Environment Canada Environnement Canada

Uncertainty Analysis of Criteria Air Contaminants from Mobile Sources in Canada

Science & Technology Branch

Pollutant Inventories and Reporting Division

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Executive summary

This summary presents the key findings of a statistical analysis of the variables, data, models and methods used for the estimation of emissions of criteria air contaminants (CACs) from mobile sources. These pollutants affect human health and contribute to air pollution problems such as smog, acid rain and visibility. They include total particulate matter (TPM), particulate matter ≤10 microns (PM_{10}), particulate matter ≤2.5 microns ($PM_{2.5}$), sulphur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO) and ammonia (NH_3).

Confidence levels were quantified for emission estimates for these pollutants from aircraft, on-road vehicles, off-road engines, locomotives and marine sources. This uncertainty analysis is of value for the development and implementation of regulations for air quality management in Canada, and for all users of the data to understand its strengths and limitations.

The following letter scale, based on a modified version of Statistics Canada's quality indicator, was used to report on uncertainties in tabular data (summarized in Table A below).

	Coefficient of variation
A – excellent	less than 5%
B – very good	5% to 9.9%
C – good	10% to 14.9%
D – acceptable	15% to 19.9%
E – use with caution	20% to 34.9%
F – high uncertainty	35% or more

Table A – Summary of Uncertainty by Pollutant and Mobile Emission Source

	PM_{10}	$PM_{2.5}$	SO_x	NO_x	VOC	CO
	metric tonnes					
Total - aircraft	**995**^{F}	**995**^{F}	**4,841**^{F}	**61,442**^{F}	**8,218**^{F}	**46,357**^{F}
LTO	112^{B}	112^{B}	1,215^{F}	6,123^{B}	4,060^{E}	9,931^{C}
Cruise	883^{F}	883^{F}	3,626^{F}	55,319^{F}	4,158^{F}	36,426^{F}
Marine transportation	**5,820**^{F}	**5,565**^{F}	**32,359**^{F}	**117,096**^{F}	**8,035**^{F}	**9,572**^{F}
Total - on-road vehicles	**6,286**^{B}	**5,726**^{B}	**9,700**^{B}	**408,341**^{B}	**370,331**^{C}	**8,068,222**^{B}
Light-duty gasoline vehicles	402^{B}	369^{B}	740^{B}	90,347^{D}	153,043^{E}	3,502,235^{D}
Light-duty gasoline trucks	553^{E}	460^{D}	934^{B}	131,233^{B}	205,727^{C}	4,502,841^{C}
Light-duty diesel vehicles	375^{E}	344^{E}	419^{F}	3,431^{F}	1,193^{F}	5,791^{F}
Light-duty diesel trucks	387^{F}	355^{F}	598^{F}	3,448^{F}	1,629^{F}	4,281^{F}
Heavy-duty gasoline vehicles	54^{E}	44^{E}	19^{E}	4,620^{E}	1,310^{E}	17,417^{E}
Heavy-duty diesel vehicles	4,515^{B}	4,154^{B}	6,991^{C}	175,263^{B}	7,430^{B}	35,656^{B}
Total - off-road engines	**48,254**^{F}	**45,248**^{F}	**7,434**^{F}	**355,299**^{E}	**872,464**^{F}	**9,429,408**^{F}
Off-road use of diesel	16,805^{E}	16,301^{E}	7,138^{F}	230,271^{C}	17,959^{E}	100,982^{E}
Off-road use of gasoline	31,449^{F}	28,947^{F}	296^{F}	125,028^{F}	854,505^{F}	9,328,426^{F}
Total - locomotives	**4,411**^{A}	**4,277**^{A}	**7,199**^{F}	**112,082**^{A}	**10,620**^{A}	**25,923**^{A}
Freight	4,097^{A}	3,973^{A}	6,624^{F}	101,703^{A}	9,672^{B}	23,705^{A}
Switching	139^{A}	135^{A}	245^{F}	4,803^{A}	453^{A}	971^{A}
Passenger	175^{A}	170^{A}	330^{F}	5,576^{A}	495^{A}	1,248^{A}

The analysis found that uncertainty in the emission estimates varied significantly by source or vehicle type. For example:

- Emission estimates for most CACs from locomotives were found to be "excellent" (coefficient of variation less than 5%), due to the high quality, detail and accessibility of information on the locomotive fleet in Canada.

