vehicle is plugged into the Tier 0 BER place. Subsequently, a light-duty diesel exhaust emissions standards look-up table is used to obtain the Tier 2 emission standard and the Tier 0 emission standard. The ratio of these two latter standards is used to adjust the Tier 0 DET_S and hence obtain the Tier 2 DET_S.

G.2.4.4 1980- 2003 VEHICLE TECHNOLOGY DISTRIBUTION [14]

For estimating MOBILE6 base emission rates, it is imperative to have the fraction of vehicles distributed technology wise. Tabulated below in Tables G-1 – G-4, are the fractions assumed for the light duty vehicle and trucks category.

It is assumed that there are no ULEV and Tier's interims (i.e. Interim, Interim A and Interim B) in the fleet. Post 2003, all new cars and light-duty trucks conform to the strict Tier 2 standards.

LDGV	CARB	FI	PFI	TBI	TIER 0	TIER 1	LEV
1980	1	0	0	0	0	0	0
1981	0.91	0.09	0.061	0.029	0	0	0
1982	0.832	0.168	0.062	0.106	0	0	0
1983	0.729	0.271	0.088	0.183	0	0	0
1984	0.608	0.392	0.11	0.282	0	0	0
1985	0.485	0.515	0.307	0.208	0	0	0
1986	0.324	0.676	0.392	0.284	0	0	0
1987	0.259	0.741	0.372	0.369	0	0	0
1988	0.101	0	0.492	0.407	0	0	0
1989	0.128	0	0.597	0.275	0	0	0
1990	0.019	0	0.793	0.188	0	0	0
1991	0.002	0	0.79	0.208	0	0	0
1992	0.002	0	0.902	0.096	0	0	0
1993	0	0	0.891	0.109	0	0	0
1994	0	0	0.961	0.039	0.6	0	0.4
1995	0	0	0.988	0.012	0.2	0	0.8
1996	0	0	1	0	0	0.4	0.6
1997	0	0	0	0	0	0.8	0.2
1998	0	0	0	0	0	1	0
1999	0	0	0	0	0	1	0
2000	0	0	0	0	0	1	0
2001	0	0	0	0	0	0	1
2002	0	0	0	0	0	0	1
2003	0	0	0	0	0	0	1

Table G-1: 1980-2003 Light Duty gasoline vehicle technology distribution.

The first four columns of the table add up to 1. The values under the Tier 0 vehicles indicate the fraction of the combined base emission rate using the first four columns. As a result, all the fractions in the last three columns should add up to one.

LDGT1/2	CARB	FI	PFI	TBI	TIER0	TIER1	LEV
1980	1	0	0	0	0	0	0
1981	1	0	0	0	0	0	0
1982	1	0	0	0	0	0	0
1983	0.998	0.002	0.002	0	0	0	0
1984	0.978	0.022	0.022	0	0	0	0
1985	0.887	0.113	0.066	0.047	0	0	0
1986	0.626	0.374	0.238	0.136	0	0	0
1987	0.393	0.607	0.327	0.28	0	0	0
1988	0.132	0	0.416	0.452	0	0	0
1989	0.091	0	0.54	0.369	0	0	0
1990	0.054	0	0.552	0.394	0	0	0
1991	0.021	0	0.484	0.495	0	0	0
1992	0.021	0	0.66	0.319	0	0	0
1993	0.011	0	0.688	0.301	0	0	0
1994	0	0	0.728	0.272	0.6	0	0.4
1995	0	0	0.746	0.254	0.2	0	0.8
1996	0	0	0	0	0	0.4	0.6
1997	0	0	0	0	0	0.8	0.2
1998	0	0	0	0	0	1	0
1999	0	0	0	0	0	1	0
2000	0	0	0	0	0	1	0
2001	0	0	0	0	0	0	1
2002	0	0	0	0	0	0	1
2003	0	0	0	0	0	0	1

Table G-2: 1980-2003 Light Duty gasoline truck (LDT 1 and LDT 2) technology distribution.

LDGT 3/4	CARB	FI	PFI	TBI	TIER0	TIER1
1980	1	0	0	0	0	0
1981	1	0	0	0	0	0
1982	1	0	0	0	0	0
1983	0.998	0.002	0.002	0	0	0
1984	0.978	0.022	0.022	0	0	0
1985	0.887	0.113	0.066	0.047	0	0
1986	0.626	0.374	0.238	0.136	0	0
1987	0.393	0.607	0.327	0.28	0	0
1988	0.132	0	0.416	0.452	0	0
1989	0.091	0	0.54	0.369	0	0
1990	0.054	0	0.552	0.394	0	0
1991	0.021	0	0.484	0.495	0	0
1992	0.021	0	0.66	0.319	0	0
1993	0.011	0	0.688	0.301	0	0
1994	0	0	0.728	0.272	1	0
1995	0	0	0.746	0.254	1	0
1996	0	0	0	0	0.5	0.5
1997	0	0	0	0	0	1
1998	0	0	0	0	0	1
1999	0	0	0	0	0	1
2000	0	0	0	0	0	1
2001	0	0	0	0	0	1
2002	0	0	0	0	0	1
2003	0	0	0	0	0	1

Table G-3: 1980-2003 Light Duty gasoline truck (LDT 3 and LDT 4) technology distribution.

LDD	TIER 0	LEV	TIER 1
1994	0.6	0.4	0
1995	0.2	0.8	0
1996	0	0.6	0.4
1997	0	0.2	0.8
1998	0	0	1
1999	0	0	1
2000	0	0	1
2001	0	1	0
2002	0	1	0
2003	0	1	0

Table G-4: 1994-2003 Light Duty diesel vehicles and light-duty trucks technology distribution.

G.3 HEAVY DUTY BASE EMISSION RATES [10, 11, 12]

Emission factors for heavy-duty vehicles were obtained differently from those for light duty vehicles. Due to the prohibitive costs inherent in testing heavy-duty vehicles on chassis dynamometers (light duty vehicle testing is done on a chassis dynamometers), heavy-duty vehicles are tested, instead, on engine dynamometers.

As a result, the rate at which emissions are produced on an engine dynamometer is calculated in units of grams per brake horsepower-hour (g/bhp-hr). This rate is termed as a work-specific emission level [10]. A correction factor is then applied to convert the emission rate into grams per mile. The correction factor is a function of the vehicle's fuel economy, fuel density, and brake-specific fuel consumption (BSFC). It is provided on a bhp-hr/mi basis. In this way, product of the work-specific emission level and the correction factor gives a gram per mile emission factor. This factor is being used by CALMOB6 to estimate emissions.

$$\begin{array}{c}\textbf{Emission}\\ \textbf{Factor}\\ \textbf{(g/mi)}\end{array} = \begin{array}{c}\textbf{Work-Specific}\\ \textbf{Emission Level}\\ \textbf{(g/bhp-hr)}\end{array} \text{ X } \begin{array}{c}\textbf{Conversion}\\ \textbf{Factor}\\ \textbf{(bhp-hr/mi)}\end{array}$$

Equation G-10: Estimating the ZML and DET emission factors on a g/mile basis [10].

Moreover, MOBILE6 does not give the emission rates from the different possible emission heavy-duty vehicle technologies. Consequently, estimating base emission rates for heavy-duty vehicles does not require as much effort as for the light-duty vehicles. For the latter vehicles, MOBILE6 separates the emission rates according to the different vehicle technologies.

Further, with this method of emissions testing results, only one set of emission factors is obtained – i.e. for the running conditions. This is unlike the light duty vehicles where, two sets of emission factors (running and start) were developed. As such, the method for calculating base emission rates (BER) for heavy-duty vehicles is much simpler than that used for other vehicles.

$$BER_{HD} = ZML + (DET \times Mil) \quad \text{..... E.q G-11}$$

where,

BER_{HD} = Base Emission Rate for Heavy Duty Vehicles
ZML = Zero Mile Level Emissions (grams/mile)
DET = Deterioration Rate (grams/mile/10,000 miles)
Mil = vehicle mileage (10,000s of miles)

REFERENCES

1. US EPA, "Determination of Running Emissions as a Function of Mileage for 1981-1993 Model Year Light-Duty Cars and Trucks", EPA420-R-02-002, M6.EXH.001, Jan 2002.
2. US EPA, "Determination of Start Emissions as a Function of Mileage and Soak Time for 1981-1993 Model Year Light-Duty Vehicles", EPA420-R-01-058, M6.STE.003, Nov 2001.
3. US EPA, "Basic Exhaust Emission Rates of Open Loop Vehicles for MOBILE6: Exhaust Emissions at High and Low Altitudes for Engine Starts and Running Emissions for Motorcycles, Light-Duty Diesel Vehicles and trucks and Pre-1981 Model Year Light-Duty Gasoline Vehicles and Trucks", EPA420-R-01-027, M6.EXH.005, Apr 2001.
4. US EPA, "Determination of CO Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs", EPA420-R-03-011, M6.EXH.012, Sept 2003.
5. US EPA, "Determination of NOx and HC Basic Emission Rates, OBD and I/M Effects for Tier 1 and Later LDVs and LDTs", EPA420-R-01-056, M6.EXH.007, Nov 2001.

6. US EPA, “MOBILE6 Estimates of Exhaust Emissions for 1994-and-later Light Duty Diesel Cars and Trucks”, EPA420-R-01-041, M6.EXH.011, Jul 2001.
7. US EPA, “Federal and California Exhaust and Evaporative Emission Standards for the Light-Duty Vehicles and Light-Duty Trucks”, EPA420-B-00-001, Feb 2000.
8. Wikipedia Encyclopedia, http://en.wikipedia.org/wiki/Edmonton, Canada (site accessed on June 18, 2006)
9. US EPA, “Update Heavy-Duty Engine Emission conversion factors for MOBILE6 – Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities”, EPA420-R-02-006, M6.HDE.002, Jan 2002.
10. US EPA, “Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6”, EPA420-R-99-010, M6.HDE.001, Apr 1999.
11. US EPA, “Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6 – Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors”, EPA420-R-02-005, M6.HDE.004, Jan 2002.
12. US EPA, “Accounting for the Tier 2 and Heavy-Duty Requirements in MOBILE6”, EPA420-R-01-057, M6.EXH.004, Nov 2001.
13. US EPA, “MOBILE6.1 Particulate Emission Factor Model Technical Description – Final Report”, EPA420-R-03-001, M6.PM.001, Jan 2003.
14. Philpott, S., “MOBILE5C User Guide”, Environment Canada, Hull, Québec, Canada, 60 pp., 1993.

APPENDIX H

Fleet Age Distribution

During any vehicle emission simulation, it is important to consider the base emission rates of every vehicle category distributed age wise over the fleet. For that, it is assumed that the fleet is composed of a maximum of 23-year old vehicles for a particular calendar year. Vehicles aged twenty-three or above are considered to emit at the same rates. It is only then can a composite base emission rate, representative of the emissions from all the vehicles in the fleet, be obtained. In this context, a fleet age distribution for each vehicle category is required. Appendix H illustrates the different fleet age-distribution profiles for the different vehicle categories.

H.1 INTRODUCTION

To run urban simulations for a given year, emission rates that represent a vehicle fleet of typical vintage is needed; some new vehicles and a lot more ageing vehicles from previous model years. The actual fleet age distribution is obviously important in setting the emission rates during any simulation. To accommodate this, the fleet for each class of vehicles is considered to consist of vehicles over an age span of zero to twenty-three years, (with vehicles more than twenty-three years old added to the 'Age 23' fraction of the fleet). Light-duty vehicle and heavy-duty vehicle (HDV 2B-HDV 8B) information has been obtained from the registries. Bus fleet information, however, has been obtained from the Edmonton public transit organization. Bus fleet information is more precise and representative of the Edmonton Transit. Hence, specific information of such fleet can be used for better emission and fuel consumption inventories.

Figures H-1 – H-5 illustrate the fleet age profiles for the light-duty vehicles and the heavy-duty vehicles (except buses). These profiles were developed using VIN-decoded information from the vehicle registries. Figure H-6 compares the different age-profiles of the vehicles.

Figures H-7 – H-11 present the fleet age profiles for the transit buses. Such fleet information was obtained from Edmonton Transit. Information was available for years 1989, 1994, 1996, 2000 and 2005. Subsequently, using the 'replacement and growth' plan of the Edmonton Transit, together with some assumptions, the fleet age-distribution was estimated and projected up to year 2030 with 5-year steps. These are demonstrated by Figures H-12 to H-16. Given the unavailability of school bus information, it is further assumed that the same profiles are applicable to the school bus fleet as well.

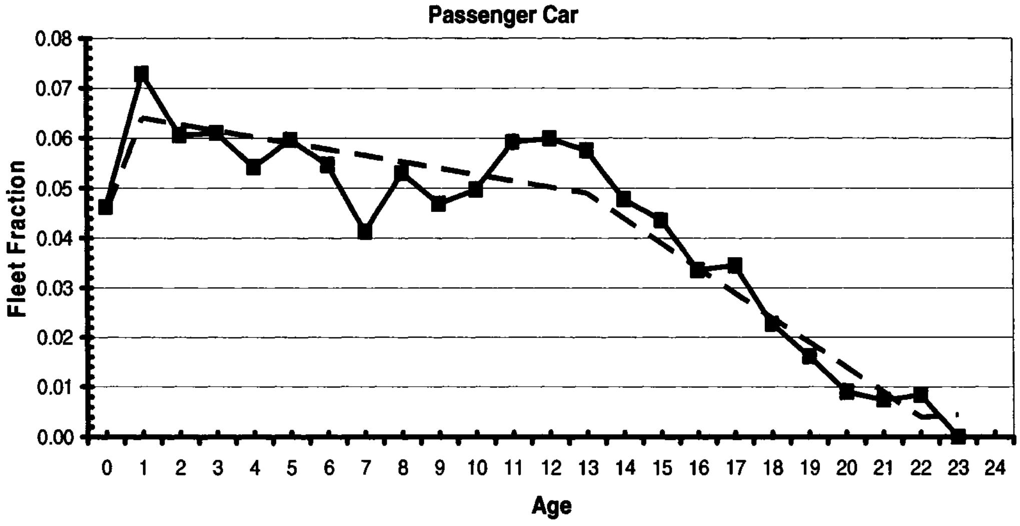


Figure H-1: Fleet age distribution extracted from 2005 registration data for Edmonton region *passenger cars* (solid). The modeled general trend for that category is also shown (dotted).

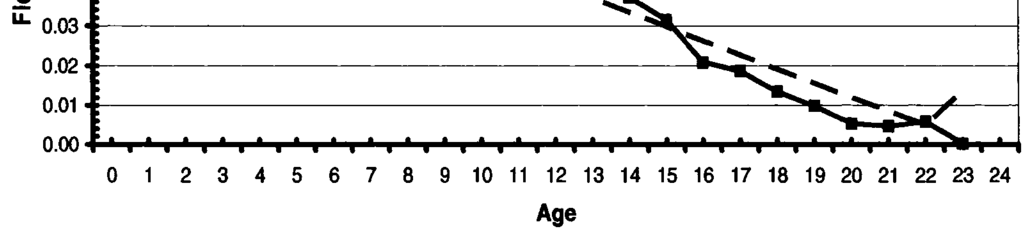


Figure H-2: Fleet age distribution extracted from 2005 registration data for Edmonton region *light-duty trucks (0-6,000 lbs GVW)* (solid). The modeled general trend for that category is also shown (dotted).

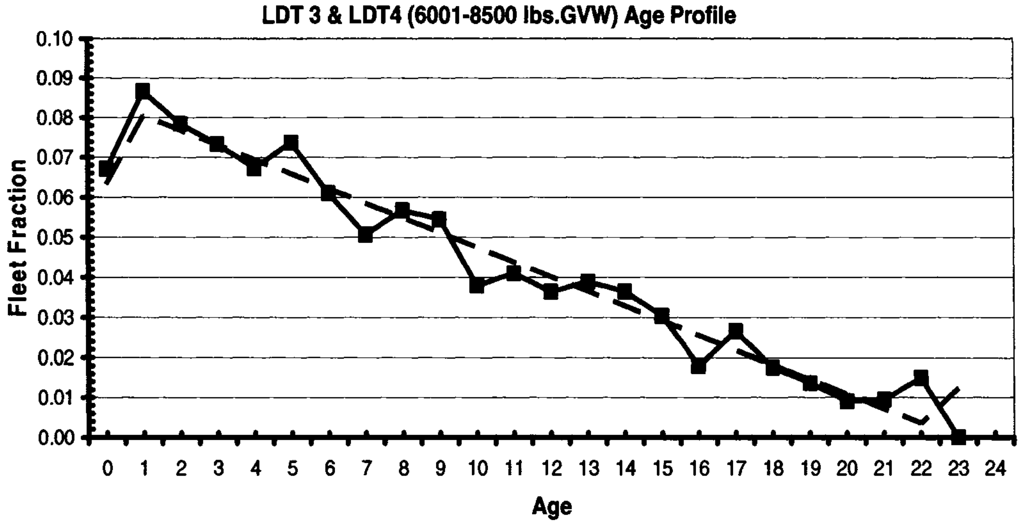


Figure H-3: Fleet age distribution extracted from 2005 registration data for Edmonton region *light-duty trucks (6,001-8,500 lbs GVW)* (solid). The modeled general trend for that category is also shown (dotted).

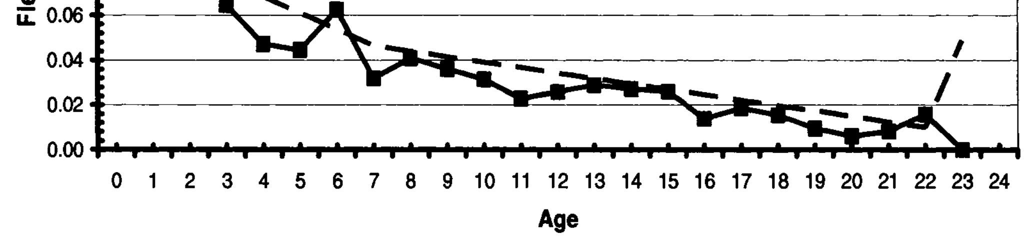


Figure H-4: Fleet age distribution extracted from 2005 registration data for Edmonton region *heavy-duty trucks (HDV 2B and HDV 3)* (solid). The modeled general trend for that category is also shown (dotted).

