CALMOB6: A Fuel Economy and Emissions Tool for Transportation Planners

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ABSTRACT

This paper describes a Matlab-based emissions and fuel consumption model customized for the City of Edmonton. The City needs a tool to quantify the environmental effects of planned transportation control and urban development measures. The CALMOB6 program calculates emissions and fuel consumption effects of proposed developments or regulations before they are implemented, aiding in selecting the most suitable project. The program handles the criteria air pollutants (carbon monoxide, nitrogen oxides, hydrocarbons and particulates) and greenhouse gas emissions (carbon dioxide and methane), as well as fuel consumption rates for vehicles operating in an urban region.

CALMOB6 uses the output of urban travel forecasting models (such as EMME/2 or VISSIM) to describe vehicle movements. With this as a base, the model develops a second-by-second speed trace for each vehicle type in a particular traffic situation based on both the traffic model output and local parameters such as road grade and ambient weather conditions. The vehicle speed trace matches the specified average speed while incorporating stops, idling times, permissible speeds and realistic acceleration rates for each vehicle class. A class-specific vehicle dynamic model is applied to this speed trace to calculate a tractive power trace which is then applied to emissions and fuel consumption functions developed at the University of Alberta. The emissions functions for each vehicle class are calibrated against emission rates embodied in the US EPA's MOBILE6, (hence CALMOB6) as a standard for vehicles driving EPA test cycles. Similarly, fuel consumption is calibrated against past fleet fuel economy and extended with future fuel economy trends obtained from technical literature.

INTRODUCTION AND PAPER OUTLINE

Developing a Transportation Master Plan for the City of Edmonton led to the need to estimate overall vehicle emissions and fuel consumption. The aim of this project was to develop a tool to quantify the effects of Master Plan parameters on fuel consumption and pollutant emissions. The tool was to be responsive to a range of factors including traffic growth, fleet renewal, infrastructure development and regulatory changes as well as modal choices, ambient conditions and other factors both inside and external to the Transportation Master Plan. The tool developed can generate past and current emissions and fuel consumption inventories, as well as predict inventories over the next twenty years based on traffic and technology forecasts. In this context, this paper has been split into three major parts. The first section deals with the information inputs and processing required by the CALMOB6 model to calculate emissions and fuel consumption inventories. The second part describes the calibration of these calculations against MOBILE6 and other sources. The third part provides some examples of inventories generated by CALMOB6 to illustrate its capability to address situations of interest.

PART 1: CALCULATING FUEL CONSUMPTION AND EMISSIONS

Emissions and fuel consumption for a vehicle depend strongly on the vehicle type, age and condition as well as on the vehicle driving pattern and, to a lesser extent, on the ambient conditions.

i. On-Road Vehicle Types

An emissions calculator requires a fleet model that is both representative of the traffic forecasting on-road fleet and that can be classified in the same manner as the calibration base fleet, (in this case US EPA's MOBILE6 fleet). The fleet developed for the Edmonton version of CALMOB6 includes twenty-seven of the twenty-eight MOBILE6 vehicle classes. (Motorcycles are not considered since they are not included in Edmonton's transportation forecasting model and their numbers and emissions are negligibly small compared to other vehicle classes).

The MOBILE6 model fleet is split into 5 superclasses: Light-Duty Vehicle (passenger car), Light-Duty Truck, Heavy-Duty Vehicle, Bus and Motorcycle. These super-classes are also separated by fuel type, (gasoline or diesel), and are further subdivided by weight and purpose to produce the twenty-eight classes in Table 1.

MOBILE6 Group *Number*	*Abbreviation*	**MOBILE6 Vehicle Classifications** *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, greater than 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
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 1: MOBILE6 Vehicle Classifications [3]

For traffic forecasting, the fleet is normally described by four or less vehicle classes; for example, Light Duty (cars and light trucks), Medium Duty Vehicle (single body trucks), Heavy Duty Vehicle (trailer trucks) and Transit Bus. The CALMOB6 program accommodates this by allowing the user to specify the traffic using these traffic classes and the program populates the classes from MOBILE6 vehicle sub-classes. (The program has a default distribution or the user can specify a particular distribution of MOBILE6 vehicle types in each traffic class). Also, 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) as well as 4 categories of light-duty trucks, (LDT1, LDT2, LDT3 and LDT4). Further, because of the particular interest in transit fleet emissions, several bus types can be specified. As a customization for the City of Edmonton fleet, categories include New (New-Flyer 40 ft low-floor buses), Old (older GM 2-Stroke buses), Long (60 ft low-floor buses) and Short (Fords) whereas the School Buses are classified into Long and Short. The Bus and Light-Duty Vehicle splits were made to better represent actual vehicle characteristics (mass, frontal area, coefficient of rolling resistance and coefficient of drag) and thus improve the capability to test the effects of future changes in vehicle type, usage pattern, etc. Table 2 shows the CALMOB6 vehicle classifications.

Apart from defining the subclass population fractions, the user has the ability to specify the fraction of alternative-fuelled vehicles for each. 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 from provincial vehicle registration data. The total vehicle population registered in the Edmonton region was extracted using postal code data and this population was broken into subclass fractions using a computer program which decodes vehicle identification numbers. CALMOB6 includes a default model fleet and also the ability to modify and save specific fleets. Hence, the emissions effects of different fleet composition scenarios can be tested using the model.

S/N	Abbreviation	MOBILE6 Group Number	Description		
1	LDV	1,14	Passenger car Mini	Mini	
2	LDV	1,14	Passenger car Economy	Economy	
3	LDV	1,14	Passenger car Large	Large	
4	LDT 1	2,15	Trucks (Light duty)	0-6000 lbs. GVWR	0-3750 lbs.LVW
5	LDT 2	3,15	Trucks (Light duty)	0-6000 lbs. GVWR	3751-5750 lbs.LVW
6	LDT 3	4,28	Trucks (Light duty)	6001-8500 lbs. GVWR	0-5750 lbs.ALVW
7	LDT 4	5,28	Trucks (Light duty)	6001-8500 lbs. GVWR	>5751 lbs.ALVW
8	HDV2b / MDV2b	6,16	Trucks (Heavy/Medium duty)	8501-10000 lbs. GVWR	
9	HDV3 / MDV3	7,17	Trucks (Heavy/Medium duty)	10001-14000 lbs. GVWR	
10	HDV4 / MDV4	8,18	Trucks (Heavy/Medium duty)	14001-16000 lbs. GVWR	
11	HDV5 / MDV5	9,19	Trucks (Heavy/Medium duty)	16001-19500 lbs. GVWR	
12	HDV6	10,20	Trucks (Heavy duty)	19501-26000 lbs. GVWR	
13	HDV7	11,21	Trucks (Heavy duty)	26001-33000 lbs. GVWR	
14	HDV8a	12,22	Trucks (Heavy duty)	33001-60000 lbs. GVWR	
15	HDV8b	13,23	Trucks (Heavy duty)	>60000 lbs. GVWR	
16	BUS T&U	25,26	Transit & Urban Bus	Long, New, Old, Short	
17	BUS S	25,27	School Bus	Long, Short	