However, emissions of sulphur dioxide from locomotives were found to have a higher level of overall uncertainty, due to the uncertainty related to the differences in fuel characteristics and the spatial distribution of SO_2 emissions.

- Emission estimates for on-road vehicles were found to be “good” to “very good”—similarly due to the quality, detail and availability of statistical information for on-road vehicles in Canada.

- Aircraft, marine transportation and off-road emission estimates were found to have a high level of uncertainty associated with them (coefficient of variation of over 35%), due to the use of highly aggregated data as input for aviation, the sparse data available for commercial marine and the fragmented nature of the spatial distribution of off-road equipment.

Opportunities for future improvements to mobile source emission estimates include the use of Canadian-specific data that is spatially and temporally distributed at a high level of resolution.

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Abbreviations

ASC	Statistics Canada Aviation Statistics Centre
CAC	Criteria Air Contaminant
CFI	Construction, Farm and Industrial
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Canadian Vehicle Survey
DB	Dynamic Braking (locomotives)
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
HC	Hydrocarbons
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquified Petroleum Gas
LTO	Landing and Take-Off
MSOD	Mobile Source Observation Database
NH_3	Ammonia
NO_x	Nitrogen Oxides
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter ≤2.5 microns
PM_{10}	Particulate Matter ≤10 microns
RAC	Railway Association of Canada
RESD	Report on Energy Supply-Demand
RVP	Reid Vapour Pressure
SO_x	Sulphur Oxides
UNFCCC	United Nations Framework Convention on Climate Change
VKT	Vehicle Kilometres Travelled
VMT	Vehicle Miles Travelled
VOC	Volatile Organic Compound

Notation

$A, B, C, \ldots$	known quantity
$\mathcal{A}, \mathcal{B}, \mathcal{C}, \ldots$	random variable (unknown quantity)
$\mathcal{A} \sim N(\mu, \sigma)$	$\mathcal{A}$ has normal distribution with mean μ and variance σ
$\boldsymbol{\mathcal{A}} = \big(\mathcal{A}_1, \ldots, \mathcal{A}_n\big)$	random vector
$\hat{\mathcal{A}}$	point estimate
$(\mathcal{A}_L, \mathcal{A}_U)$	confidence interval
$F\big(\{a, b, c\}, \{d, e\}\big)$	$\big\{F(a, d), F(a, e), F(b, d), F(b, e), F(c, d), F(c, e)\big\}$
$\sum F(a, \{b, c, d\}, e)$	$F(a, b, e) + F(a, c, e) + F(a, d, e)$
$\mathcal{E}, \mathcal{E}_{PM}, \mathcal{E}_{NOx}, \ldots$	emission factor
$\mathcal{C}$	CVS number of vehicles
$\mathcal{G}$	gasoline
$\mathcal{D}$	diesel
$\mathcal{F}$	fuel
$\mathcal{V}_{LDGV}, \ldots, \mathcal{V}_{HDD8B}$	MOBILE vehicle classes
$\mathcal{M}_1, \ldots, \mathcal{M}_{28}$	MOBILE vehicle miles travelled
$\mathcal{S}$	NONROAD source

1 Introduction

This report follows a comprehensive survey (Taylor, 2007a) of the variables, data, models and methods used for the estimation of emissions of criteria air contaminants (CACs) from mobile sources by Environment Canada. These pollutants affect human health and contribute to air pollution problems such as smog, acid rain and visibility. They include total particulate matter (TPM), particulate matter ≤10 microns (PM_{10}), particulate matter ≤2.5 microns ($PM_{2.5}$), sulphur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO) and ammonia (NH_3).