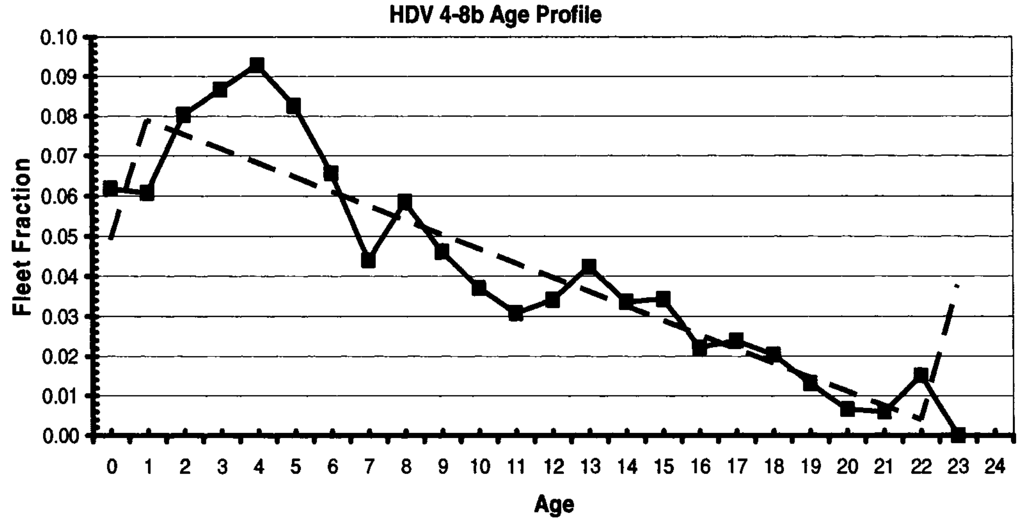


Figure H-5: Fleet age distribution extracted from 2005 registration data for Edmonton region *heavy-duty trucks (HDV 4 through HDV 8B)* (solid). The modeled general trend for that category is also shown (dotted).

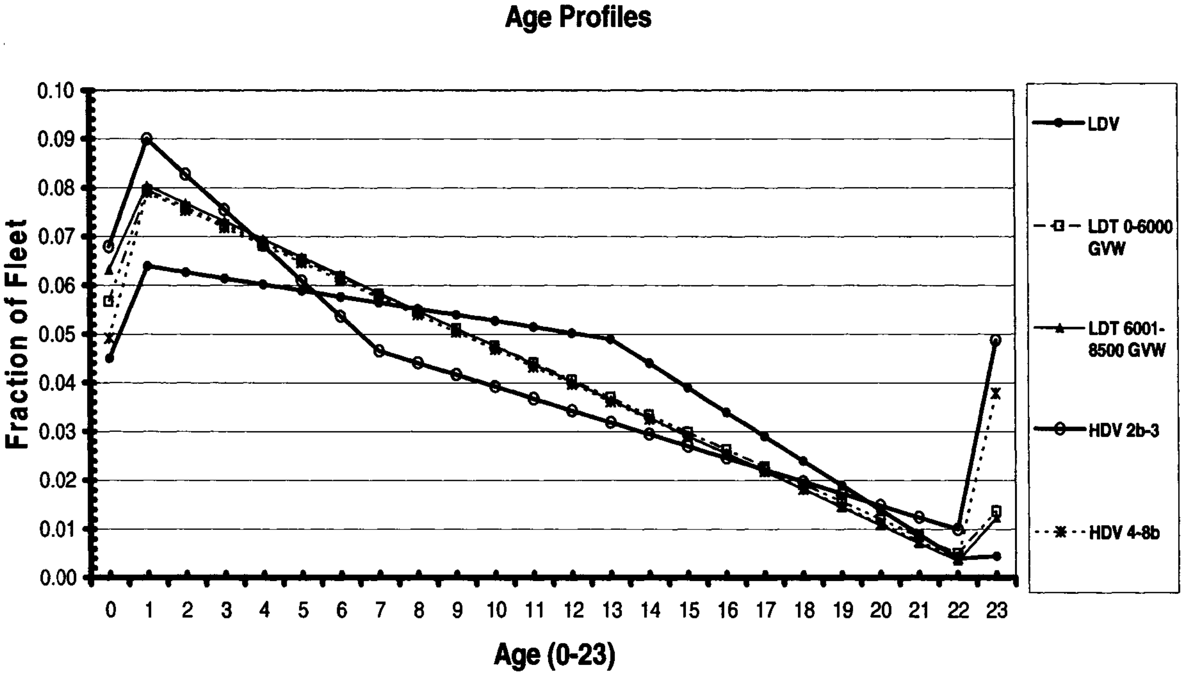


Figure H-6: Comparison of the modeled general trend for the passenger car, LDT 1 and LDT 2, LDT 3 and LDT 4, HDV 2B-3 and HDV 4-8B.

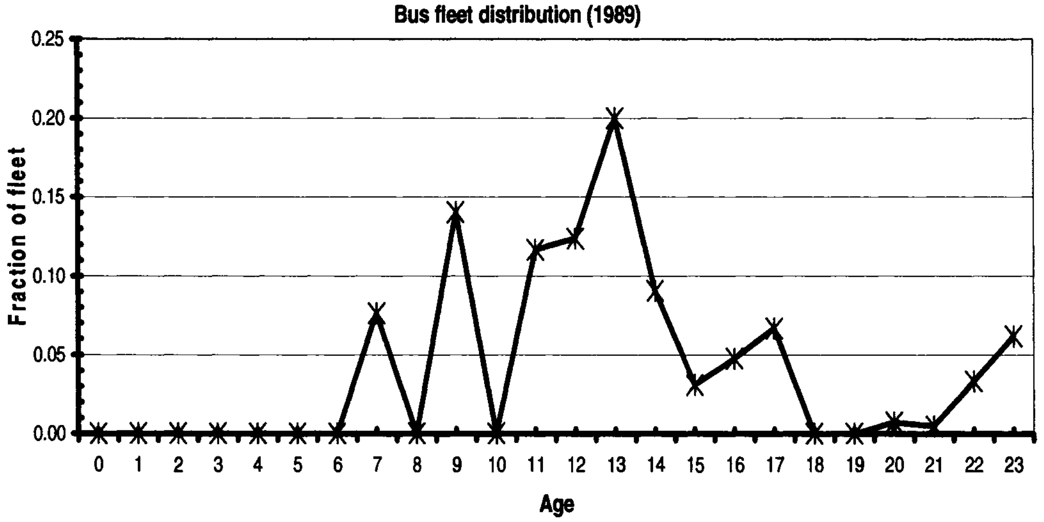


Figure H-7: Bus fleet age distribution extracted from the list of vehicles operating in 1989.

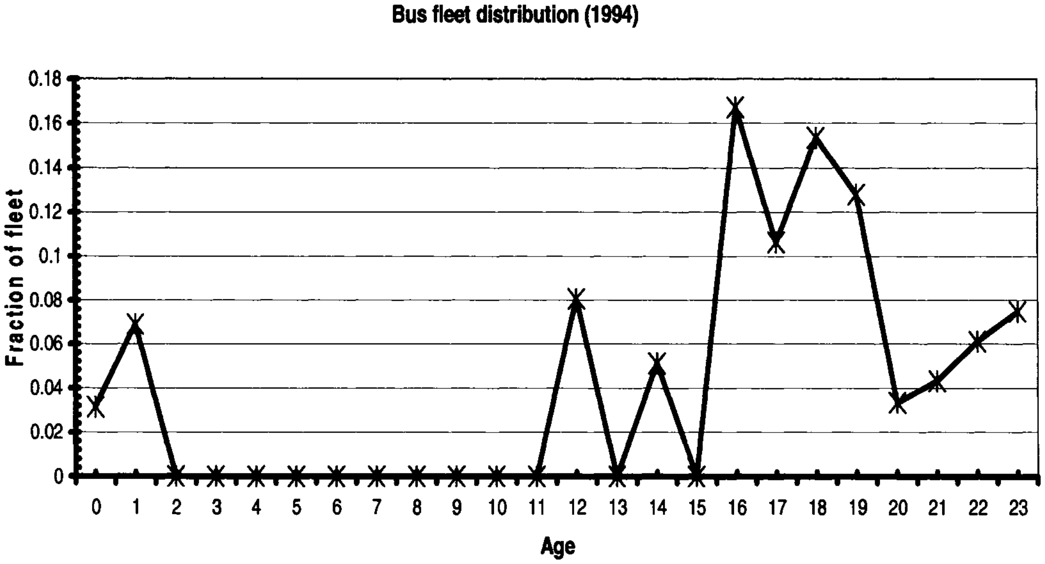


Figure H-8: Bus fleet age distribution extracted from the list of vehicles operating in 1994.

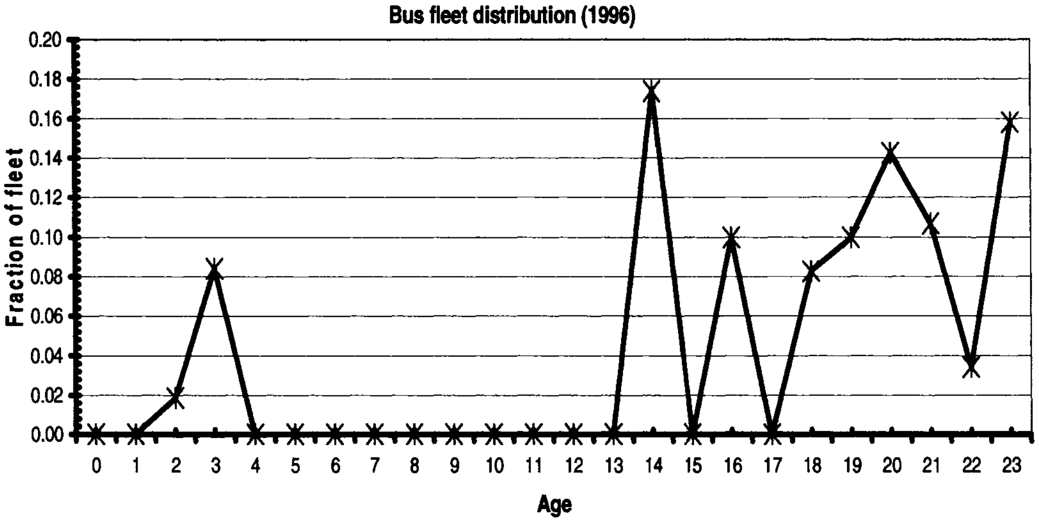


Figure H-9: Bus fleet age distribution extracted from the list of vehicles operating in 1996.

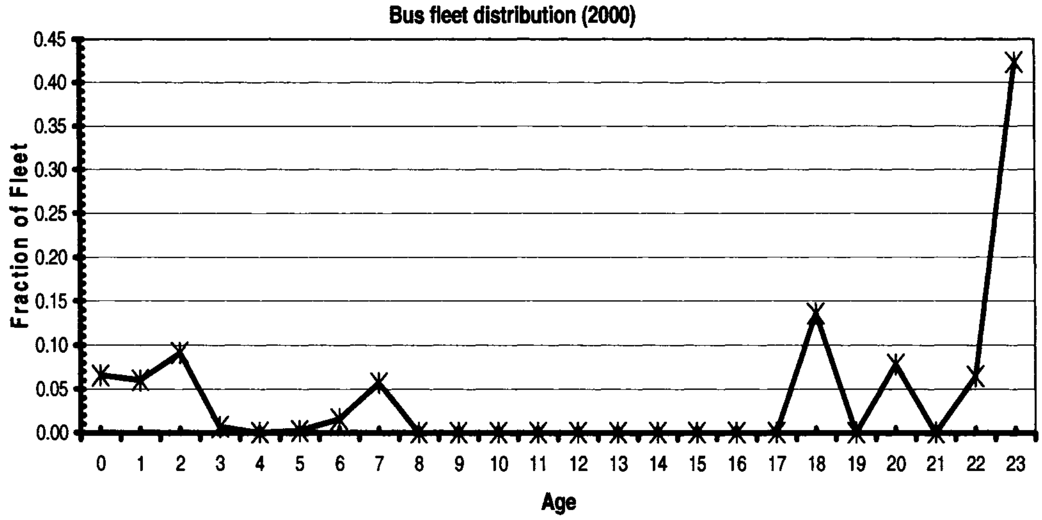


Figure H-10: Bus fleet age distribution extracted from the list of vehicles operating in 2000.

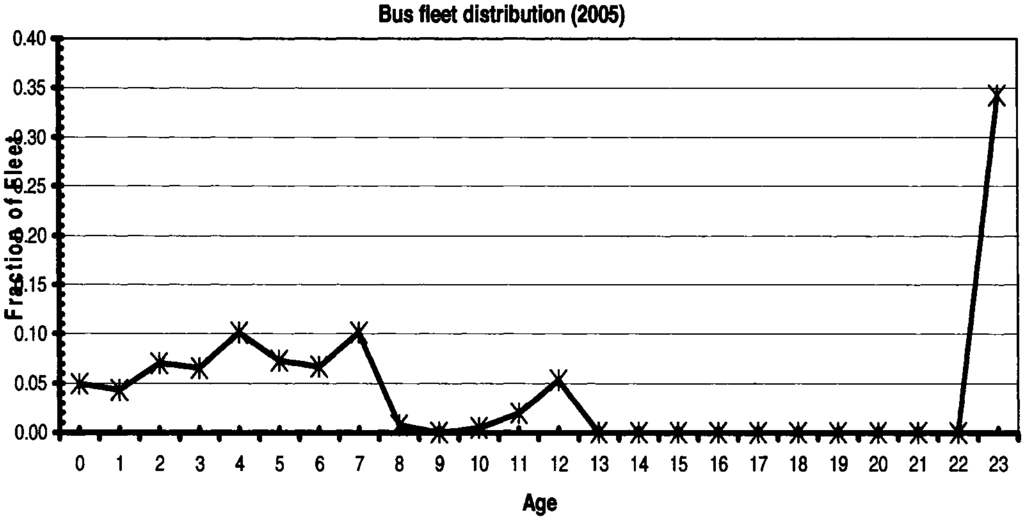


Figure H-11: Bus fleet age distribution extracted from the list of vehicles operating in 2005.

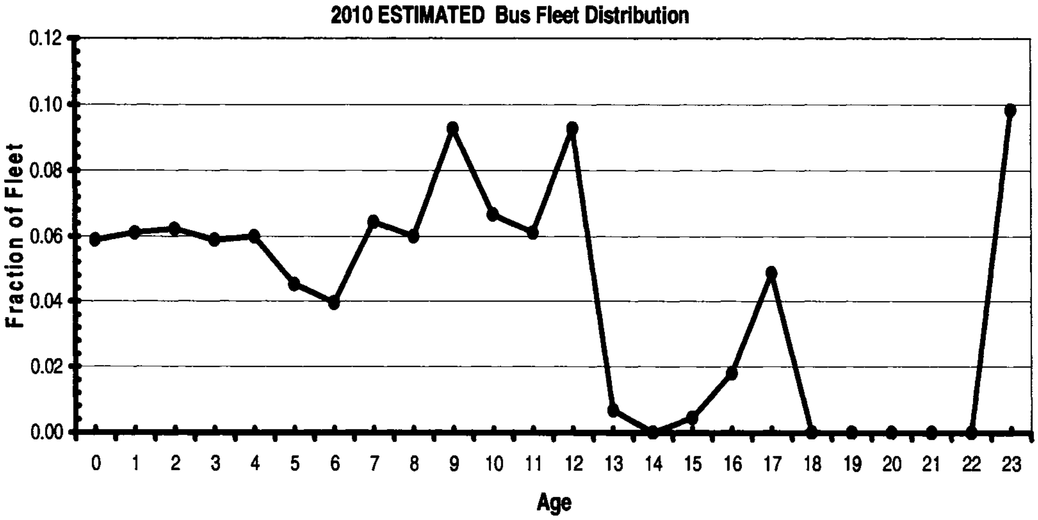


Figure H-12: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2010.

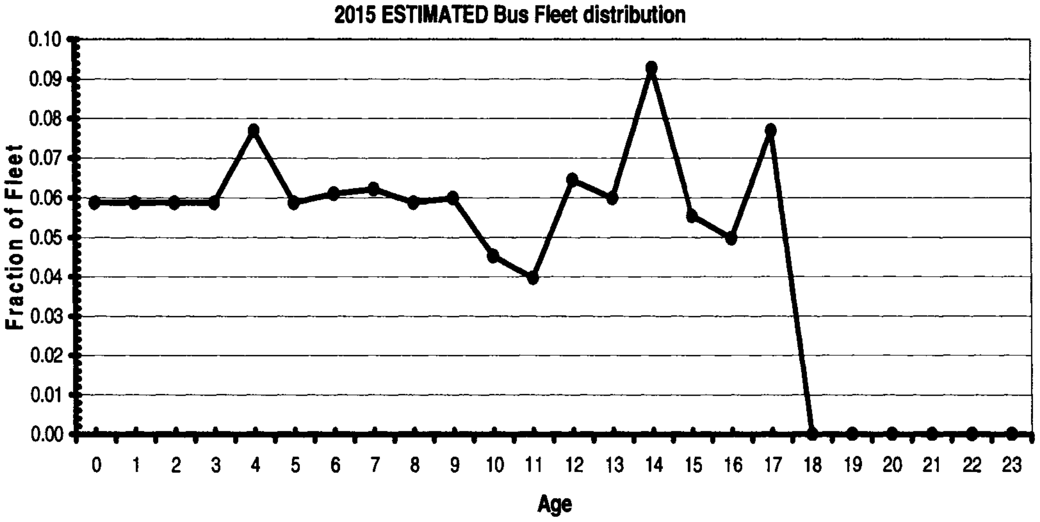


Figure H-13: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2015.