Table 2: CALMOB6 Vehicle Classifications

ii. <u>Traffic Forecasting Model and Link with CALMOB6</u>
The City of Edmonton uses EMME/2 to model traffic flow over the regional road network. 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 permissible speed specified. The traffic forecasting process specifies the road network and the number of vehicles originating and stopping at each zone during a particular period. The traffic forecasting model, EMME/2, distributes of traffic flow across all available links and, considering the capacity of those links, assigns an average speed for each type of vehicle on each link and zone. This information is returned in tabular form for all links and zones involved in a traffic simulation.

The CALMOB6 program is set up to read EMME/2 tabular output files in a comma separated variable (.CSV) format such as can be produced by typical spread sheet programs. Each line of the file provides information for one traffic link or zone. It includes the key parameters describing the link or zone and the additional parameters that describe traffic of all vehicle classes on that link or zone. Table 3 shows a typical example. The link or zone is defined by starting/ending nodes, a *link type*, (used by the City to separate results), a link length (or zone average travel distance), a *volume delay function* (used again to classify the type of link or zone), a maximum permissible travel speed and a gradient. This is followed by sets of values describing the traffic for each vehicle class on the link. For passenger cars or light duty trucks, three values are provided: the number of vehicles in that class, the average speed along the link and the fraction of cold start vehicles of that class on this link. The cold start fractions are not used for medium duty, heavy duty or transit vehicle classes so only two values are provided: number of vehicles and average speed.

Description of the Link							Description of the Traffic				
inode	jnode	Link	Length	vdf	MaxSpeed	Gradient	Light Duty Cars			…	
		Type	(km)		(km/hr)		No.	km/hr	% cold	No.	km/hr
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: Data input file model describing link or zone parameters and traffic to CALMOB6

iii. <u>Traffic Motion Micro-Simulation</u>
Using information such as the link length, the limit speed and the average speed, CALMOB6 internally develops a traffic motion model for each vehicle type. There are four main classes of traffic motion:

a. *No delay*: All vehicles drive through at the maximum speed
b. *Some stops*: Some vehicles cruise through and some make one stop and possibly idle
c. *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.
d. *Congested*: The vehicles make more than one stop and the maximum speed is reduced.

CALMOB6 simulates the traffic motion such that model travel times on the simulated speed trace exactly match the travel time specified in the forecasting model output, (ie. by EMME/2). Realistic acceleration/deceleration rates are used at different split speeds on links and zones. For example, light-duty vehicle types accelerate/decelerate at $1.5m/s^2$ up to 50km/hr beyond which that rate is reduced to $1.0m/s^2$. Similarly, the heavy-duty vehicles accelerate/decelerate at $0.9\ m/s^2$ below 35km/hr, $0.6m/s^2$ up to 52.5km/hr and $0.4m/s^2$ above 52.5 km/hr. In addition, heavy-duty vehicles (HDV2b-HDV8b) and buses may be power-limited to even lower accelerations if the road slope is high. Power limits range from 100kW for HDV2b to 450kW for HDV8b. Within zones, an initial idle period of 30s is included to account for vehicles getting out on the streets. Moreover, CALMOB6 uses a free cruise speed of 4/3 of the average speed specified on the EMME/2 outputs for zones; but is limited to a maximum of 80 km/hr. Using these rules, a set of speed traces is generated on each link and zone for each type of traffic specified on that link or zone.

iv. <u>Vehicle Tractive Power</u>
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 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).

In equation form, the tractive force can be calculated from the other terms as:

Tractive Force = Mass.Acceleration + Rolling Resistance + Slope Resistance + Aero Resistance

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

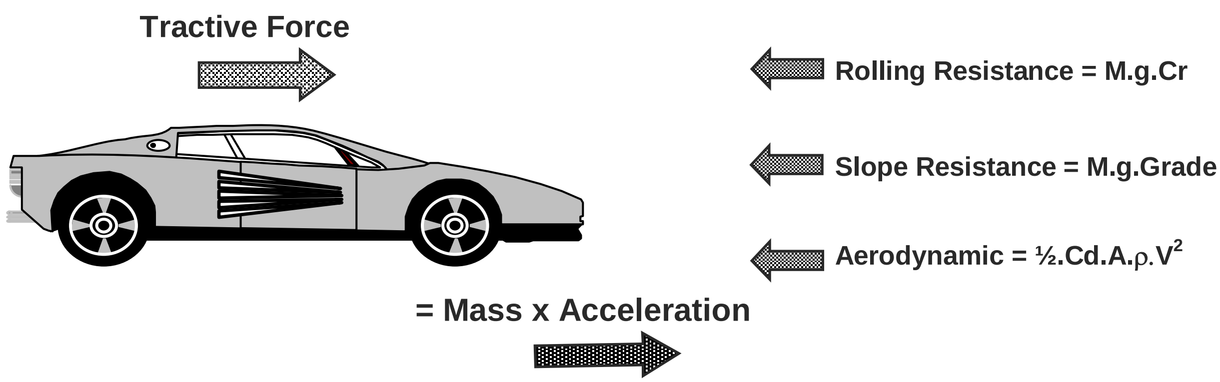

Figure 1: Representative forces influencing vehicle motion

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. 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. (Note 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)

v. <u>Emission and Fuel Consumption Functions</u>

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. Some emissions and fuel consumption functions were obtained by plotting the datasets obtained during laboratory dynamometer testing at the University of Alberta. Examples of these functions are shown in Figure 2.

While these emissions and fuel consumption functions provide a means of calculating inventories, there are concerns that newer vehicles may have different power / emissions behaviour. This is being addressed by another project where on-road vehicles are run under a range of conditions. Simultaneously, the fuel consumption and speed are measured. The work aims to obtaining real-time emission/fuel consumption measurements which may generate more appropriate functions to be employed in CALMOB6 at a later stage.