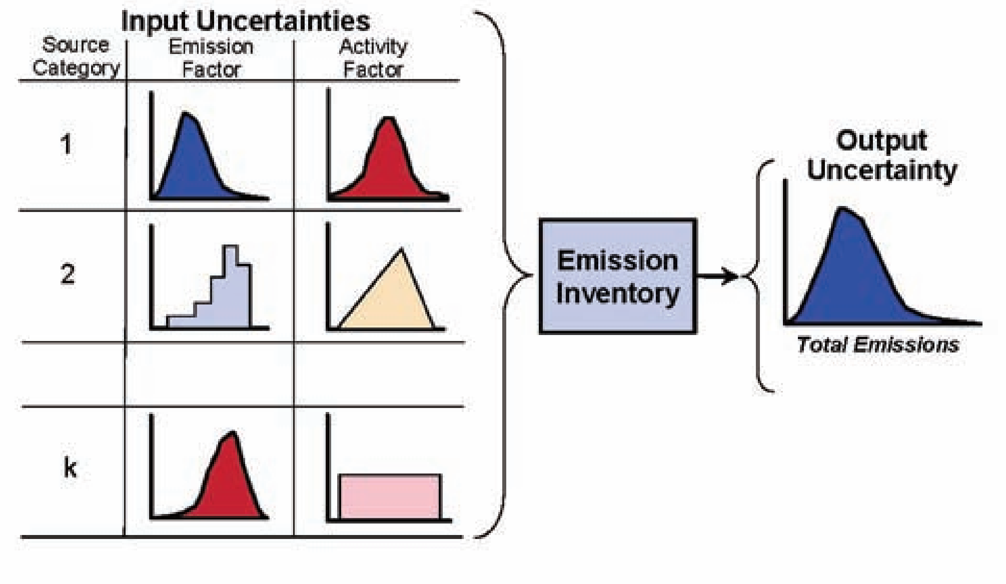

Figure 1: Input and output uncertainty

The primary objective of this report is to perform an uncertainty analysis on the emission estimates from mobile sources. This uncertainty analysis quantifies the level of confidence in the emissions estimates, by generating error bounds around each variable in the methodology used to estimate emissions from aircraft, commercial marine vessels, on-road vehicles, off-road engines/vehicles and locomotives. Uncertainties arising from both activity data and emission factors are combined to obtain an overall measure of uncertainty for the estimation of total CAC emissions (Figure 1).

CACs are related to local air quality while greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are related to global climate change. However, there are spatial and temporal dimensions to both categories of emissions. Intercontinental transport and hemispheric air pollution by ozone jeopardize agricultural and natural ecosystems worldwide and have a strong effect on climate. Aerosols, which are spread globally but have a strong regional imbalance, change global climate through their direct and indirect effects on radiative forcing (Akimoto, 2003).

This report brings the CAC inventory uncertainty analysis in line with that of the GHG inventory. The mobile source component of the CAC inventory has many components prepared using varied methodologies depending on available information. As such, emission estimates are wide-ranging in their accuracy and associated uncertainty. Uncertainty information helps prioritize efforts to improve the accuracy of inventories and guide decisions on methodological choice.

Uncertainty analysis is common in the study of GHG emissions (Winiwarter and Rypdal, 2001; Webster et al., 2003; Davies et al., 2006; Gosling and O'Hagan, 2007; Kennedy et al., 2008). Under the United Nations Framework Convention on Climate Change (UNFCCC), Annex I Parties are required to quantitatively estimate the uncertainties in data used for all source and sink categories of their National Greenhouse Gas Inventories using good practice guidance (Frey et al., 2006) from the Intergovernmental Panel on Climate Change (IPCC). This report follows the IPCC Tier 2 (Monte Carlo) method of uncertainty analysis, which is also discussed in NARSTO (2005).

Environment Canada has considered the uncertainty of its GHG estimates for many years (McCann, 1994; SGA, 2000; ICF, 2004, 2005). The study of uncertainties of CAC emission estimates is, by comparison to GHGs, a developing field. It is widely recognized that uncertainty in off-road emissions estimation is significant, but currently data and past study in this specific field are limited, with most of the research being done at the engineering department of North Carolina State

University (Bammi, 2001; Zheng and Frey, 2001; Frey and Bammi, 2002a,b, 2003; Chi, 2004; Frey, 2007).