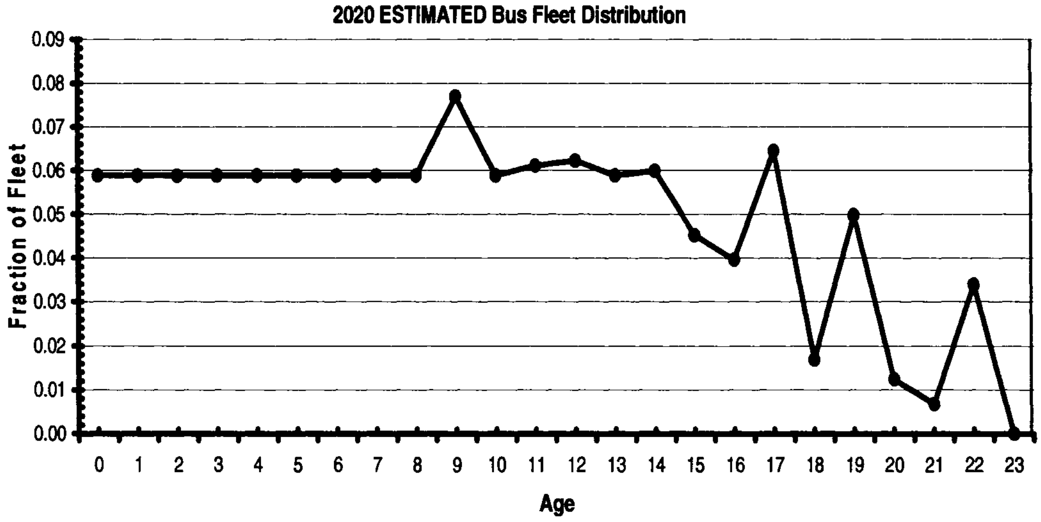


Figure H-14: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2020.

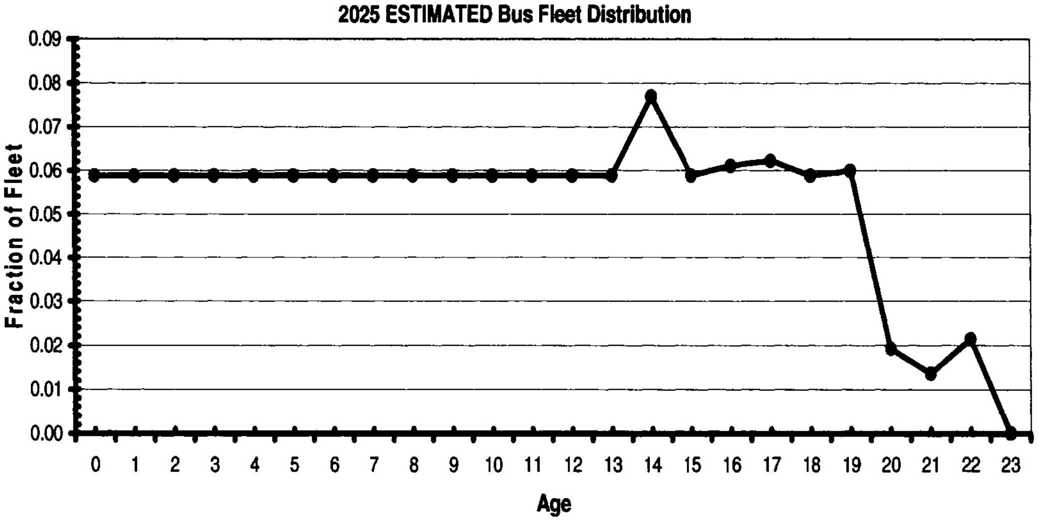


Figure H-15: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2025.

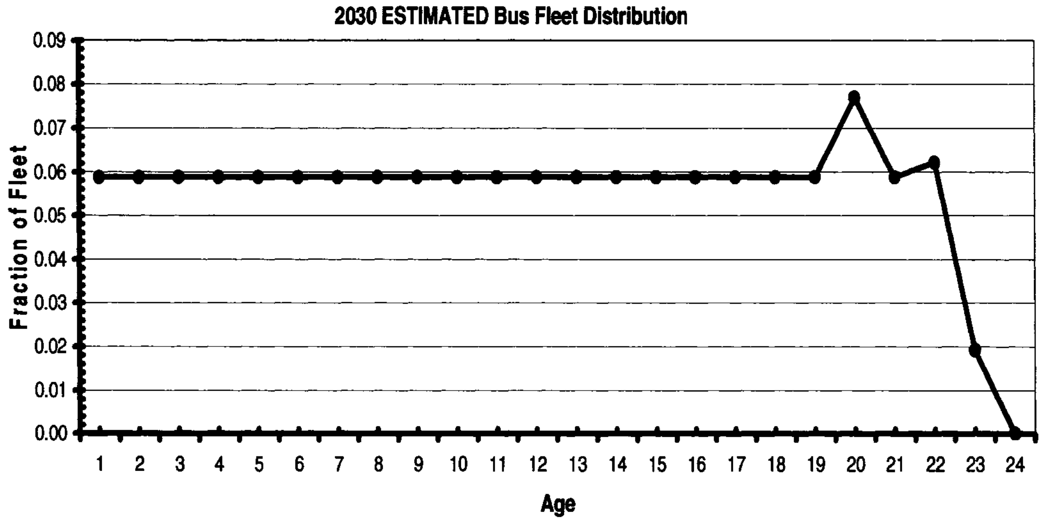


Figure H-16: Bus fleet age distribution extracted from the predicted number of vehicles operating in 2030.

REFERENCES

1. US EPA, "Fleet Characterization Data for MOBILE6: Development and Use of Age Distributions, Average Annual Mileage Accumulation Rates and Projected Vehicle Counts for Use in MOBILE6", EPA420-P-99-011, M6.FLT.007, Apr 1999.
2. Busawon, R.; Checkel, M.D., "Predicting On-Road Vehicle Emissions Inventories", Association Québécoise du Transport et des Routes (AQTR), Québec, April 2006.
3. *City of Edmonton vehicle registration data for the year 2005. Forwarded by Lorraine Doblanko of City of Edmonton, Transportation Planning.

APPENDIX I

Bus Composite Base Emission Rates

As for the buses, specific information about the evolution of the bus fleet was obtained from Edmonton Transit. It was seen that the fleet-age distribution profile has been changing drastically over past years. Hence, it is important to consider the changing bus fleet when estimating the composite base emission rates. Appendix I presents the composite base emission rates for the buses.

I.1 INTRODUCTION

Edmonton Transit provided specific information about the bus fleet. Drastic change in the fleet-age distribution profile has been observed over the past years. With the future development plan of Edmonton Transit, the profile is expected to change further. Such profiles were available for years 1989, 1994, 1996, 2000 and 2005. They were predicted for years 2010, 2015, 2020, 2025 and 2030. For each of those years, past and future, a composite base emission rate has been extracted for the *heavy-duty gasoline bus* (HDGB), *heavy-duty diesel transit bus* (HDDBT) and *heavy-duty diesel school* bus (HDDBS). Subsequently, linear interpolation between the data-points gives the composite base emission rates for the remaining years. These are demonstrated by Figures I-1 – I-4 for hydrocarbon, carbon dioxide, nitrogen oxides and the particulates. These composite are used in the calibration process of the emission and fuel consumption functions for the buses. Table I-1 gives the composite base emission rates for the buses.

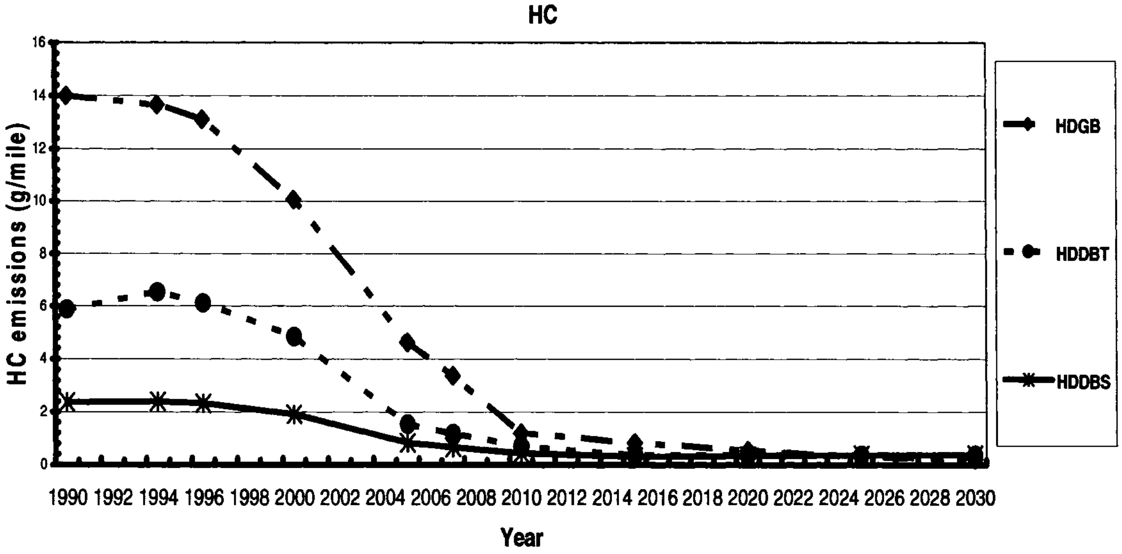


Figure I-1: Evolution of the composite base emission rate of hydrocarbon from the transit and school bus fleet.

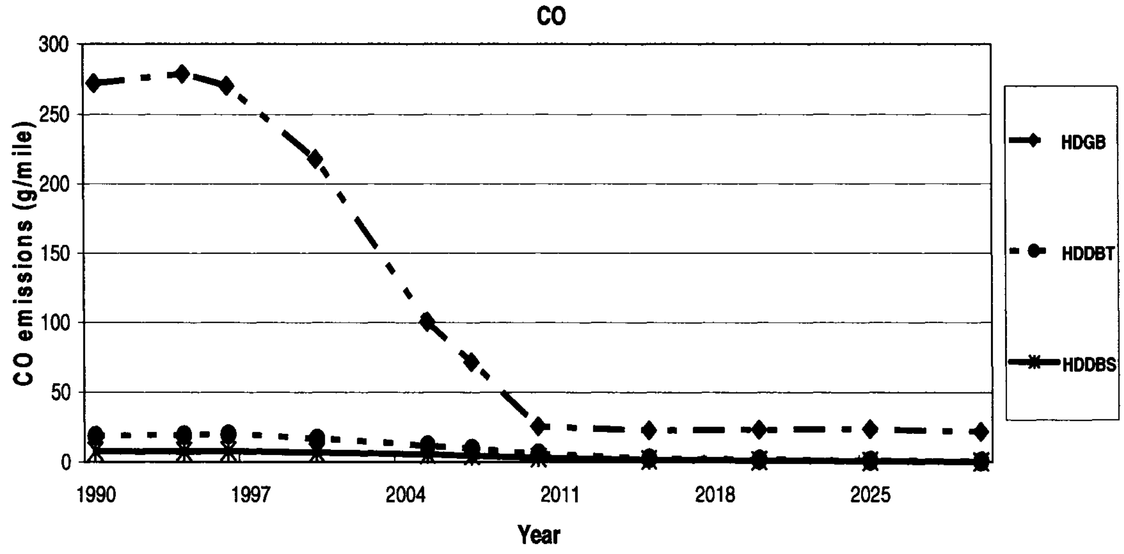


Figure I-2: Evolution of the composite base emission rate of carbon dioxide from the transit and school bus fleet.

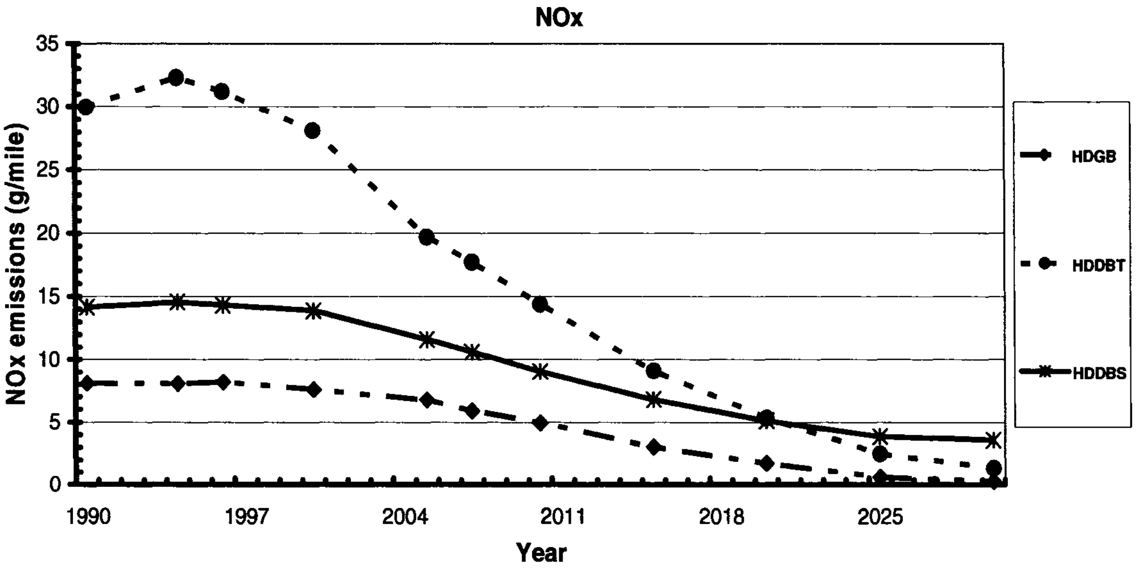


Figure I-3: Evolution of the composite base emission rate of nitrogen oxides from the transit and school bus fleet.

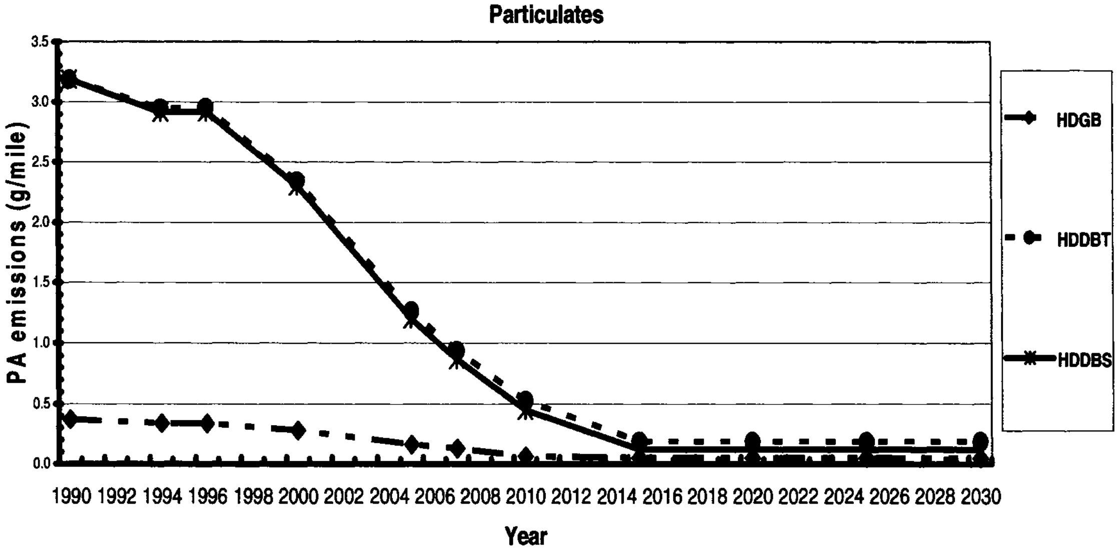


Figure I-4: Evolution of the composite base emission rate of particulate matter from the transit and school bus fleet.