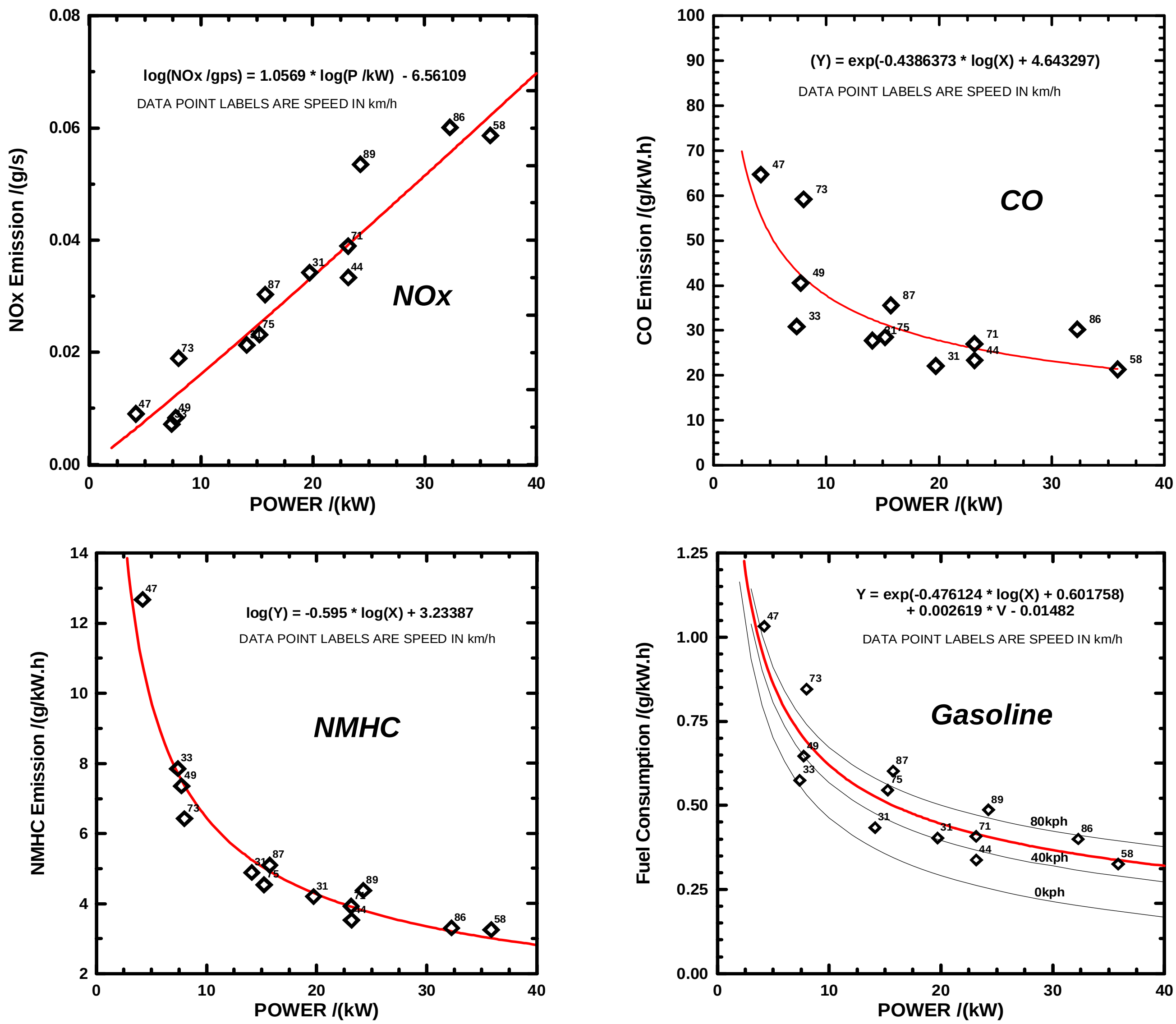

Figure 2: Power based emissions and fuel consumption functions (NOx, NMHC, CO and gasoline) for a gasoline-fuelled vehicle [1]

PART 2: CALIBRATING FUEL CONSUMPTION AND EMISSIONS FUNCTIONS

i. <u>MOBILE6 Emission Rates</u>

MOBILE6 includes a database of emissions to be expected when specific classes of vehicles are run over standard FTP (Federal Test Procedure) cycles. 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 the above mentioned 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.

ii. Composite Base Emission Rates and Fleet-Age Distribution

To run urban simulations for a given year, emission rates that represent a vehicle fleet of typical vintage are needed. This accounts for the fleet comprising mainly of ageing vehicles from previous model years and a small fraction of some new vehicle. The actual fleet age distribution is obviously important in setting the emission rates during any simulation. To accommodate this age distribution, the fleet for each class of vehicles is considered to be made up 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).

Information on the fleet distribution for Edmonton region has been extracted from year 2005 registration data for the City of Edmonton and the surrounding regions. The VIN numbers in this registration data base 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.