This report is the first systematic uncertainty study of CAC emission estimates from mobile sources in Canada, making every effort to present an unbiased assessment of point and confidence interval CAC estimates conditioned on data available at this time. The use of Dirichlet distributions in Monte Carlo uncertainty analysis is introduced, a novel and effective technique to estimate uncertainties related to subgroups for which only an aggregate measure is known.

The report considers activity data and emission factors data from Canadian, U.S. and European environmental and statistical agencies (Table 1). Gaps in these data sets and areas of potential improvement are addressed in Section 7, Conclusion. Limited information was available on which to base emission factors for NH_3 (Coe et al., 1996). The most important future enhancements include the Mobile Source Observation Database from the U.S. Environmental Protection Agency (EPA), and higher resolution data from the Canadian Vehicle Survey (see Table 18 for details).

Table 1: Activity data and emission factors

	Activity data	Emission factors
Aircraft	Statcan Aircraft Movements Statistics	EMEP/CORINAIR (2007); FOCA (2006)
Commercial marine	Statcan Shipping in Canada	EMEP/CORINAIR (2007)
On-road vehicles	Statcan CVS aggregate data	MOBILE default
Off-road engines	Statcan Vehicle Survey and Report on Energy Supply-Demand	NONROAD default
Locomotives	Railway Association of Canada	Dunn and Eggleton (2002); Fritz (2004); Moshiri (2006)

A review of necessary statistical concepts for this uncertainty analysis, such as the probability distributions, is included in the Appendix. A letter scale, based on a modified version of Statistics Canada's quality indicator (Table 2), is used to report uncertainties in tabular data (see Table 17).

Table 2: Modified version of Statistics Canada's quality indicator

	Coefficient of variation
A – excellent	less than 5%
B – very good	5% to 9.9%
C – good	10% to 14.9%
D – acceptable	15% to 19.9%
E – use with caution	20% to 34.9%
F – high uncertainty	35% or more

A summary of key areas where uncertainty is high, or where significant improvements in accuracy are possible, is included for future consideration in the conclusion. Also included is a comprehensive list of references related to uncertainty analysis of emissions data.

Lastly, in the interest of transparency and scientific replicability, the following uncertainty analysis relies on several data sources, all of which are publicly available. A compilation of these significant data sets is available by request to the authors.

2 Aircraft

This sub-sector covers CAC emissions from aircraft, but not airport support equipment, which is captured under off-road engines. Patterson (2005) evaluates the current Environment Canada methodology used to estimate emissions from aircraft, and recommends potential improvements.

Jets, turboprops, helicopters and military aircraft are assumed to use turbo aviation fuel, known simply as jet fuel. The most common jet fuel is an unleaded kerosene oil-based fuel classified as Jet A-1, which is produced to an internationally standardized set of specifications (Wikipedia, 2008). Piston aircraft are assumed to use aviation gasoline. Emissions from aircraft are further stratified into landing/take-off and cruise.

The landing and take-off cycle (LTO) is defined as all activities near the airport taking place below the altitude of 3000 feet (1000 m), including taxi-in and -out, take-off, climb-out, and approach-landing (Figure 2). Cruise is defined as all activities taking place at altitudes above 3000 feet, including climb from the end of climb-out in the LTO cycle to cruise altitude, cruise, and descent from cruise altitude to the start of the LTO cycle.