MODEL	HDGB				HDDBT				HDDBS			
YEAR	*HC*	*CO*	*NOx*	*Pa*	*HC*	*CO*	*NOx*	*Pa*	*HC*	*CO*	*NOx*	*Pa*
1990	**13.993**	**271.876**	**8.086**	**0.370**	**6.871**	**18.644**	**29.972**	**3.185**	**2.365**	**7.589**	**14.162**	**3.185**
1991	13.909	273.581	8.072	0.362	6.033	18.788	30.549	3.126	2.373	7.578	14.265	3.118
1992	13.826	275.285	8.059	0.354	6.195	18.932	31.126	3.066	2.382	7.566	14.368	3.050
1993	13.743	276.990	8.046	0.346	6.356	19.076	31.702	3.007	2.391	7.554	14.471	2.983
1994	**13.659**	**278.694**	**8.033**	**0.338**	**6.518**	**19.220**	**32.279**	**2.948**	**2.400**	**7.542**	**14.575**	**2.915**
1995	13.381	274.452	8.108	0.338	6.316	19.589	31.724	2.950	2.364	7.707	14.450	2.916
1996	**13.102**	**270.209**	**8.182**	**0.338**	**6.114**	**19.958**	**31.169**	**2.953**	**2.329**	**7.871**	**14.326**	**2.916**
1997	12.343	257.103	8.029	0.322	5.792	19.171	30.401	2.800	2.223	7.639	14.214	2.762
1998	11.583	243.998	7.876	0.307	5.471	18.385	29.633	2.648	2.117	7.407	14.101	2.609
1999	10.824	230.892	7.723	0.291	5.150	17.599	28.865	2.495	2.011	7.175	13.988	2.455
2000	**10.065**	**217.786**	**7.570**	**0.276**	**4.828**	**16.813**	**28.098**	**2.342**	**1.905**	**6.943**	**13.876**	**2.301**
2001	8.975	194.341	7.396	0.253	4.169	15.812	26.419	2.126	1.692	6.646	13.423	2.081
2002	7.886	170.896	7.221	0.230	3.509	14.811	24.741	1.911	1.478	6.350	12.970	1.861
2003	6.797	147.451	7.047	0.208	2.849	13.809	23.062	1.695	1.264	6.054	12.517	1.641
2004	5.708	124.006	6.873	0.185	2.189	12.808	21.384	1.480	1.051	5.757	12.064	1.420
2005	**4.619**	**100.560**	**6.698**	**0.162**	**1.530**	**11.807**	**19.705**	**1.264**	**0.837**	**5.461**	**11.612**	**1.200**
2006	3.989	86.074	6.278	0.145	1.355	10.689	18.700	1.101	0.752	5.053	11.111	1.034
2007	3.359	71.588	5.857	0.128	1.181	9.571	17.695	0.938	0.667	4.645	10.610	0.868
2008	2.637	56.139	5.549	0.107	1.020	8.442	16.598	0.801	0.593	4.199	10.086	0.728
2009	1.915	40.691	5.240	0.086	0.859	7.313	15.502	0.664	0.518	3.754	9.561	0.588
2010	**1.194**	**25.242**	**4.932**	**0.065**	**0.698**	**6.184**	**14.406**	**0.527**	**0.444**	**3.308**	**9.037**	**0.449**
2011	1.120	24.677	4.543	0.063	0.633	5.491	13.337	0.459	0.418	2.991	8.587	0.383
2012	1.046	24.111	4.154	0.060	0.568	4.798	12.268	0.391	0.392	2.673	8.137	0.317
2013	0.972	23.546	3.765	0.058	0.503	4.105	11.199	0.323	0.366	2.356	7.686	0.251
2014	0.898	22.980	3.376	0.056	0.439	3.412	10.130	0.255	0.339	2.039	7.236	0.186
2015	**0.824**	**22.415**	**2.987**	**0.054**	**0.374**	**2.719**	**9.062**	**0.187**	**0.313**	**1.722**	**6.786**	**0.120**
2016	0.770	22.506	2.729	0.054	0.374	2.527	8.315	0.187	0.319	1.598	6.448	0.120
2017	0.715	22.597	2.472	0.054	0.374	2.335	7.568	0.187	0.326	1.474	6.110	0.120
2018	0.661	22.688	2.214	0.054	0.374	2.143	6.822	0.187	0.332	1.350	5.772	0.120
2019	0.606	22.779	1.957	0.054	0.374	1.951	6.075	0.187	0.339	1.226	5.434	0.120
2020	**0.552**	**22.871**	**1.699**	**0.054**	**0.374**	**1.759**	**5.328**	**0.187**	**0.345**	**1.102**	**5.096**	**0.120**
2021	0.503	22.935	1.483	0.054	0.374	1.591	4.751	0.187	0.350	0.993	4.849	0.120
2022	0.454	22.999	1.267	0.054	0.374	1.423	4.175	0.187	0.356	0.885	4.602	0.120
2023	0.406	23.063	1.051	0.054	0.374	1.255	3.598	0.187	0.362	0.777	4.355	0.120
2024	0.357	23.127	0.835	0.054	0.374	1.087	3.021	0.187	0.367	0.668	4.108	0.120
2025	**0.308**	**23.192**	**0.619**	**0.054**	**0.374**	**0.920**	**2.444**	**0.187**	**0.373**	**0.560**	**3.861**	**0.120**
2026	0.292	22.838	0.550	0.053	0.374	0.839	2.222	0.187	0.375	0.494	3.804	0.120
2027	0.277	22.485	0.481	0.051	0.374	0.758	1.999	0.187	0.378	0.428	3.746	0.120
2028	0.261	22.131	0.412	0.050	0.374	0.677	1.777	0.187	0.381	0.361	3.689	0.120
2029	0.246	21.778	0.343	0.048	0.374	0.596	1.554	0.187	0.383	0.295	3.632	0.120
2030	**0.230**	**21.424**	**0.274**	**0.047**	**0.374**	**0.515**	**1.332**	**0.187**	**0.386**	**0.229**	**3.574**	**0.120**

Table I-1: Composite base emission rates for the transit and school buses.

APPENDIX J

Estimating Carbon Dioxide Emission and Fuel Consumption for Cold-Started Light-Duty Vehicle

US EPA has given emission rates for the criteria pollutants for cold-started light-duty vehicle or light-duty truck. No emission rate for carbon dioxide has been provided. Moreover, fuel consumption for cold-started vehicles is unavailable. This section develops a methodology to estimate such emission and fuel consumption for cold-started light-duty vehicles.

J.1 INTRODUCTION

Cold-started vehicles emit higher and consume more. This excess emission and fuel consumption make a significant contribution to the emission inventory. As a result, it is vital to account for the effect of cold starts. It is worth to recall that CALMOB6 assumes that these excess emissions are emitted linearly over a distance of 2 km after a light-duty vehicle is cold-started.

US EPA has developed extensive database of base emission rates of criteria pollutants (CO, NOx and HC). Further, it has accounted the effects of cold-starts on those criteria pollutants for light-duty vehicles only – passenger cars and light-duty trucks. No emission of carbon dioxide and fuel consumption have, however, been considered by the US EPA for cold-starts.

This section presents a simple methodology to estimate the effect of cold starts on fuel consumption and carbon dioxide emission.

J.2 LITERATURE AVAILABLE

Not many studies are available to demonstrate the effects of cold-starts on carbon dioxide and fuel consumption for North American vehicles. Hawirko *et al* [1] has tried to correlate such effects. In this context, a three-quarter ton regular GMC pickup was used as test vehicle. The model year of the light-duty truck is 1990. The odometer read approximately 187,000 at the start of the experiment to reach around 189,000 by the end.

The vehicle was run on specific speed traces, closely matching the FTP cycles. In this way, amount of emissions and fuel consumption have been measured for the Bag 1, Bag 2 and Bag 3 portions of the model FTP-75 cycle followed (see Figure G-1). Amongst the emissions considered are CO, NOx, CO_2 and HC. Gasoline was the fuel used.

The tests were performed when the vehicle has been cold-started. Three sample test-results are presented. These were obtained when emission and fuel consumption data were collected by running the vehicle on three different days. Further more, the data was averaged to give a better picture of the effect of cold-starts.

J.3 METHODOLOGY

Following the vehicle classification schemes, the ¾-ton GMC truck has been classified as LDT 3. Moreover, according to the accumulated mileage, the vehicle has been correlated to a 6.5-year old one. As a result, the MOBILE6 composite base emission rate for model year 1996 is applicable to this vehicle.

With respect to the EPA requirements, the effect of cold-start is obtained through the difference between Bag 1 and 3 emissions. This accounts for the excess resulting emissions.

The following table illustrates the averaged emission and fuel consumption values.

	Segment (or Bag)		
	I	**II**	**III**
CO (g)	178	63.8	27.0
CO_2 (g)	2300	3520	1540
NOx (g)	5.52	2.20	0.92
THC (g)	5.43	5.36	1.27
Fuel (g)	891	1233	542

Table J-1: Total amounts of emissions and fuel consumption measured under the three segments – Bag 1, Bag 2 and Bag 3. These are averaged values from three tests [1].

Hence, the effect of cold start is accountable. It can be observed that 349 g of excess fuel has been consumed; i.e. (891 g – 542 g). This applies for a LDT 3 of model fleet year 1996.

As discussed previously, Natural Resources Canada has a database of fuel consumption rate for light-duty vehicles. This applies for the Light-duty vehicles and light-duty trucks as illustrated in section 3.6.1 and Appendix E.2 (reproduced in Figure J-1). Information is available for model years starting 1980 and ending 2001. With suitable projection, the fuel consumption (FC) has been extended to 2030. It is assumed, here, that the amount of excess fuel consumed due to cold start will follow the same trend as the FC rate predicted over the years.

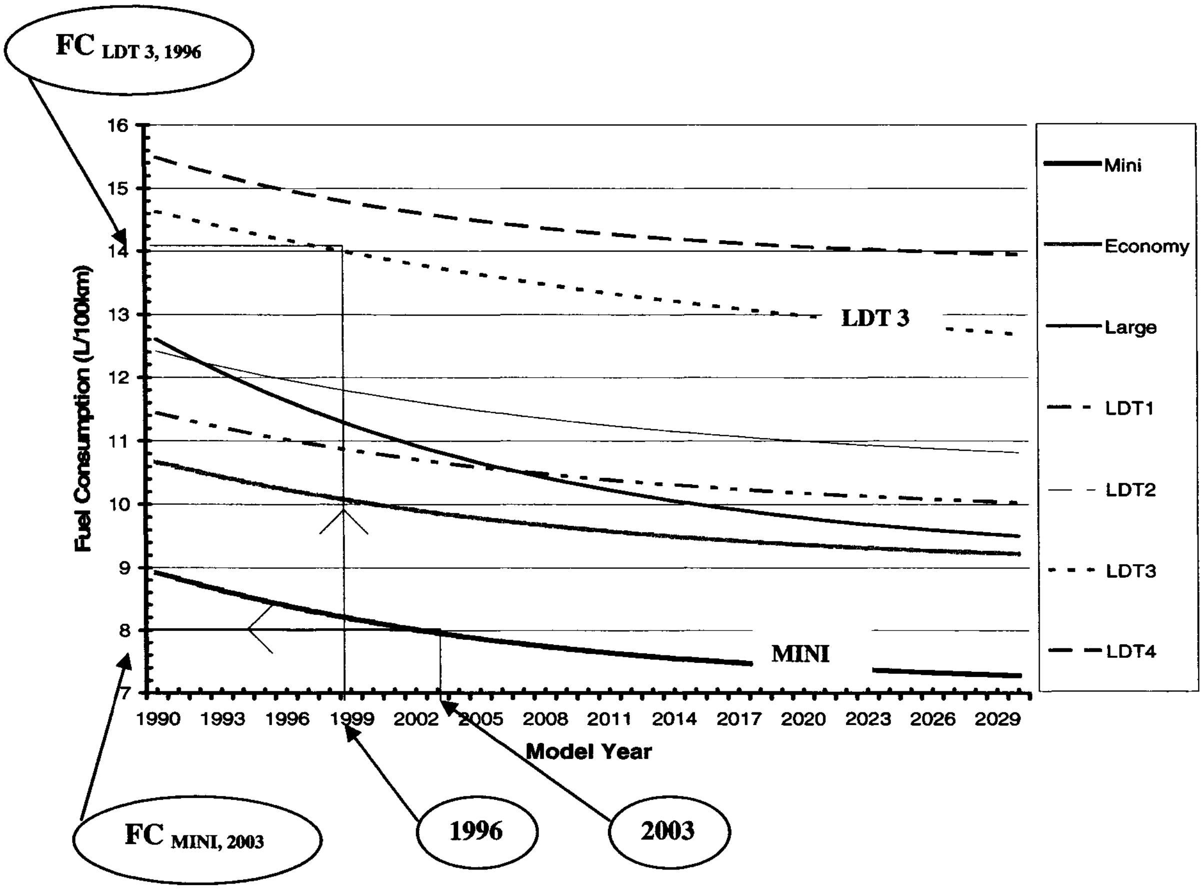


Figure J-1: Comparison of the Light-Duty fleet predicted gasoline fuel consumption.

The NR Can FC for LDT 3 and model year 1996 is used as a baseline. Thus, to estimate the cold-start fuel consumption for other light duty vehicles, a linear adjustment is made.

Figure J-1 shows the usual rate of fuel consumption for an LDT 3 ($FC_{LDT\,3,\,1996}$) in model year 1996. $FC_{LDT\,3,\,1996}$ is the baseline. To estimate cold start fuel consumption rate for a say, a Mini car in 2003, $FC_{MINI,\,2003}$ is needed as well. Subsequently, the following relationship is applied to have the amount of fuel consumed when a Mini car is cold-started:

$$\textbf{Fuel Consumption due to cold-start of Mini Car} = \textbf{349 grams} \times \left(\frac{FC_{MINI,\,2003}}{FC_{LDT\,3,\,1996}} \right)$$

Equation J-1: Equation used to generate the excess amount of fuel consumption when a light-duty vehicle is cold-started.

In this way, the amount of excess fuel consumed during cold-starts can be estimated for all the light-duty vehicle subclasses and for the wide range of years. Finally, using the normal mass balance Equations 3-2 and 3-3, the amount of cold-start carbon dioxide can be computed.

REFERENCES

1. Hawirko, J.D.; Checkel, M.D., "Quantifying vehicle Emission Factors for Various Ambient Conditions using an On-Road, Real-Time Emissions System", SAE 2003-01-0301, Mar 2003.

APPENDIX K

Comparative Emissions and Fuel Consumption from Alternative-Fuelled Vehicles

Appendix K is a literature review on the alternative-fuel vehicles. Emission rates and fuel economy from these vehicles are gathered from various published technical literatures. These rates and economy values are compared with the standard vehicles. For light-duty vehicles, the standard fuel is gasoline while diesel is the baseline fuel for the heavy-duty vehicles. Subsequently, comparative factors that relate the E&FC rates from alternative-fuel vehicles to the baseline-fuel vehicles are given.

K.1 INTRODUCTION

CALMOB6 has been adapted to include emission and fuel consumption for various vehicles including those powered by natural gas, propane (liquefied petroleum gas), methanol (M85), ethanol (E85) and electricity. Comparative factors were used to adjust E&FC from gasoline/diesel vehicles to those from alternative-fuel vehicles. This is described by the following equation:

$$\mathbf{E\&FC}_{\mathrm{ALT.\text{-}FUEL}} = \textbf{\textit{COMPARATIVE FACTOR}} \times \mathbf{E\&FC}_{\mathrm{GASOLINE/DIESEL}} \quad \ldots\ldots. E.q\ K\text{-}1$$

CALMOB6 applies these comparative factors to adjust the already calibrated E&FC functions for gasoline and diesel vehicles.

The following is a literature review of the emission and fuel consumption rates for light- and heavy-duty vehicles. Most literatures use gasoline to compare such rates for the light-duty fleet. Likewise, diesel is mainly used as baseline for the heavy-duty vehicles.

K.2 NMHC, CO, NOX EMISSIONS FROM NATURAL GAS, PROPANE AND METHANOL LIGHT- AND HEAVY-DUTY VEHICLES

Dhaliwal *et al* [1] has already compiled a set of relative indexes for hydrocarbon, nitrogen oxides and carbon monoxide emissions. They apply both for the light and heavy-duty vehicles. For the light-duty vehicles, the alternative fuels concerned are Liquid Petroleum Gasoline (LPG - 90% of which is propane), Compressed Natural Gas (CNG) and Methanol (M85).The same fuels are considered for the heavy-duty vehicles, except that Methanol (M100) was compared rather that M85. Gasoline was used as baseline fuel for the light-duty vehicles whereas diesel was the baseline for the heavy-duty vehicles.

Tabulated below (in Tables K-1 – K-6) are the set of relative emissions indices (REI) as a percentage change. These are averaged. The relative emissions index is given by [1]:

Relative Emissions Index, REI = 100% x (A-B) / B ....*E.q K-2*

where:

A: emission rate of pollutant from Alternative fuelled vehicles

B: emission rate of pollutant from the Baseline fuelled vehicles.

From the relative index, the comparative factors can be described as follows:

Comparative Factor = 1 + (Average REI) / 100 ....*E.q K-3*

S/N	NMHC	CO	NOx
1	n/a	-30	-40
2	-14	69	32
3	-80	-64	-81
4	-90	-58	-50
5	n/a	-60	-13
6	-72	-21	39
7	-99	-42	-11
8	-80	274	160
9	-53	42	13
10	-83	-66	-31
11	-84	218	150
Average	**-73**	**24**	**15**

Table K-1: Average of relative emissions indices, from CNG *light-duty* vehicles. Baseline: Gasoline.

S/N	NMHC	CO	NOx
1	n/a	-71	210
2	n/a	-19	40
3	n/a	-36	53
4	178	-67	77
Average	**178**	**-48**	**95**

Table K-2: Average of relative emissions indices, from LPG *light-duty* vehicles. Baseline: Gasoline.

S/N	NMHC	CO	NOx
1	55	-13	-11
2	n/a	8	-5
3	55	81	-20
4	n/a	0	18
5	45	-2	11
6	67	67	-43
7	n/a	-55	11
8	-23	-17	34
9	-57	-44	87
Average	**24**	**3**	**9**

Table K-3: Average of relative emissions indices, from Methanol (M85) *light-duty* vehicles. Baseline: Gasoline.

S/N	THC	CO	NOx	PM
1	-42	-90	-57	-99
2	756	-37	-6	n/a
3	265	-94	-36	-97
4	321	-84	-26	-93
5	450	-87	-76	-96
6	-83	-93	-99	-94
7	216	200	-72	-81
8	281	-94	-36	-98
9	1083	43	6	-77
10	658	-93	-52	-99
11	530	17	-54	-98
12	n/a	-75	-56	-90
13	554	-94	-55	-99
Average	**416**	**-45**	**-48**	**-93**

Table K-4: Average of relative emissions indices, from CNG *heavy-duty* vehicles. Baseline: Diesel.

S/N	NMHC	CO	NOx	PM
1	-38	-95	-55	-94

Table K-5: Average of relative emissions indices, from LPG *heavy-duty* vehicles. Baseline: Diesel.

S/N	THC	CO	Nox	PM
1	-89	-99	-33	-81
2	335	-15	-43	-85
3	525	52	-54	-79
4	230	-15	-43	-71
5	324	-47	-24	-87
6	-37	-24	-41	-84
7	-5.4	-33	1.3	-22
8	-22	-45	-62	-80
9	-100	12	-37	-80
10	30	11	-6.3	n/a
11	679	69	-64	-80
12	13	-22	-48	-84
Average	**157**	**-13**	**-38**	**-76**

Table K-6: Average of relative emissions indices, from Methanol (M100) *heavy-duty* vehicles. Baseline: Diesel.