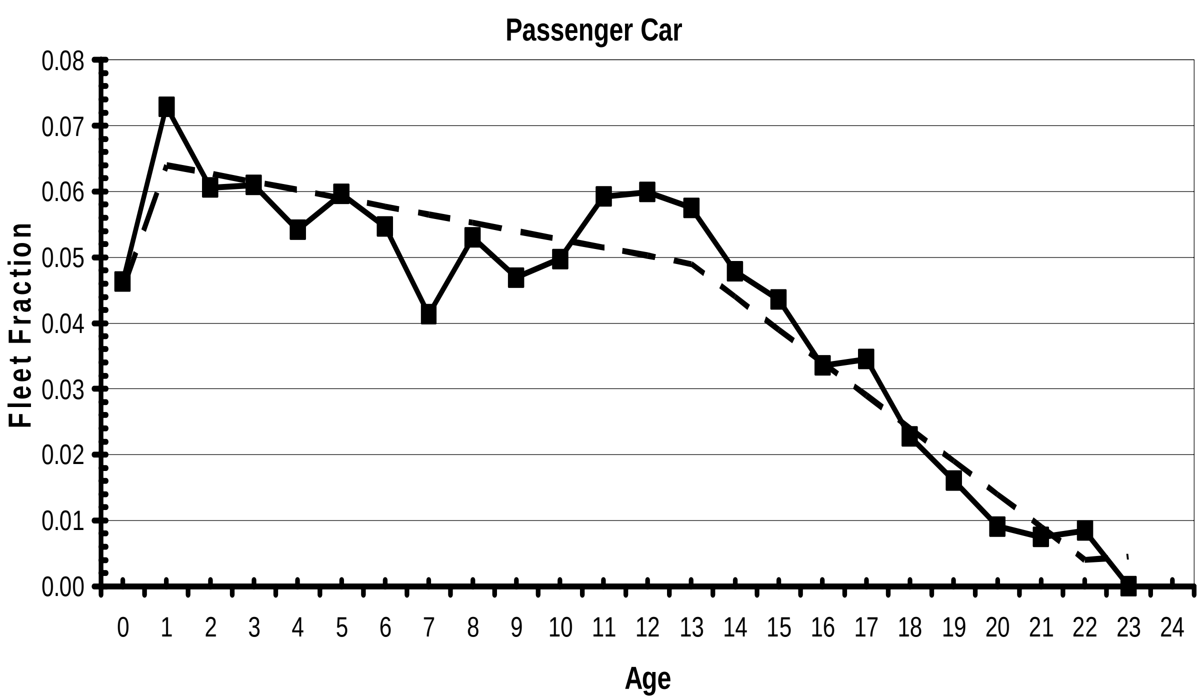

Figure 3: Fleet age distribution extracted from 2005 registration data for Edmonton region passenger cars (solid). The modeled general trend for that category is also shown (dotted).

Real fleet age profiles like that in Figure 3 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 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 used in CALMOB6 and are used in the calibration of emission and fuel consumption functions.

iii. <u>NRCan Fuel and US EPA Fuel Consumption Rates</u>

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. Their 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 4 which also gives the corresponding CALMOB6 vehicle class. These vehicles are representative of the Canadian Light – Duty fleet.

NRCan 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 4: Natural Resources Canada vehicle categories as re-categorized for CALMOB6 [7]

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 and 2000. Example is shown in Figure 4.

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).

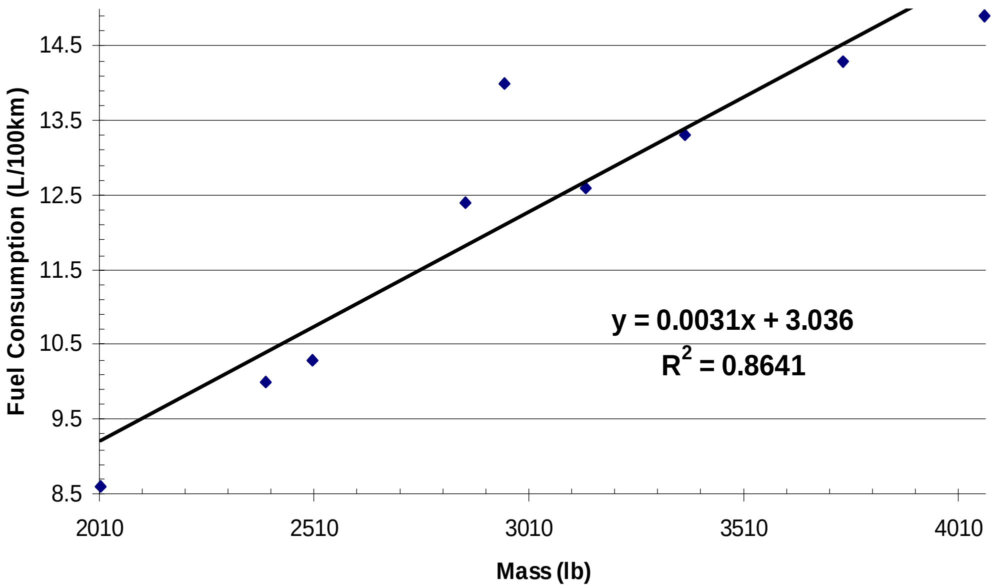

Figure 4: Mass effect on fuel consumption for same-class vehicles. (1980 cars)

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

$$F.C_{adjusted} = F.C^* - \text{'m'}\{ Weight^* - Weight_{average} \}$$

where,

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

Looking at trends of $FC_{adjusted}$ 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 5 gives an example for a particular vehicle class, showing the substantial gains made in same-mass fuel consumption over recent decades.

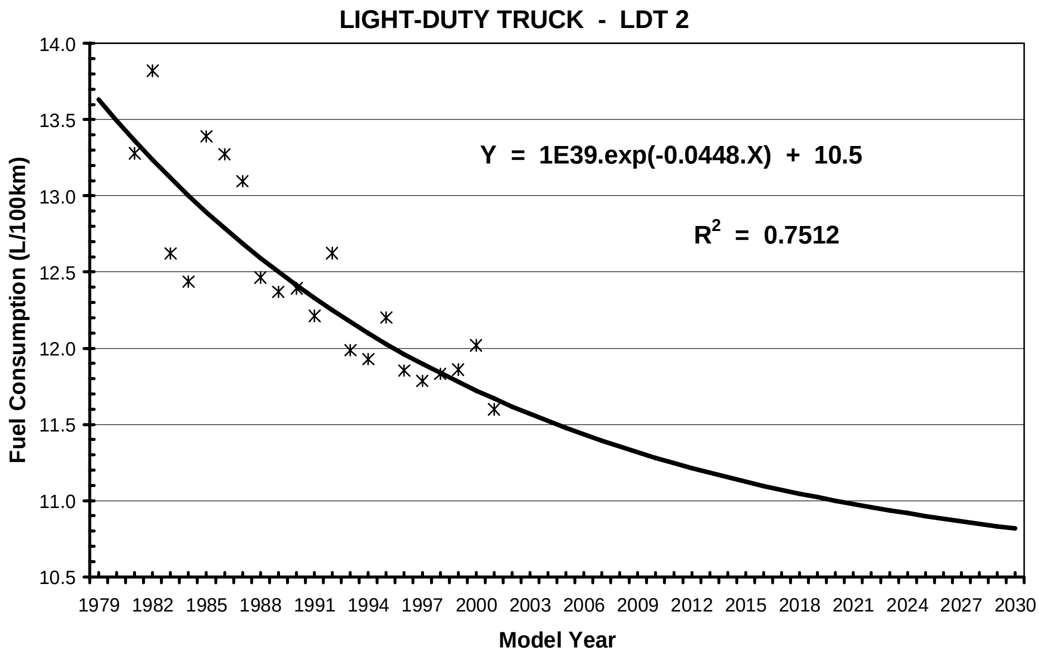

Figure 5: Example of the predicted fuel consumption trend extending up to 2030.

(LDT2 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.

For heavy duty trucks, Browning of the US EPA has developed curve fits of fuel economy in miles per gallon (mpg) as a relation with vehicle model year [8]. These data have been translated to reflect the evolution of fuel economy in L/100km.

iv. <u>Calibrating the Model Functions: Emissions and Fuel Consumption</u>

Each vehicle of model mass, frontal area, coefficient of drag and coefficient of rolling resistance is simulated to follow the respective speed-time traces as used by the US EPA for the emissions and the heavy duty's fuel consumption. The City/Highway split is, for instance, used to simulate the light-duty's motion when dealing with the latter fuel consumption. See Figure 6A for a model speed trace.

Knowing the vehicle characteristics, the power trace can be modeled to best represent the tractive force on the vehicle (Figure 6B). Finally, using the power-based emissions and fuel consumption functions derived previously at the University of Alberta, we can generate the second-by-second emissions and fuel consumption traces. By integrating Figures 6A and 6C 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. However, the rate of fuel consumed, is usually converted from gram/mile to L/100km.

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

Model Year Emissions Calibration Factor = { MOBILE6 [gram/mile] } / { CALMOB6 Model [gram/mile] }

Model Year Consumption Calibration Factor = { NRCan [L/100km] } / { CALMOB6 Model [L/100km] }

This model year calibration factor is calculated by CALMOB6. The factor is used to adjust the emissions/fuel consumption functions for each vehicle model over the range of years extending to 2030.

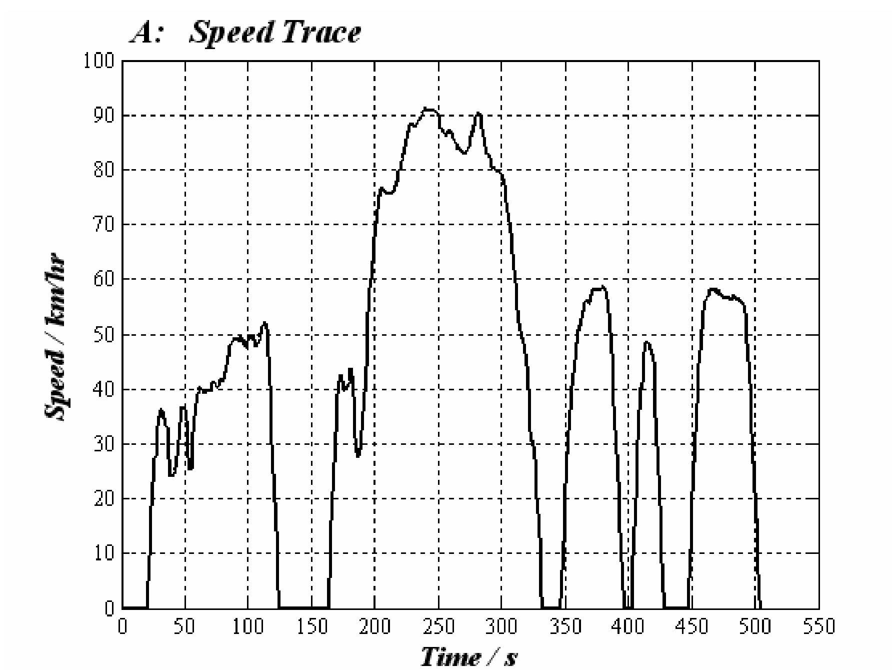

Figure 6A: Example of a speed trace for an emission and/or fuel consumption certification cycle.

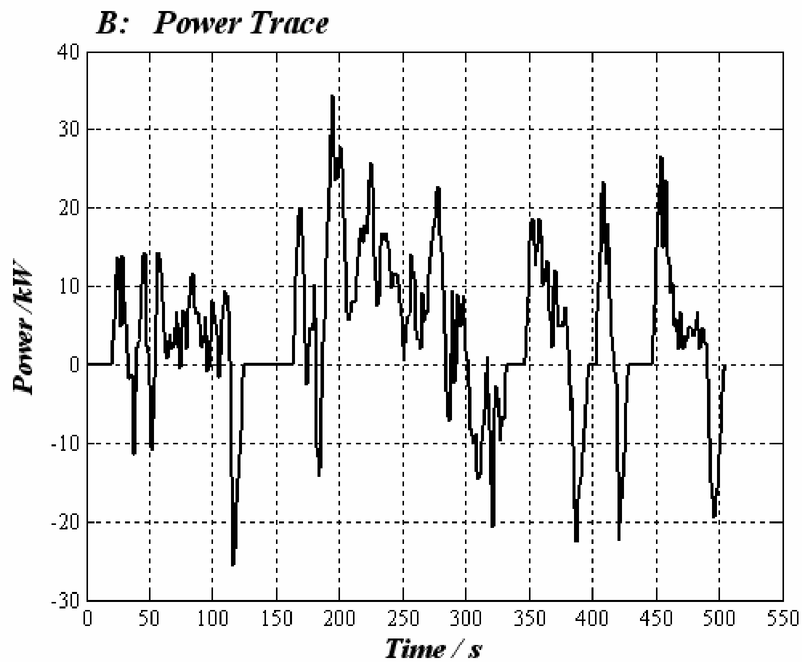

Figure 6B: Modeled power trace of a vehicle following the above speed trace.

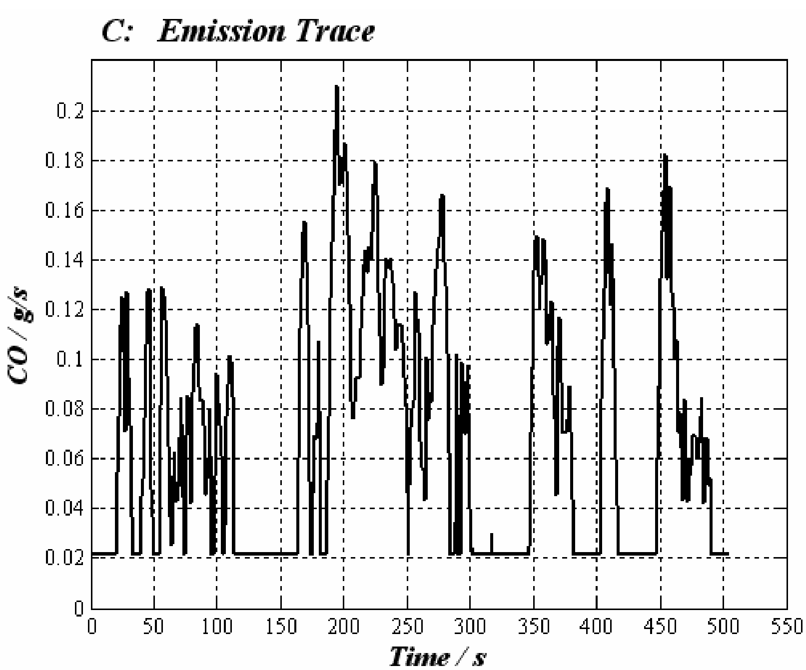

Figure 6C: Second-by-second emission trace obtained after applying the power-based emission functions on the power trace.