K.3 FUEL CONSUMPTION RATE FROM NATURAL GAS, PROPANE AND METHANOL LIGHT-DUTY VEHICLES

Kelly *et al* [2] have made two laboratory tests on CNG light-duty vehicles. In laboratory test '1', they obtained a fuel economy of 11.54 mpg for CNG and of 13.10 mpg for Gasoline. In laboratory test '2', CNG consumption was rated at 13.47 mpg while gasoline consumption was rated at 13.91 mpg. On average, the CNG consumption is 12.51 mpg. Similarly, the gasoline consumption is 13.51 mpg. Thence, the comparative factors amounts to 1.08; with gasoline as baseline.

Sun et al [3] stated that the fuel economy on a gasoline equivalent-energy basis of LPG was about 4% lower than that of the baseline gasoline. As a result, this leads to a comparative index of 1.04 for the propane fuel.

Finally, Kelly et al [4] made three laboratory tests on a FFV (Flexible Fuel Vehicle) Dodge Spirit using methanol (M85) and gasoline. Table K-7, below, summarizes the results and gives the average of the 3 tests.

	LAB 1 ,mpg	LAB 2, mpg	LAB 3, mpg	Average ,mpg
Methanol, M85	13.58	12.54	12.78	12.97
Gasoline, RFG	22.82	21.41	24.06	22.76

Table K-7: Average of Methanol (M85) fuel consumption for light-duty vehicles. Baseline: Gasoline.

Hence, the comparative factor results to 1.76 for the Methanol fuel, with gasoline as baseline.

K.4 FUEL CONSUMPTION RATE FROM NATURAL GAS, PROPANE AND METHANOL HEAVY-DUTY VEHICLES

Clark et al [5] performed tests on buses powered by Cummins L-10 Natural Gas Engines. They concluded that the energy-equivalent fuel consumption of the CNG buses was 28.1% poorer than for the diesel buses. Hence, the comparative index of the natural gas heavy-duty vehicle is around 1.28; diesel as baseline.

The Ontario Ministry of Transportation [6] compared two propane trucks destined for a class-8 truck application. Simultaneously, a diesel-powered truck in similar service was monitored. Propane fuel economy averaged to 94 L/100km, relative to 45 L/100km with the diesel. Thus, the propane comparative factor is 2.09; diesel as baseline.

Finally, NYSERDA (New York State Energy Research and Development Authority) states that if the fuel economy of a methanol bus was 1mpg and that of a similar diesel bus was 2.3 mpg, they would both be using fuel with the same efficiency [7]. In this case, if same efficiency is assumed, the comparative factor results to 2.3 for the methanol fuelled heavy-duty vehicle.

K.5 EMISSIONS AND FUEL CONSUMPTION RATES FROM ETHANOL LIGHT-DUTY VEHICLES

Chandler *et al* [8] have made a wide range of tests on ethanol-fuelled light duty vehicles. These are E85 flexible fuel vehicles. Tabulated below are the set of emission rates and fuel economy for the E85 consumption of the FFV and for a standard gasoline engine.

	Ethanol, E85	Standard Gasoline	Comparative Factor
NMHC	0.149 g/mi	0.114 g/mi	1.31
CO	1.33 g/mi	1.39 g/mi	0.96
NOx	0.09 g/mi	0.22 g/mi	0.41
Fuel Economy	15.81 mpg	21.32 mpg	1.35

Table K-8: Emission rates and fuel economy from an Ethanol (E85) FFV and a standard gasoline vehicle [8]. Comparative factors are given as well. Baseline: Gasoline.

K.6 EMISSIONS AND FUEL CONSUMPTION RATES FROM ETHANOL HEAVY-DUTY VEHICLES

Paul Norton of the NREL (National Renewable Energy Laboratory) delegated the task of finding the performance of ethanol fuel trucks to the WVU (West Virginia University) team. The results obtained by the latter team were given as appendix 3 in report [9]. It is worth pointing out that four E95 ethanol fuel was used. Besides, the tests were made on WVU and CBD cycles. The results from the different Test

Sequence Numbers (internal to the WVU team results) are tabulated below (Tables K-9 and K-10), together with the comparative factors in Table K-11.

S/N	Test Sequence No.	CO g/mi	NOx g/mi	RHC g/mi	PM g/mi	Fuel Economy mpg
1	275	27.7	18.5	7.66	0.41	1.23
2	276	15.8	14.4	3.49	0.27	2.07
3	278	38.1	14.0	6.31	0.66	1.52
4	279	23.3	12.6	3.56	0.20	2.84
Average		**26.2**	**14.9**	**5.26**	**0.39**	**1.92**

Table K-9: Emission rates and fuel economy from Ethanol (E95) trucks [9].

S/N	Test Sequence No.	CO g/mi	NOx g/mi	HC g/mi	PM g/mi	Fuel Economy mpg
1	280	8.1	21.2	3.6	1.40	2.87
2	281	4.1	18.8	1.7	0.78	4.93
Average		**6.1**	**20.0**	**2.7**	**1.09**	**3.90**

Table K-10: Emission rates and fuel economy from Diesel trucks [9].

CO g/mi	NOx g/mi	HC g/mi	PM g/mi	Fuel Economy mpg
4.30	0.74	1.98	0.35	2.03

Table K-11: Comparative factors for the emission rates and fuel economy from Ethanol (E95) trucks [9].

K.7 SUMMARY

The following tables (K-12 and K-13) give a summary of the overall results gathered from the various technical literatures. The comparative factors are tabulated and used in CALMOB6 for adjusting the emissions and fuel consumption for alternative-fuel vehicles. Gasoline and diesel are used as baseline fuels for the light- and heavy-duty vehicles respectively.

	NMHC	CO	NOx	Fuel
Natural Gas	0.27	1.24	1.15	1.08
Propane	2.78	0.52	1.95	1.04
Methanol	1.24	1.03	1.09	1.76
Ethanol	1.31	0.96	0.41	1.35

Table K-12: Comparative factors obtained/calculated for the Light-Duty fleet with Gasoline as reference.

	NMHC	CO	NOx	PM	Fuel
Natural Gas	5.16	0.55	0.52	0.07	1.28
Propane	0.62	0.05	0.45	0.06	2.09
Methanol	2.57	0.87	0.62	0.24	2.3
Ethanol	1.98	4.30	0.74	0.35	2.03

Table K-13: Comparative factors obtained/calculated for the Heavy-Duty fleet with Diesel as reference.

REFERENCES

1. Dhaliwal, B.; Yi, N.; Checkel, M.D., “Emissions Effects of Alternative Fuels in Light-Duty and Heavy-Duty Vehicles”, SAE 2000-01-0692, Mar 2000.
2. Kelly, K.J.; Bailey, B.K.; Coburn, T.C.; Eudy, L.; Lissiuk, P., “Round 1 Emissions Results from Compressed Natural Gas Vans and Gasoline Controls operating in the U.S Federal Fleet”, SAE 961096, May 1996.

3. Sun, X.,; Wiedmann, T.; Hussain, S., "Fuel Management and exhaust emissions of light- and heavy-duty trucks operating on CNG and LPG", SAE 971661, May 1997.

4. Kelly, K.J.; Bailey, B.K.; Coburn, T.C.; Clark, W.; Eudy, L.; Lissiuk, P., "FTP Emissions Test results from Flexible-Fuel Methanol Dodge Spirits and Ford Econoline Vans", SAE 961090, May 1996.

5. Clark, N.N.; Lyons, D.W.; Rapp, B.L.; Gautam, M.; Wang, W.; Norton, P.; White, C.; Chandler, K., "Emissions from Trucks and Buses Powered by Cummins L-10 Natural-Gas Engines", SAE 981391, May 1998.

6. Turner, J.E; Topaloglu, T.; Hrynyk, G.S., "Development and demonstration of class 8 propane-powered truck", SAE 901499, Aug 1990.

7. New York State Energy Research and Development Authority (NYSERDA), http://www.nyserda.org/programs/pdfs/vol3sc3.pdf , (site accessed on June 23, 2006)

8. Chandler, K.,; Whalen, M.; Westhoven, J., "Final Results from The State of Ohio Ethanol-Fueled Light-Duty Fleet Deployment Project", SAE 982531, Oct 1998.

9. Norton, P., "The Ethanol Heavy-Duty Truck Fleet demonstration Project", NREL (National Renewable Energy Laboratory), NREL/SR-540-2210, DE97050805, May 1997.

10. Checkel, M.D., "Engine Emissions of Alternative Fuelled Vehicles – The City of Edmonton Transportation Master Plan", Oct 1997.

APPENDIX L

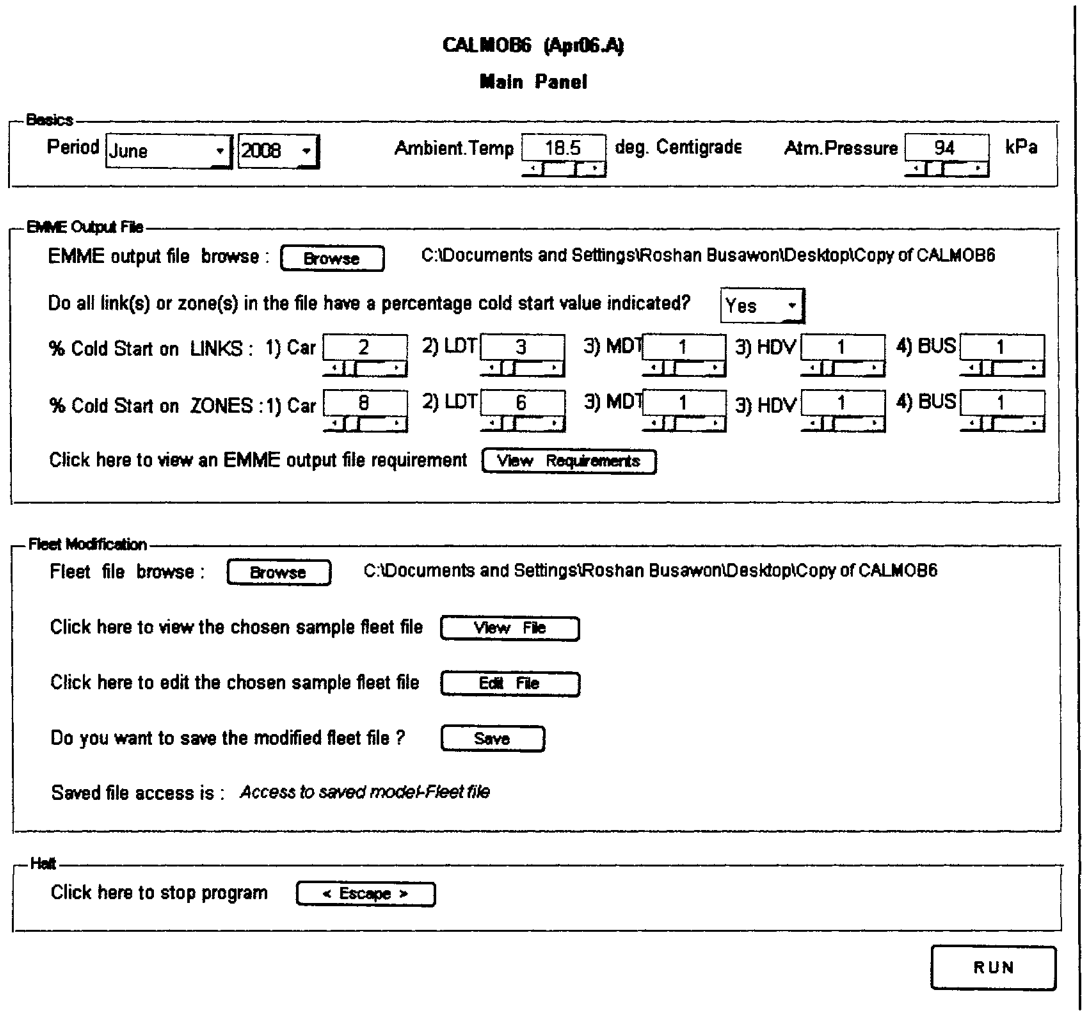
The Graphical User Interfaces (GUI's), EMME/2 Output File and the Fleet File Requirements of 'Classification 2' vehicles

Appendix L completes the section 3.12.5 by illustrating the GUI's for CALMOB6 vehicle 'Classification 2'. The EMME/2 output file requirements and the fleet file design for such classification is presented in this Appendix.

L.1 INTRODUCTION

CALMOB6 uses two main vehicle classification schemes – 'Classification 1' and 'Classification 2'. With the introduction of a new vehicle category (the medium-duty vehicle) in the 'Classification 2' and the re-shuffling of the vehicles to better represent the needs of traffic planners, design of other GUI's and input files has become inevitable.

In Chapter 3, the use of the GUI's has been demonstrated together with the EMME/2 and fleet files requirements. All the demonstration, there, is applicable to the CALMOB6 vehicle 'Classification 1' scheme. This appendix provides an overview of the requirements, in case 'Classification 2' is opted. It is done for the sake of completeness. Hence, Figures 3-25 – 3-35 (except 3-33 and 3-34) are repeated for the second vehicle classification.



CALMOB6 (Apr06.A)

Main Panel

Basics

Period June 2008 Ambient.Temp 18.5 deg. Centigrade Atm.Pressure 94 kPa

EMME Output File

EMME output file browse : C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6

Do all link(s) or zone(s) in the file have a percentage cold start value indicated? Yes

% Cold Start on LINKS : 1) Car 2 2) LDT 3 3) MDT 1 3) HDV 1 4) BUS 1

% Cold Start on ZONES :1) Car 8 2) LDT 6 3) MDT 1 3) HDV 1 4) BUS 1

Click here to view an EMME output file requirement

Fleet Modification

Fleet file browse : C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6

Click here to view the chosen sample fleet file

Click here to edit the chosen sample fleet file

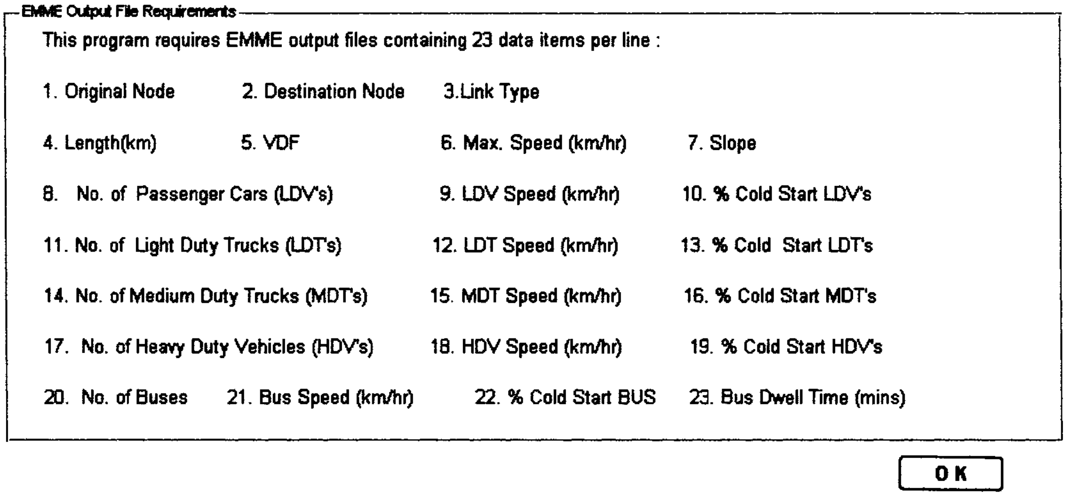
Do you want to save the modified fleet file ?

Saved file access is : *Access to saved model-Fleet file*

Halt

Click here to stop program

Figure L-1: CALMOB6 main panel where all inputs are defined (Classification 2).



EMME Output File Requirements

This program requires EMME output files containing 23 data items per line :

1. Original Node 2. Destination Node 3.Link Type

4. Length(km) 5. VDF 6. Max. Speed (km/hr) 7. Slope

8. No. of Passenger Cars (LDV's) 9. LDV Speed (km/hr) 10. % Cold Start LDV's

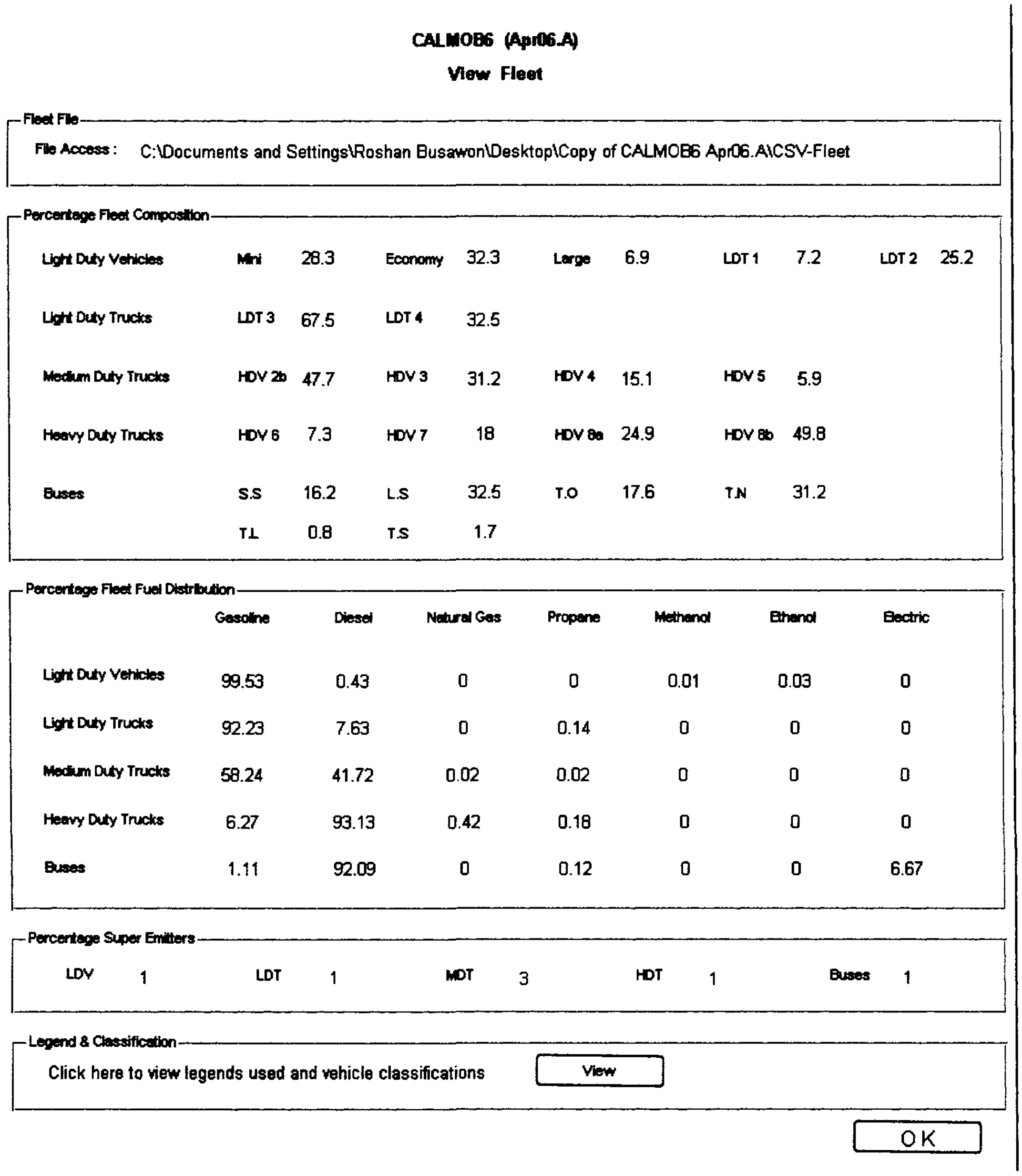
11. No. of Light Duty Trucks (LDT's) 12. LDT Speed (km/hr) 13. % Cold Start LDT's

14. No. of Medium Duty Trucks (MDT's) 15. MDT Speed (km/hr) 16. % Cold Start MDT's

17. No. of Heavy Duty Vehicles (HDV's) 18. HDV Speed (km/hr) 19. % Cold Start HDV's

20. No. of Buses 21. Bus Speed (km/hr) 22. % Cold Start BUS 23. Bus Dwell Time (mins)

Figure L-2: EMME/2 column-by-column dataset required (Classification 2).