For instance, consider a light-duty truck LDT 1 (0-6000 lbs. GVWR and 0-3750 lbs. LVW) that is gasoline fuelled. The CALMOB6 model assumes 1606 kg vehicle mass, 2.346 m^2, frontal area, 0.360 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 10.51 g/mile. MOBILE6 CO emission rates for LTD1 trucks are shown in Table 5. For fleet years ranging from 1990 to 2015, the MOBILE6 hot running emission rates vary from 19.32 g/mile to 5.668 g/mile for Edmonton's fleet distribution of LDT1 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 5. It is noteworthy that the calibration values are generally reasonable, with values falling between 0.5 (for future years) and 2 (for past years). This calibration procedure was followed for each vehicle category used in CALMOB6 and for each of the criteria pollutants (CO, HC & NOx) as well as for the particulates.

Simulation Year	Cold Start CO emission (g)	Hot Running CO Emission (g/mile)	Hot Running Calibration Values
1990	*152.272*	19.320	*1.839*
1991	*130.844*	17.226	*1.640*
1992	*113.336*	15.385	*1.465*
1993	*98.391*	13.715	*1.306*
1994	*85.352*	12.220	*1.163*
1995	*73.628*	10.879	*1.036*
1996	*63.524*	9.760	*0.929*
1997	*55.245*	8.812	*0.839*
1998	*47.987*	7.968	*0.759*
1999	*42.301*	7.319	*0.697*
2000	*37.266*	6.772	*0.645*
2001	*33.314*	6.397	*0.609*
2002	*29.817*	6.101	*0.581*
2003	*27.010*	5.937	*0.565*
2004	*23.907*	5.773	*0.550*
2005	*21.605*	5.719	*0.544*
2006	*19.564*	5.700	*0.543*
2007	*17.546*	5.713	*0.544*
2008	*16.263*	5.713	*0.544*
2009	*15.238*	5.703	*0.543*
2010	*14.400*	5.694	*0.542*
2011	*13.536*	5.665	*0.539*
2012	*12.992*	5.667	*0.539*
2013	*12.532*	5.666	*0.539*
2014	*12.194*	5.669	*0.540*
2015	*11.908*	5.668	*0.540*

Table 5: MOBILE6 CO Emissions values and CALMOB6 calibration ratios for LDT1

The cold start emissions, also shown in Table 5, 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. Similarly, adjustment factors obtained from technical literature are used to adjust 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 which adjust the rates from standard fuelled vehicles. The reference for the light-duty fleet is baseline gasoline values and the reference for the heavy-duty fleet is baseline diesel values.

PART 3. ILLUSTRATIVE INVENTORY CALCULATIONS

i. Showcase A: Simulation Compared with On-Road Measurement

This first illustration 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.

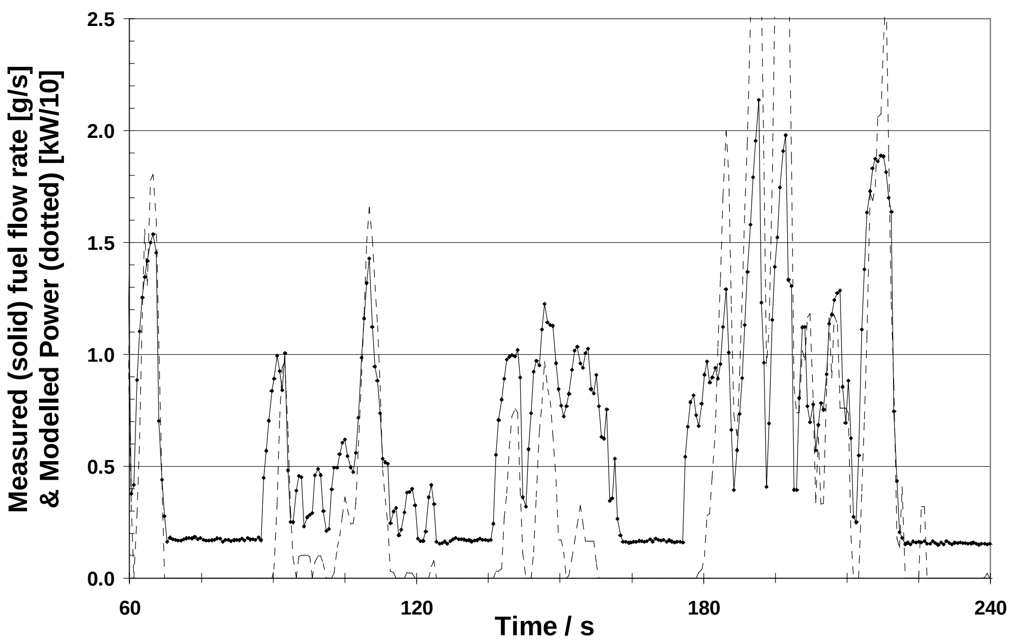

Figure 7A: Modeled Tractive Power (dotted, kW) compared to measured fuel rate (solid, g/s).

Figure 7A shows how the measured fuel consumption rate correlates with the calculated tractive power based on the urban driving speed trace of a mid-size car, (Audi A4 1.8T Quattro). The measured fuel consumption correlated well with the tractive power requirements and the importance of modelling idle fuel consumption rate at times of zero or negative tractive power is obvious since a good deal of fuel is consumed during idle periods.

Figure 7B provides a more direct comparison of the cumulative fuel consumption measured (solid line) and calculated by CALMOB6 (light line) for a large light duty vehicle (GMC 2500 Savannah van, considered LDT3). The total fuel consumed with time was predicted accurately. It is notable that the only significant discrepancy was in the early stages of the trip where this 2001 model vehicle consumed slightly less fuel than predicted by the CALMOB6 model near the end of the warm-up period.