CALMOB6 (Apr06.A)

View Fleet

Fleet File

File Access : C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6 Apr06.A\CSV-Fleet

Percentage Fleet Composition

Light Duty Vehicles	Mini	28.3	Economy	32.3	Large	6.9	LDT 1	7.2	LDT 2	25.2
Light Duty Trucks	LDT 3	67.5	LDT 4	32.5						
Medium Duty Trucks	HDV 2b	47.7	HDV 3	31.2	HDV 4	15.1	HDV 5	5.9		
Heavy Duty Trucks	HDV 6	7.3	HDV 7	18	HDV 8a	24.9	HDV 8b	49.8		
Buses	S.S	16.2	L.S	32.5	T.O	17.6	T.N	31.2		
	T.L	0.8	T.S	1.7						

Percentage Fleet Fuel Distribution

	Gasoline	Diesel	Natural Gas	Propane	Methanol	Ethanol	Electric
Light Duty Vehicles	99.53	0.43	0	0	0.01	0.03	0
Light Duty Trucks	92.23	7.63	0	0.14	0	0	0
Medium Duty Trucks	58.24	41.72	0.02	0.02	0	0	0
Heavy Duty Trucks	6.27	93.13	0.42	0.18	0	0	0
Buses	1.11	92.09	0	0.12	0	0	6.67

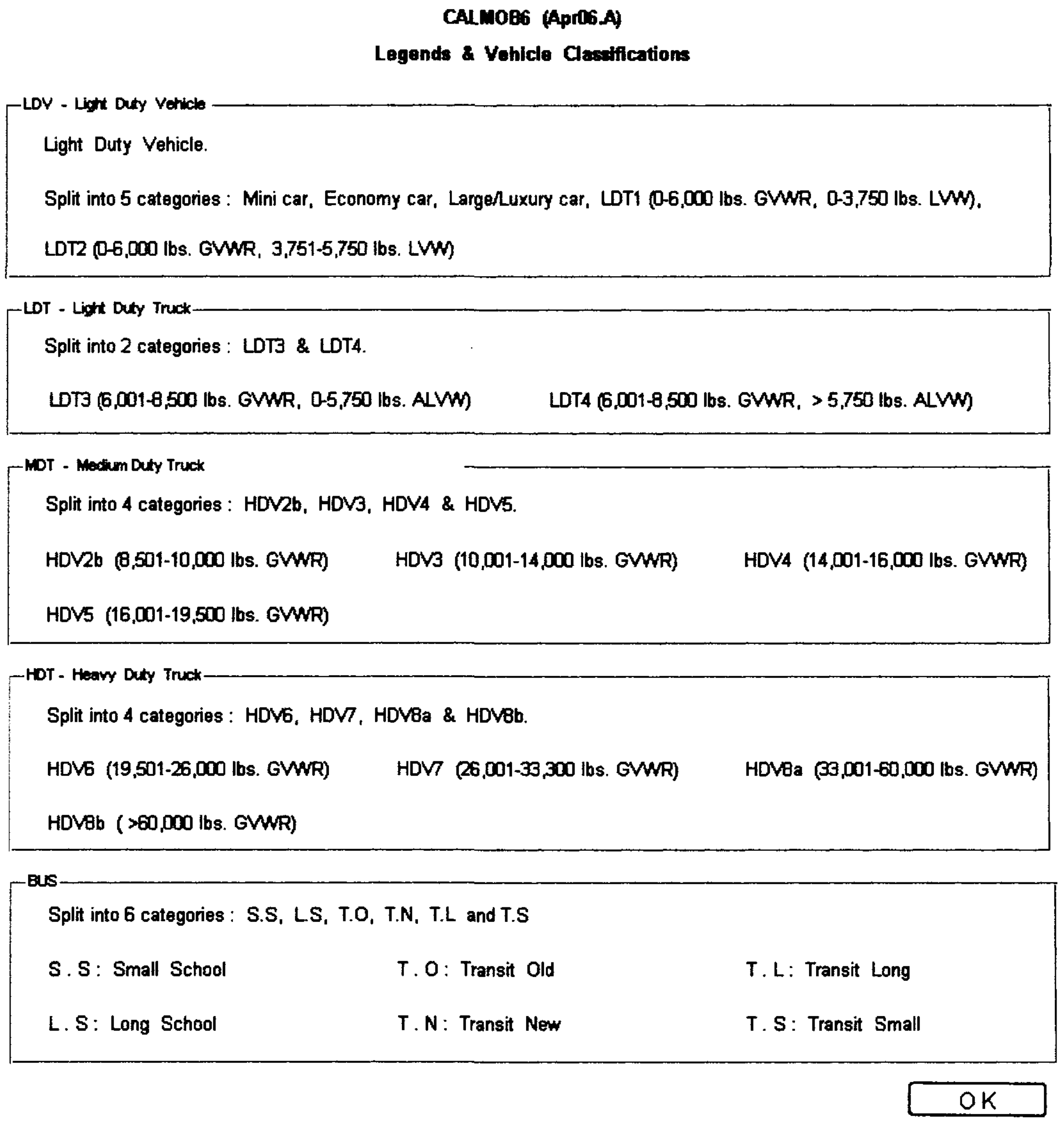
Percentage Super Emitters

LDV	1	LDT	1	MDT	3	HDT	1	Buses	1

Legend & Classification

Click here to view legends used and vehicle classifications

Figure L-3: Content of the chosen fleet file (Classification 2).



CALMOB6 (Apr06.A)

Legends & Vehicle Classifications

LDV - Light Duty Vehicle

Light Duty Vehicle.

Split into 5 categories : Mini car, Economy car, Large/Luxury car, LDT1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW),

LDT2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)

LDT - Light Duty Truck

Split into 2 categories : LDT3 & LDT4.

LDT3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW)
LDT4 (6,001-8,500 lbs. GVWR, > 5,750 lbs. ALVW)

MDT - Medium Duty Truck

Split into 4 categories : HDV2b, HDV3, HDV4 & HDV5.

HDV2b (8,501-10,000 lbs. GVWR)
HDV3 (10,001-14,000 lbs. GVWR)
HDV4 (14,001-16,000 lbs. GVWR)
HDV5 (16,001-19,500 lbs. GVWR)

HDT - Heavy Duty Truck

Split into 4 categories : HDV6, HDV7, HDV8a & HDV8b.

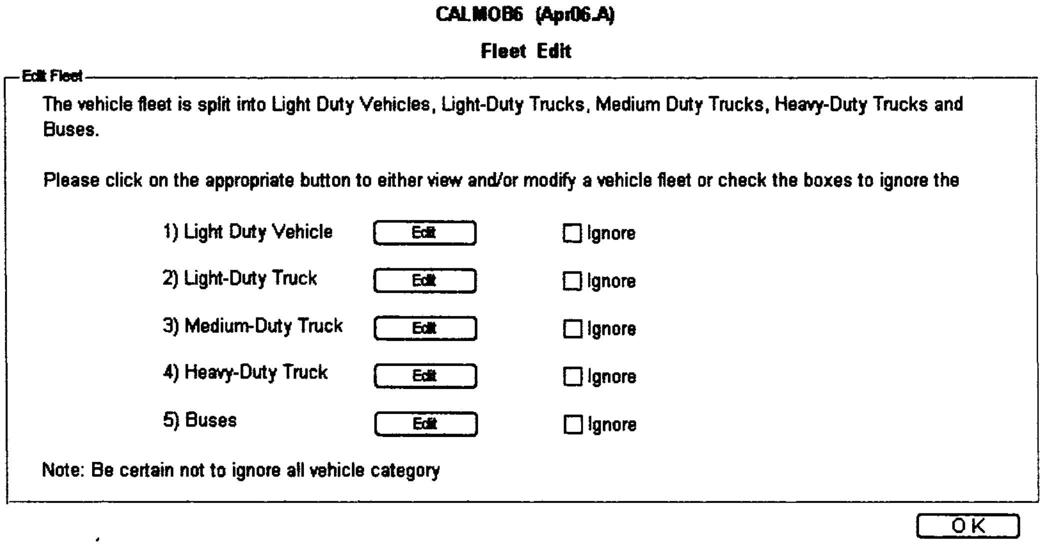
HDV6 (19,501-26,000 lbs. GVWR)
HDV7 (26,001-33,300 lbs. GVWR)
HDV8a (33,001-60,000 lbs. GVWR)
HDV8b (>60,000 lbs. GVWR)

BUS

Split into 6 categories : S.S, L.S, T.O, T.N, T.L and T.S

S . S : Small School
L . S : Long School
T . O : Transit Old
T . N : Transit New
T . L : Transit Long
T . S : Transit Small

Figure L-4: Legends and vehicle classification for the ‘Classification 2’ mode.



CALMOB6 (Apr06.A)

Fleet Edit

Edit Fleet

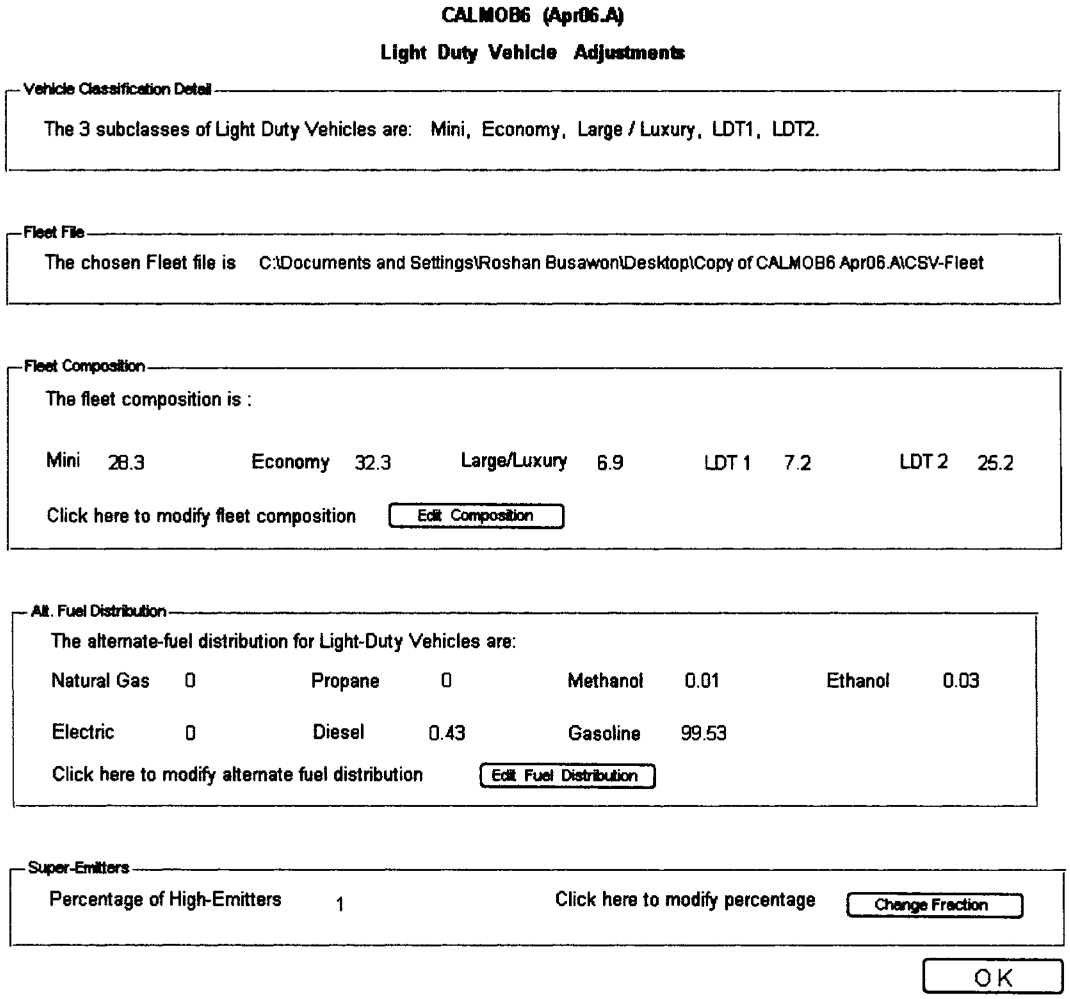
The vehicle fleet is split into Light Duty Vehicles, Light-Duty Trucks, Medium Duty Trucks, Heavy-Duty Trucks and Buses.

Please click on the appropriate button to either view and/or modify a vehicle fleet or check the boxes to ignore the

1) Light Duty Vehicle [Edit] ☐ Ignore
2) Light-Duty Truck [Edit] ☐ Ignore
3) Medium-Duty Truck [Edit] ☐ Ignore
4) Heavy-Duty Truck [Edit] ☐ Ignore
5) Buses [Edit] ☐ Ignore

Note: Be certain not to ignore all vehicle category

Figure L-5: Main window for editing the fleet (Classification 2).



CALMOB6 (Apr06.A)

Light Duty Vehicle Adjustments

Vehicle Classification Detail

The 3 subclasses of Light Duty Vehicles are: Mini, Economy, Large / Luxury, LDT1, LDT2.

Fleet File

The chosen Fleet file is C:\Documents and Settings\Roshan Busawon\Desktop\Copy of CALMOB6 Apr06.A\CSV-Fleet

Fleet Composition

The fleet composition is :

Mini 28.3 Economy 32.3 Large/Luxury 6.9 LDT 1 7.2 LDT 2 25.2

Click here to modify fleet composition

Alt. Fuel Distribution

The alternate-fuel distribution for Light-Duty Vehicles are:

Natural Gas 0 Propane 0 Methanol 0.01 Ethanol 0.03

Electric 0 Diesel 0.43 Gasoline 99.53

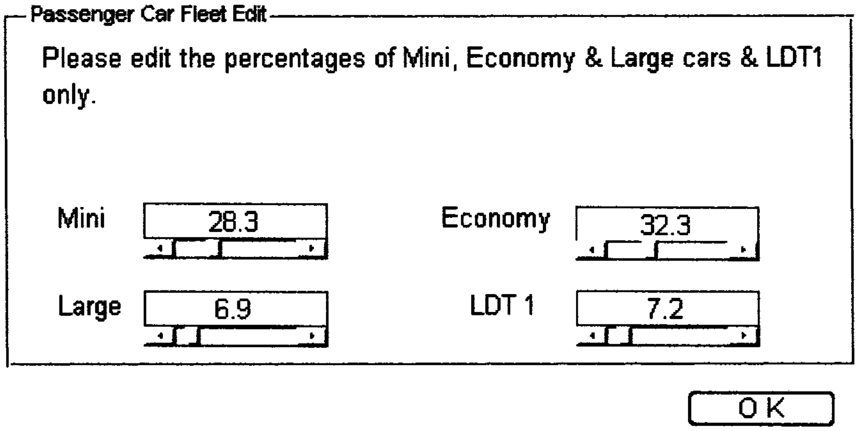
Click here to modify alternate fuel distribution

Super-Emitters

Percentage of High-Emitters 1

Click here to modify percentage

Figure L-6: Sub-window for editing the fleet of the light-duty vehicle category (Classification 2).



Please edit the percentages of Mini, Economy & Large cars & LDT1 only.

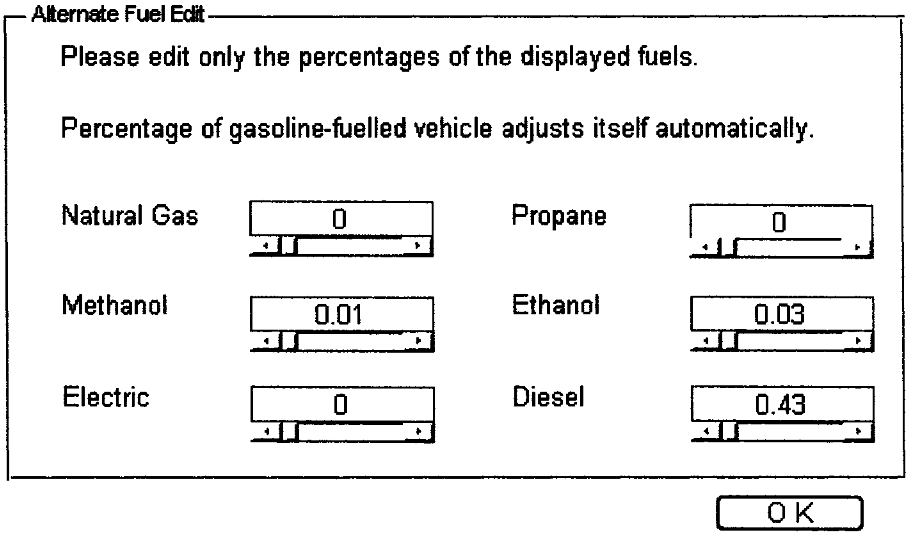
Mini 28.3

Economy 32.3

Large 6.9

LDT 1 7.2

Figure L-7: Sub-window for editing the fleet composition of light-duty vehicle category by the different subclasses (Classification 2).



Please edit only the percentages of the displayed fuels.

Percentage of gasoline-fuelled vehicle adjusts itself automatically.

Natural Gas 0

Propane 0

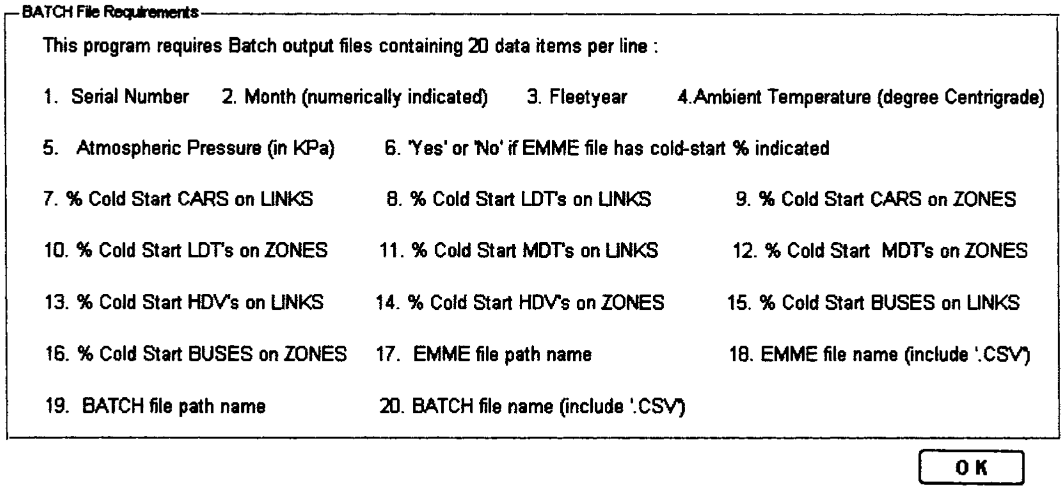
Methanol 0.01

Ethanol 0.03

Electric 0

Diesel 0.43

Figure L-8: Sub-window for editing the alternative fuelled light-duty vehicles (Classification 2).



BATCH File Requirements

This program requires Batch output files containing 20 data items per line :

1. Serial Number
2. Month (numerically indicated)
3. Fleetyear
4. Ambient Temperature (degree Centrigrade)
5. Atmospheric Pressure (in KPa)
6. 'Yes' or 'No' if EMME file has cold-start % indicated
7. % Cold Start CARS on LINKS
8. % Cold Start LDT's on LINKS
9. % Cold Start CARS on ZONES
10. % Cold Start LDT's on ZONES
11. % Cold Start MDT's on LINKS
12. % Cold Start MDT's on ZONES
13. % Cold Start HDV's on LINKS
14. % Cold Start HDV's on ZONES
15. % Cold Start BUSES on LINKS
16. % Cold Start BUSES on ZONES
17. EMME file path name
18. EMME file name (include '.CSV')
19. BATCH file path name
20. BATCH file name (include '.CSV')

Figure L-9: Description of the column-by-column information required in a batch file (Classification 2).

APPENDIX M

Demonstration of Future Emission and Fuel Consumption Trends

Appendix M completes the section 4.6 by illustrating the future emission and fuel consumption trends for passenger car, light-duty truck, heavy-duty vehicle and bus vehicle categories.

M.1 INTRODUCTION

This appendix illustrates the trend in emission and fuel consumption (E&FC) of the light-duty gasoline fleet (passenger car and light-duty truck) and the heavy-duty diesel fleet (heavy-duty vehicle and bus). For reference, the emissions and fuel consumption values are calculated for model year 1990 when such vehicle is cruising at 80 km/hr. Thereafter, the future E&FC from such vehicle category is plotted as a percentage of the base case. These are illustrated in Figures M-1 to M-12.

For each vehicle category, the trends of E&FC are made using the following:

- *Case 1*: 0% growth in traffic in future years,
- *Case 2*: 1% annual growth in traffic, and
- *Case 3*: 2% annual growth in traffic.

Case 1 demonstrates the improvement to be expected as new-standard vehicles take over more of the fleet and change fleet emission characteristics. Subsequently, with the expected growth in traffic population the amount of emissions and fuel consumption are expected to differ.

It is worth pointing out that in all cases the percentage change in carbon dioxide tally with that of fuel consumption. Thus, with negligible amounts of carbon monoxide produced in the combustion, the level of CO2 emitted is proportional to the amount of fuel consumed.

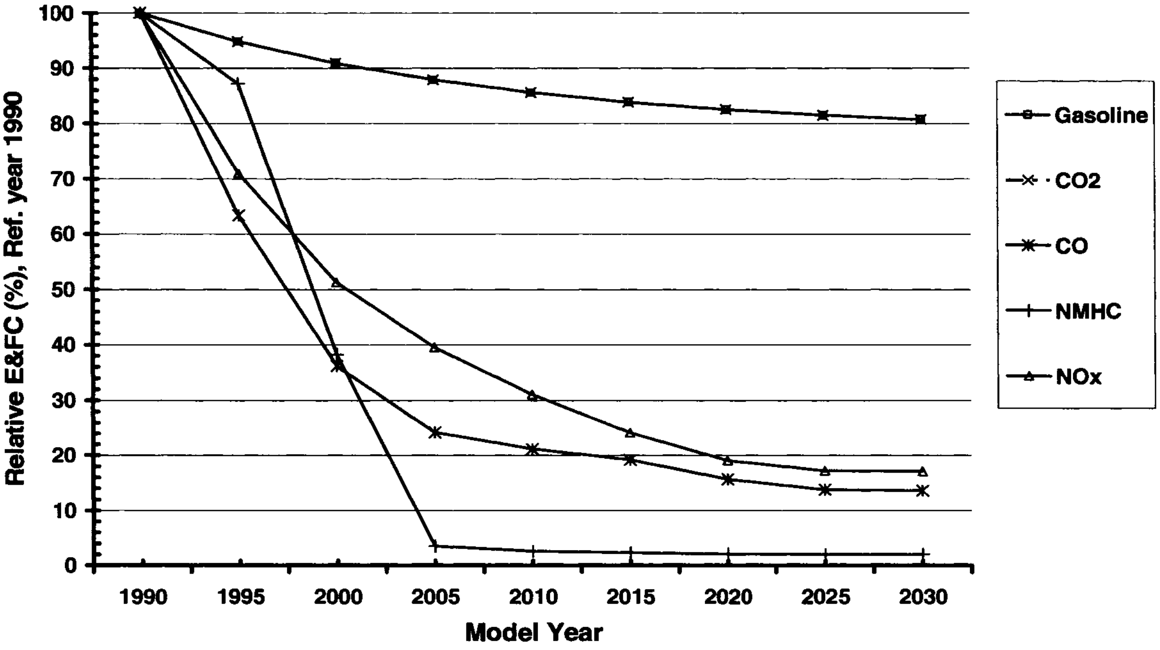


Figure M-1: E&FC trend from a *passenger car* over future years (*0% Growth*).

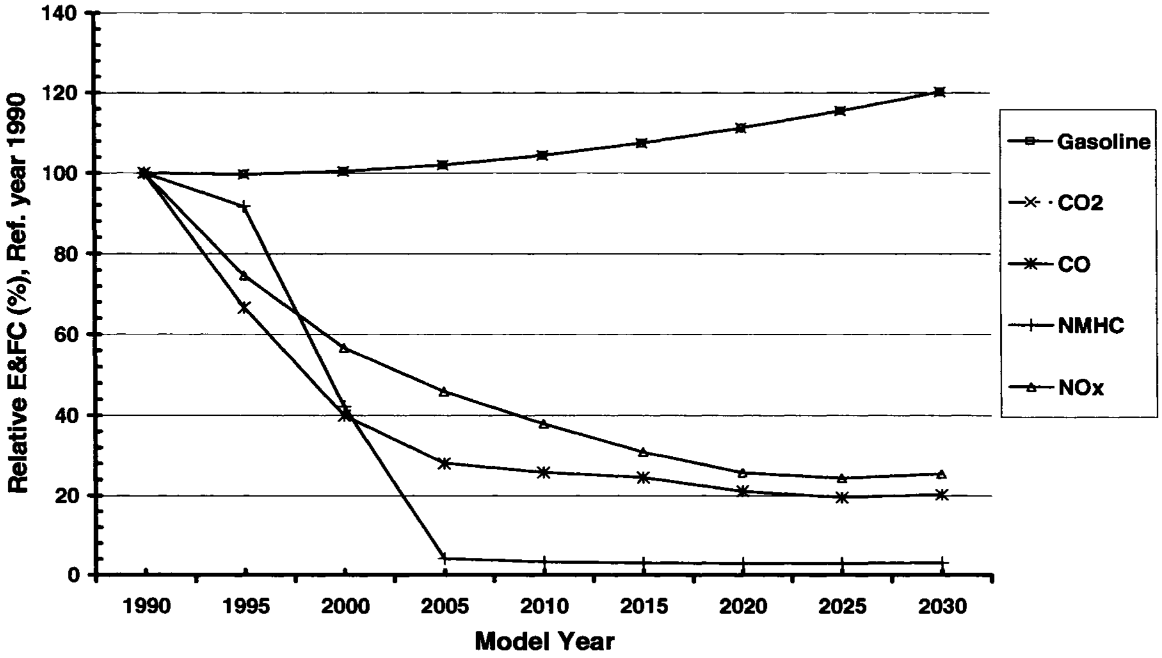


Figure M-2: E&FC trend from a *passenger car* over future years (*1% Growth*).

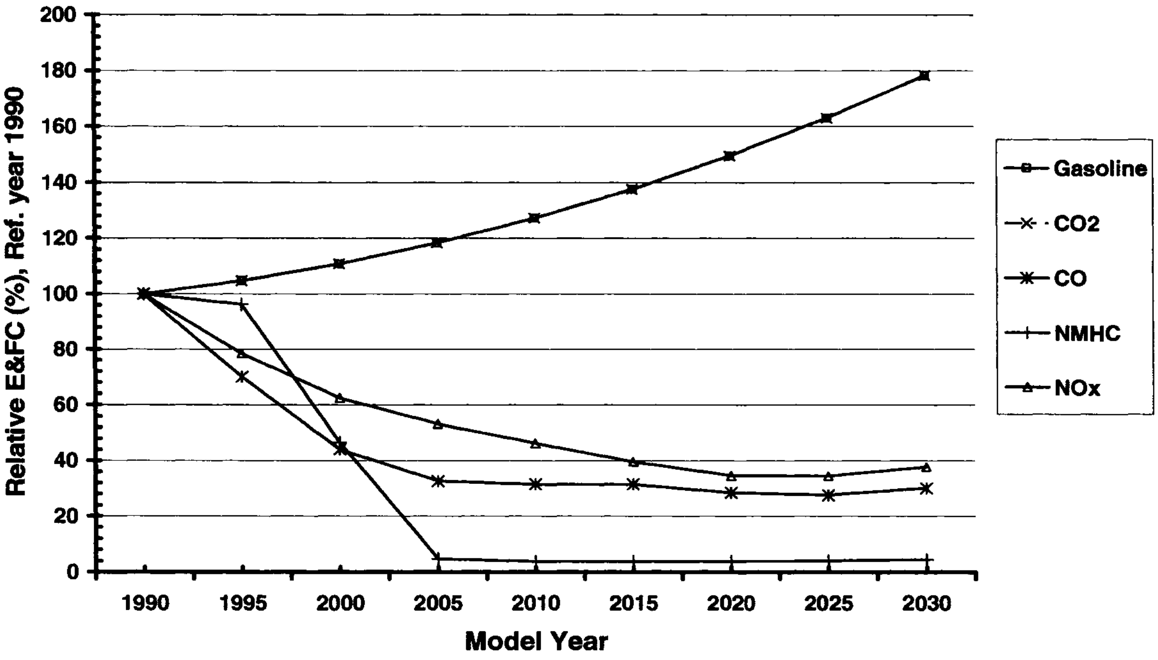


Figure M-3: E&FC trend from a *passenger car* over future years (*2% Growth*).

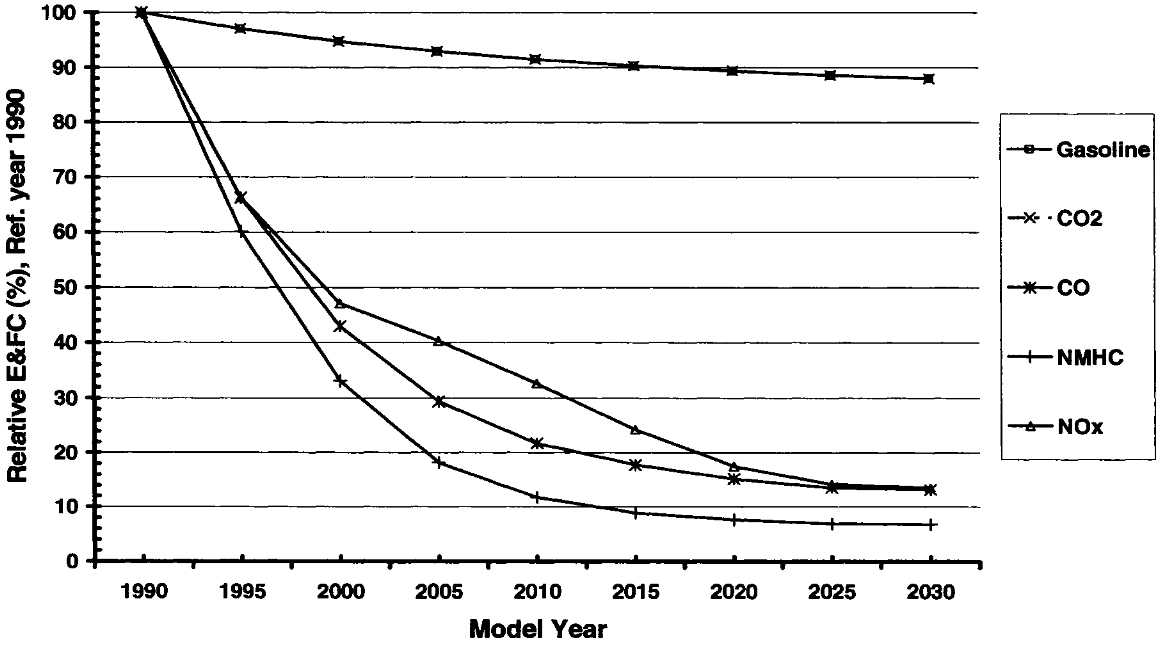


Figure M-4: E&FC trend from a *Light-Duty Truck* over future years (*0% Growth*).

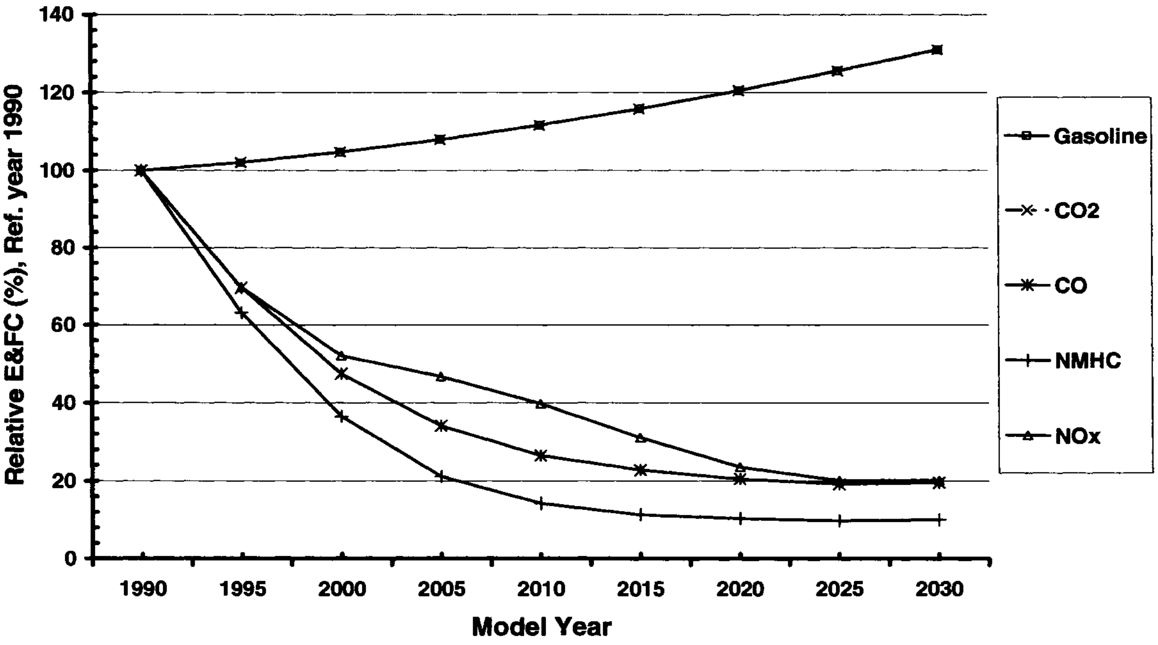


Figure M-5: E&FC trend from a *Light-Duty Truck* over future years (*1% Growth*).