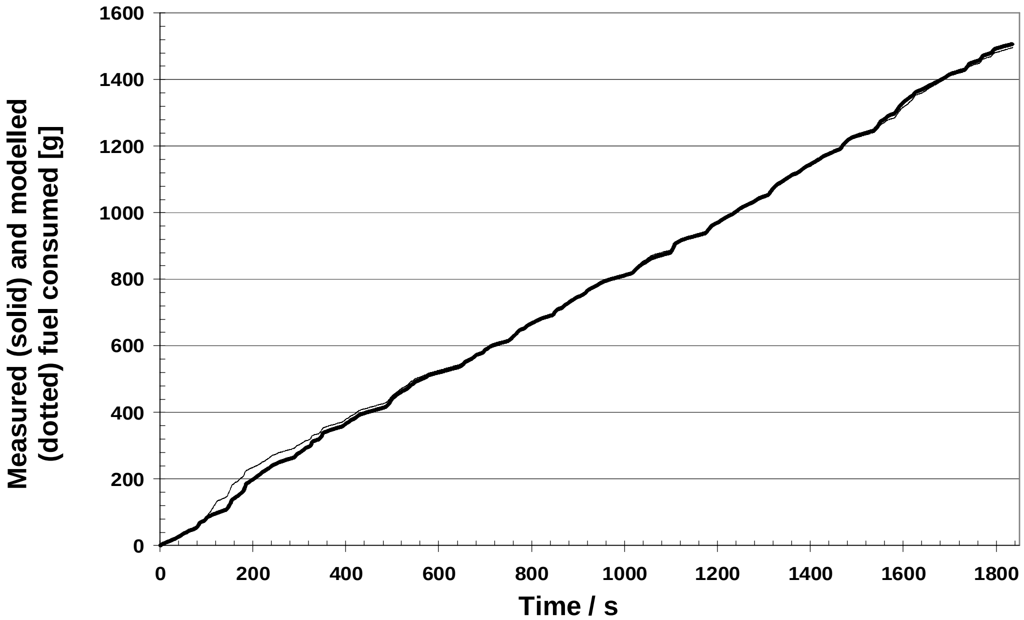

Figure 7B: Measured fuel consumption (solid) compared to modeled fuel consumption (light).

ii. Showcase B: Changes with Fleet Evolution, Traffic Growth and Congestion

The second illustration moves from considering single vehicles to considering the mixed traffic on a section of Edmonton truck route. This was based on modelling a free-flow (no signal light) section of 4 to 6 lane road with a speed limit of 100 km/hr. On a normal weekday, during the peak hour, there were 1680 light-duty vehicles, 140 medium-duty trucks and 230 heavy-duty vehicles running both ways. The default distributions based on Edmonton registration data were used to assign vehicle classes and age distributions to the traffic on this route. CALMOB6 was used to calculate base values and project the change in fuel consumption and emissions for a number of "what-if" scenarios.

As a base reference, the fleet age distribution was based on March 2006 and the average speed of all vehicles was set to match the free flow speed limit (i.e. 100 km/hr). In this case, all vehicles were cruising through the link without any decelerations, stops, idling or accelerations. Table 6 gives the base values for fuel consumed and emissions for the peak hour traffic.

Gasoline / kg	Diesel / kg	CO2 / kg	CO / kg	HC / kg	NOx / kg
148.1	48.1	602.3	6.73	0.331	2.29

Table 6: Base fuel use and emissions for year 2006 fleet cruising through test link, (Simulation test 0).

Four alternative simulation tests were made to compare with the base case.

Simulation test 1: Very Mild Congestion

The average speed on the link was reduced to 80 km/hr, (with the peak speed still set at 100 km/hr). This gives a more reasonable average speed for the slightly congested route. In this case, the traffic motion differs such that some vehicles are forced to decelerate and then re-accelerate to their maximum speed while some vehicles still cruise through. This slow-down and re-gain of speed process logically demands more power and produces more emissions than free-flow cruising. Consequently, more fuel was consumed and emission levels rose. For the 2006 fleet, this slight change in traffic congestion increased consumption and emission values by 5% to 10% compared with the base case as shown by the first set of bars in Figure 8.

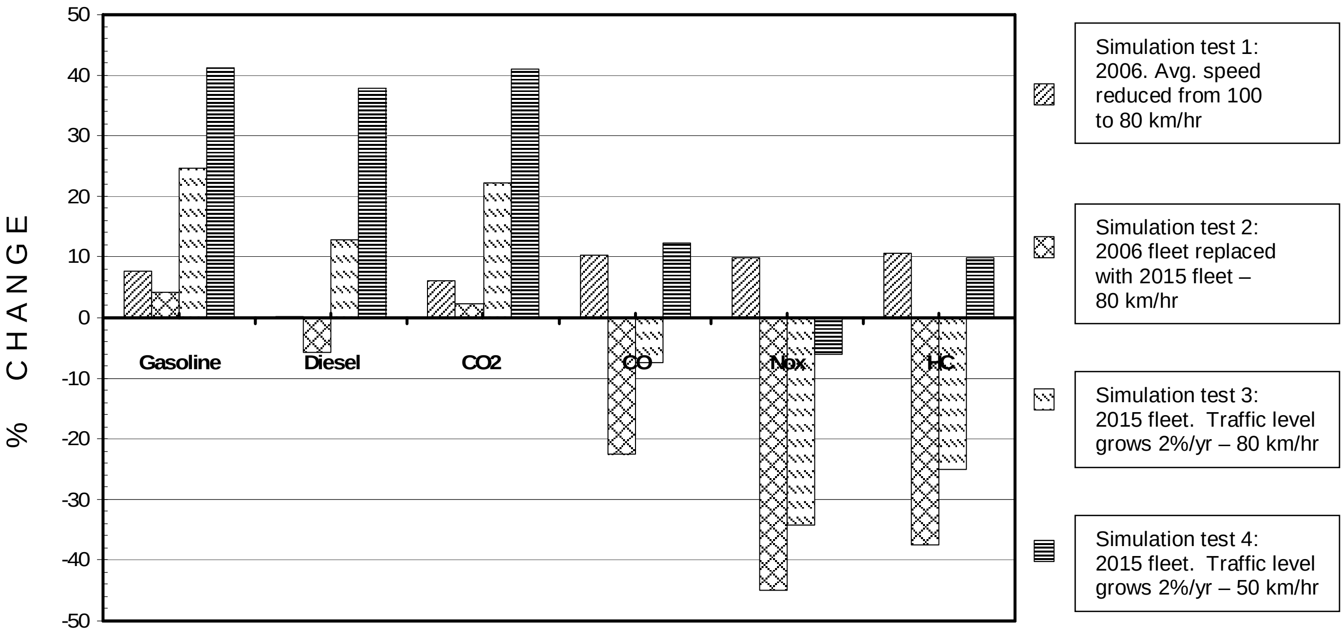

Figure 8: Changes in emissions and fuel consumption quantities for 4 simulation scenarios compared with the base case values in Table 6.

Simulation test 2: Very Slight Congestion + Update to 2015 Vehicle Fleet

For the same reduced average speed as Simulation test 1, (average speed 80 km/hr with peak speed at 100 km/hr), the 2006 fleet was replaced with a 2015 fleet. This would show the improvement to be expected as new-standard vehicles take over more of the fleet and change fleet emission characteristics. Compared with the slightly congested 2006 situation, all the emission and consumption quantities showed a net decrease with the most dramatic improvements being in NOx and HC emissions due to the rapid evolution of heavy duty emission standards.

Simulation test 3: Very Slight Congestion + 2015 Fleet + 2% Annual Traffic Growth

The third test case reflected that the actual vehicle population is likely to grow. Considering an annual traffic growth rate of 2%, there would be an overall 19.5% increase in traffic by 2015. For this case, the traffic motions and emission rates were considered to be the same as Simulation test 2 but were applied to 19.5% more traffic. As a result, the fuel consumption and green-house gas emissions ended up higher than for the 2006 base case but the criteria pollutants still showed a net decrease due to the decreased fleet fraction of old-standard vehicles.

Simulation test 4: 2% Annual Traffic Growth, Significant Congestion + 2015 Fleet

This final test case looked at a more realistic scenario for vehicle traffic increasing by 19.5% with no change of infrastructure. The average speed was decreased to 50 km/hr resulting in significant congestion with more deceleration and acceleration as well as some stopping and idling. In this scenario, the fuel consumption and greenhouse gas emissions were up by around 40% and only NOx emissions were reduced compared to the 2006 free-flow baseline case.

iii. Showcase C: Comparison of Fleet Evolution for Heavy Duty Truck and Light Duty Car

The third illustration used CALMOB6 to compare the effects of fleet evolution and tightening standards on truck emissions with those of light duty vehicles. Emissions were compared between a fleet of light-duty cars (LDV Economy) and a fleet of heavy-duty trucks (HDV6) which followed the same driving schedule as one another. The simulation was repeated for fleet years from 2000 to 2030 at 5 year intervals to follow the effect of fleet replacement with newer vehicles and the results were plotted as the absolute difference in mass emissions between a typical truck and a typical car for a given travel distance. This difference in emissions is plotted in Figure 9.

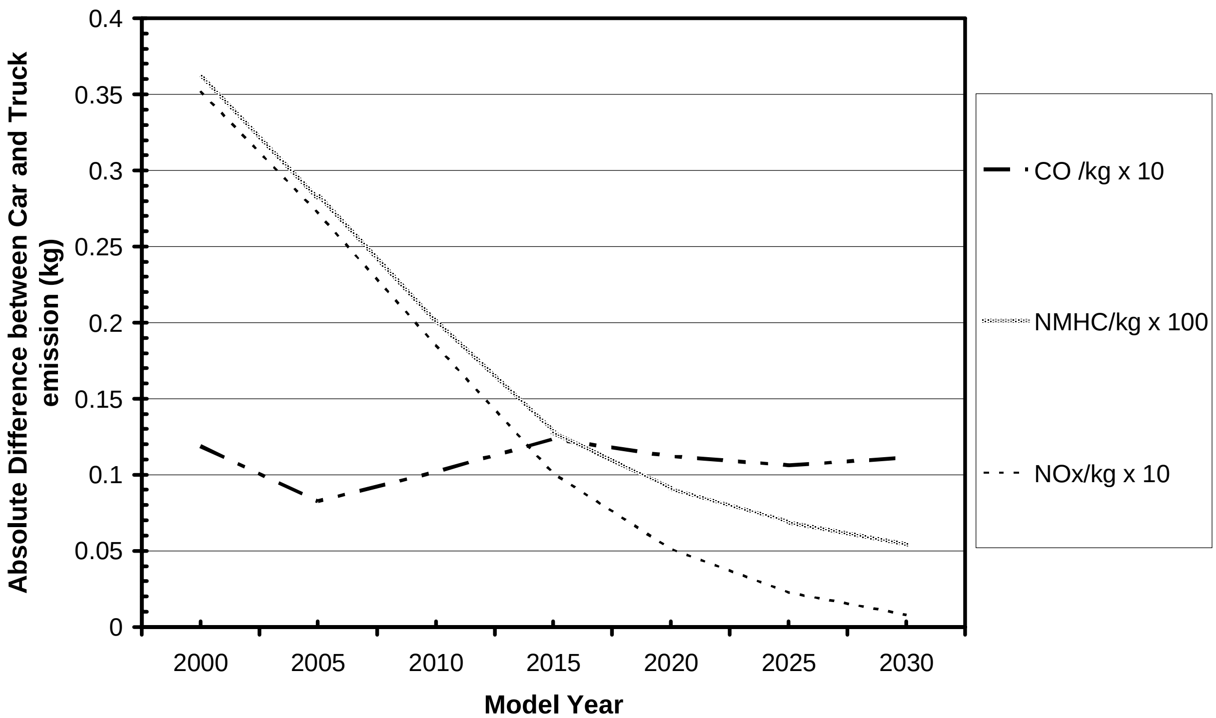

Figure 9: Effect of tightening standards for heavy-duty relative to already-tight light duty values. Quantities plotted are difference in kg between a HDV6 fleet and an Economy car.

The simulation showed that, as the current and currently planned emission standards move into the heavy duty fleet, truck fleet emissions will drop dramatically, erasing much of the difference between light duty and truck emission levels. The tightening truck emission standards have a particularly dramatic effect on NOx and HC emissions with less effect on CO emissions.

CONCLUSION AND SUMMARY

This paper describes the technical background of CALMOB6, an emissions and fuel consumption inventory tool. CALMOB6 uses traffic modeling outputs and vehicle dynamic modeling to calculate inventories of pollutant emissions and fuel consumption associated with the modelled traffic. The emissions calculator model is calibrated for standard conditions using US EPA MOBILE6 but responds to non-standard conditions including variable distributions of acceleration, speed and ambient conditions as well as variable road characteristics including intersections, slopes and traffic congestion. CALMOB6 can be used to generate past, current and future inventories and also to show the 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.

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