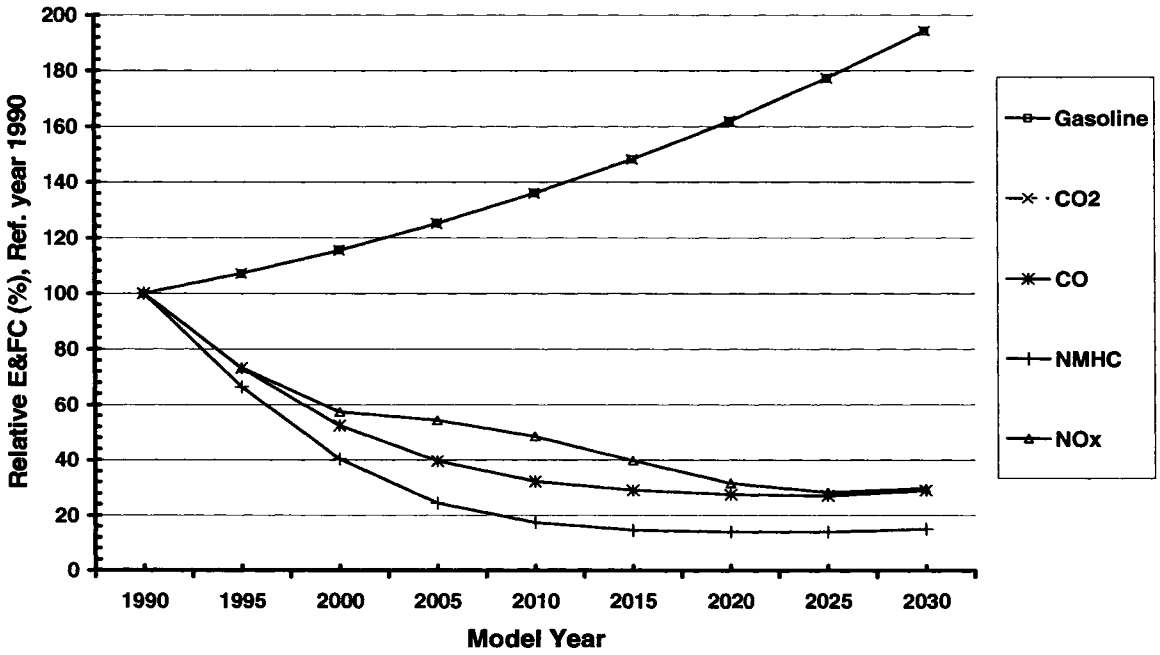


Figure M-6: E&FC trend from a *Light-Duty Truck* over future years (*2% Growth*).

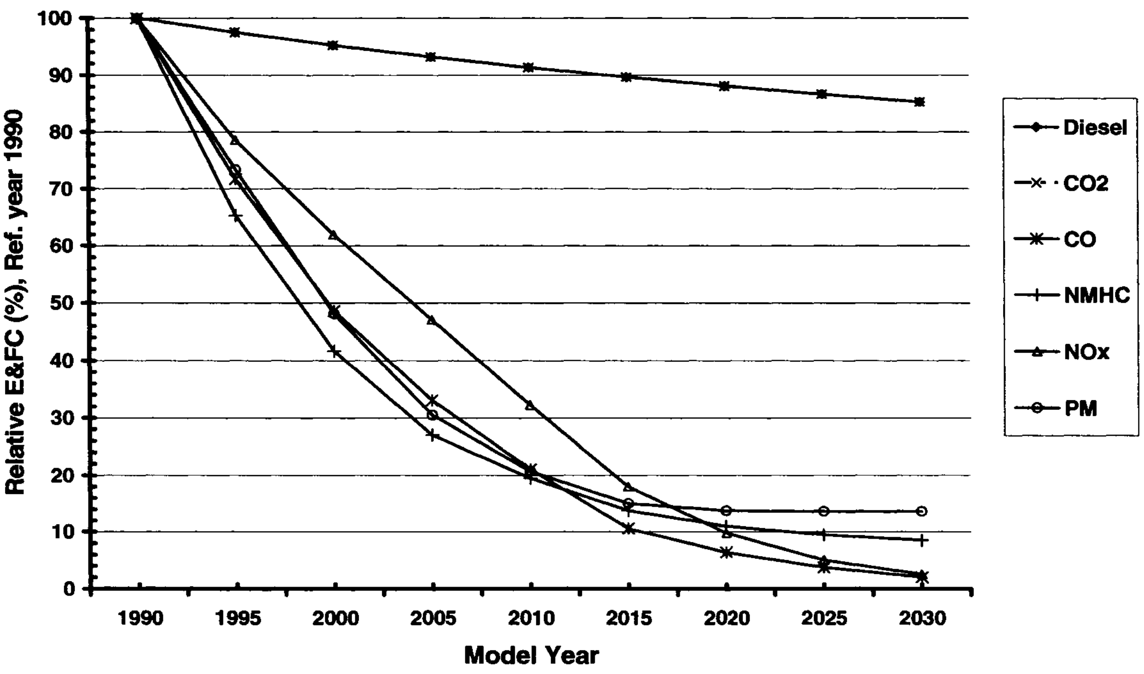


Figure M-7: E&FC trend from a *Heavy-Duty Vehicle* over future years (*0% Growth*).

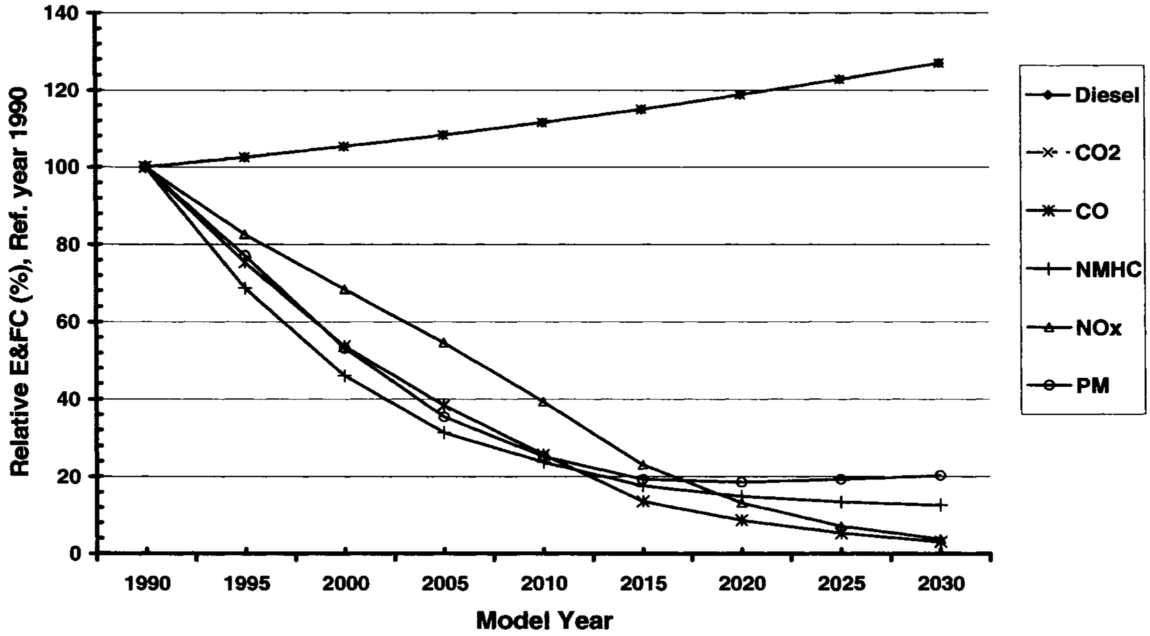


Figure M-8: E&FC trend from a *Heavy-Duty Vehicle* over future years (*1% Growth*).

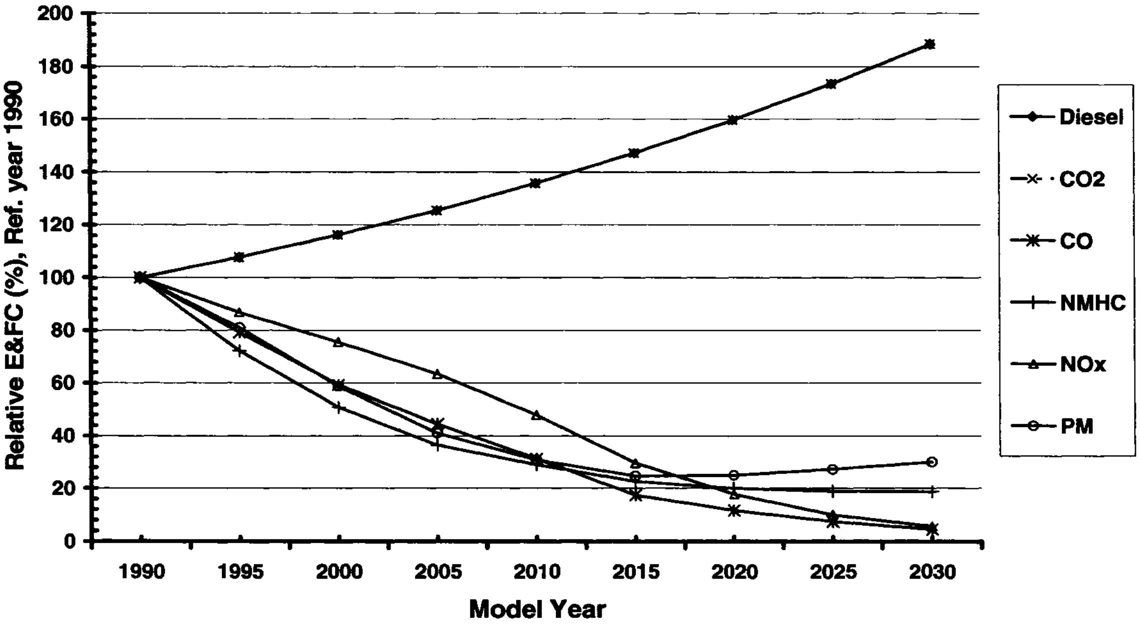


Figure M-9: E&FC trend from a *Heavy-Duty Vehicle* over future years (*2% Growth*).

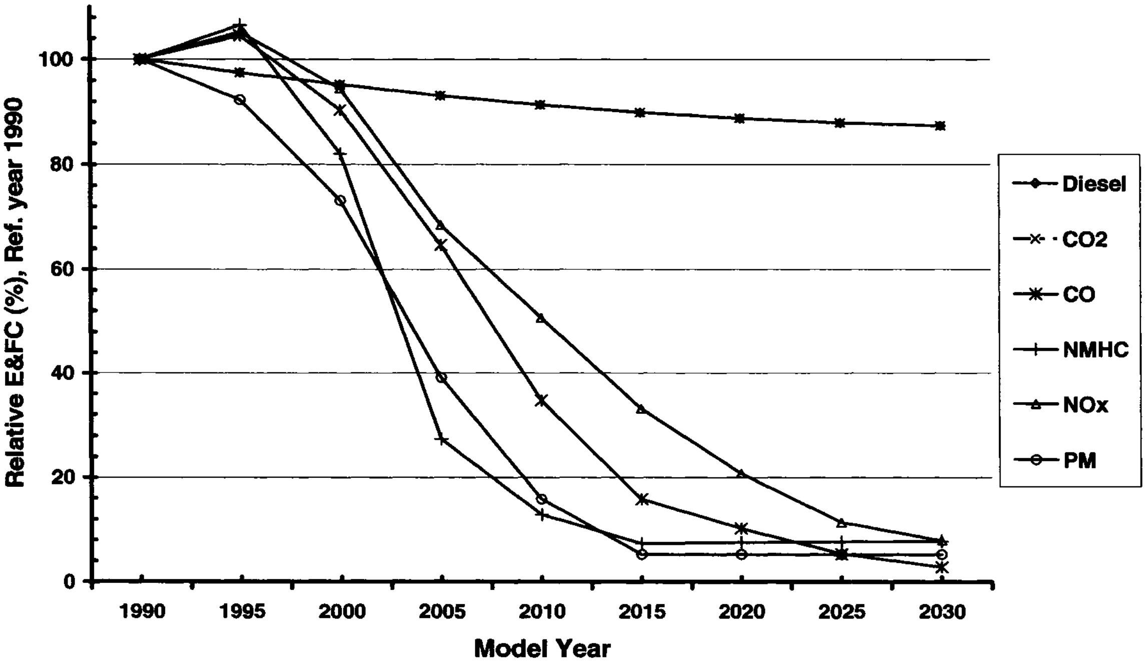


Figure M-10: E&FC trend from a *Bus* over future years (*0% Growth*).

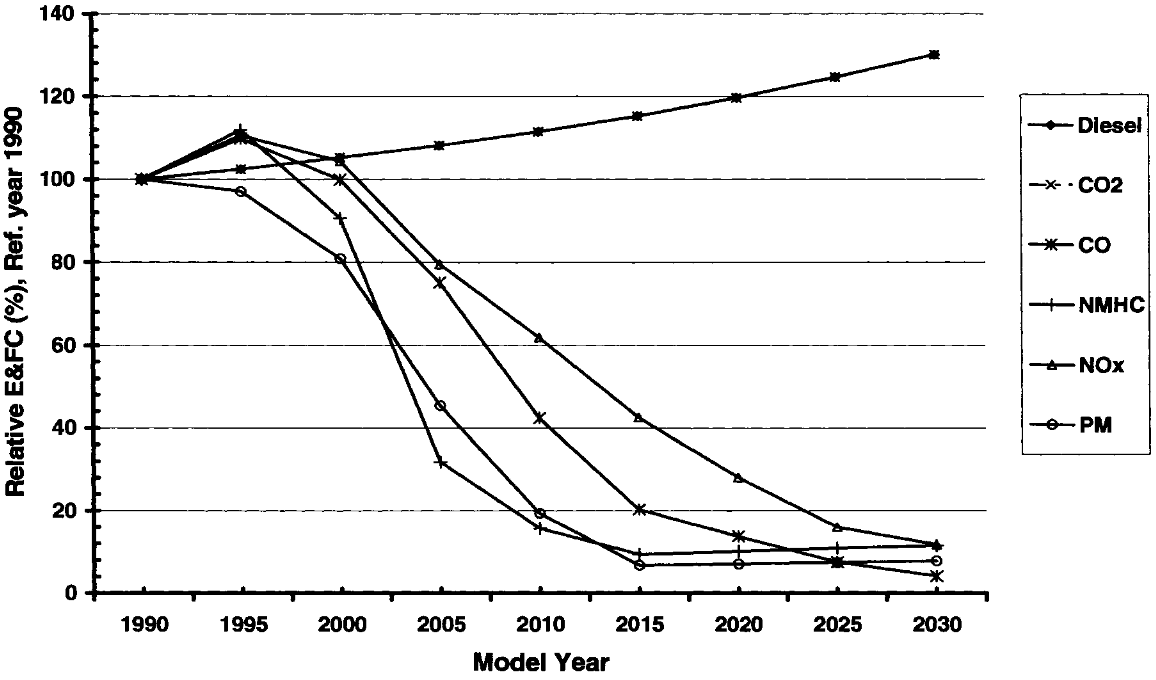


Figure M-11: E&FC trend from a *Bus* over future years (*1% Growth*).

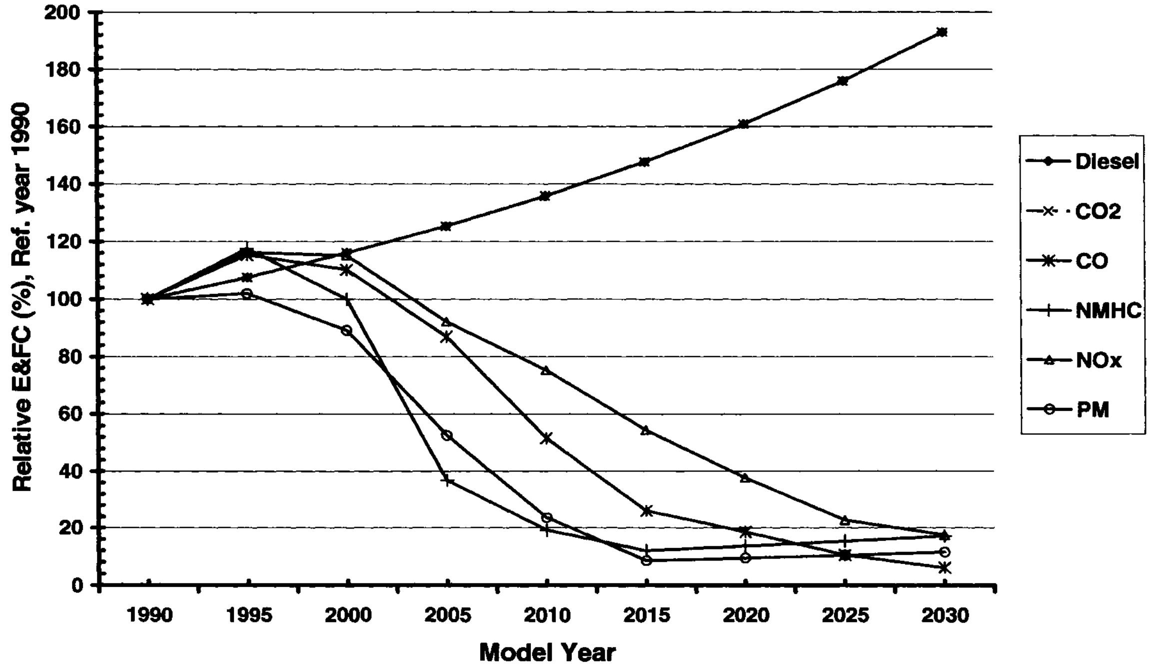


Figure M-12: E&FC trend from a *Bus* over future years (*2% Growth*).