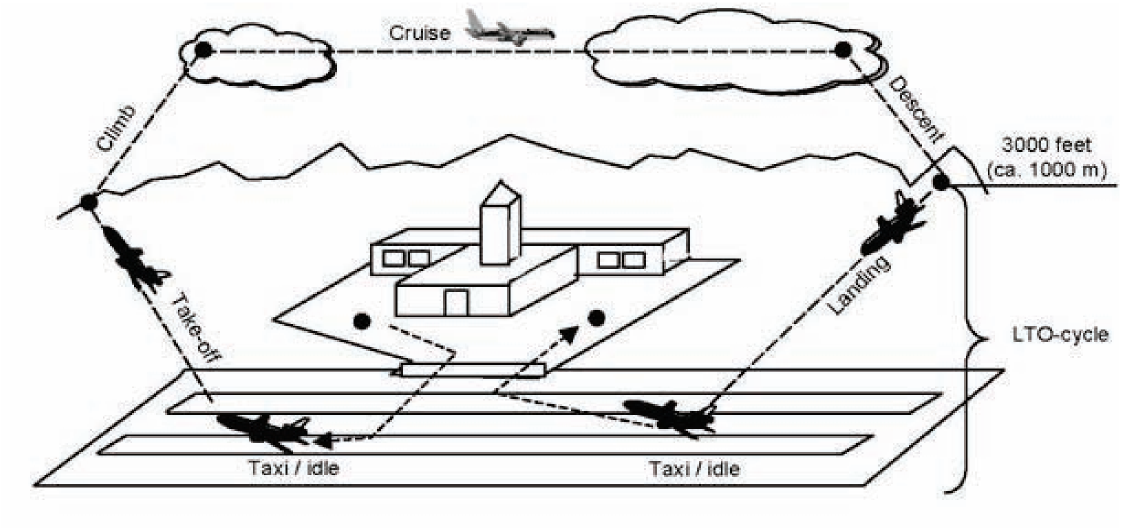

Figure 2: Landing and take-off cycle (LTO)

Typically, only LTO emissions are inventoried as contributing to ground-level ozone formation. In addition, uncertainties in estimating emissions from cruise flight are extremely large and difficult to quantify. Statistics Canada reports the amount of fuel on board domestic and foreign aircraft departing from Canadian airports; determining the portion of these fuel loads consumed in Canadian airspace would be a difficult exercise subject to large errors. Also, there is little publicly available enroute or fuel-consumed data on the approximately 30 000 overflights per month in Canadian airspace between the continental United States and Europe. For these reasons, Taylor (2007a) provides the best estimates for the cruise portion of flight available at this time (Table 17, aircraft cruise), with errors of more than 35% for all pollutants.

2.1 Aircraft movement statistics

An aircraft movement is defined as a take-off, a landing or a simulated approach by an aircraft. Aircraft movement statistics published by the Statistics Canada Aviation Statistics Centre (ASC) are accumulated from data originating with air traffic control tower units or flight service station personnel (Hillary et al., 2007). Because staff in these positions are highly trained in observation and reporting, data entries are of a high quality. ASC maintains a database of all registered aircraft, including aircraft identifications and their corresponding aircraft types, gross take-off weights, types of power plant (piston, jet or turboprop); also, whether the aircraft are fixed wing, helicopters or gliders.

Table 3 shows the aircraft movements, by take-off weight, used for aircraft activity data in this report. Movements must be divided by two to get the number of LTO cycles. Both itinerant and local movements have been considered for this uncertainty analysis; however, only the methodology for itinerant movements is discussed in this report.

Table 3: Statcan aircraft movement statistics (by take-off weight)

	NAV towers	NAV FSS	Uncontrolled	All airports
	Movements			
Total – all aircraft	**3 123 934**	**911 955**	**435 331**	**4 471 220**
2 000 kilograms and under	891 366	313 262	140 066	1 344 694
2 001 to 4 000 kilograms	254 669	122 665	96 835	474 169
4 001 to 5 670 kilograms	314 383	206 357	102 720	623 460
5 671 to 9 000 kilograms	213 019	94 460	27 524	335 003
9 001 to 18 000 kilograms	258 910	94 475	34 363	387 748
18 001 to 35 000 kilograms	407 225	62 547	28 982	498 754
35 001 to 70 000 kilograms	432 893	11 975	4 841	449 709
70 001 to 90 000 kilograms	183 602	3 963	–	187 565
90 001 to 136 000 kilograms	56 554	2 078	–	58 632
136 001 kilograms and over	111 313	173	–	111 486

2.2 Emission factors

Emission factors for jets and turboprops (Table 4) were taken from EMEP/ CORINAIR (2007). These factors are derived from the ICAO Engine Exhaust Databank (ICAO, 2008). The existing ICAO certification methodology has notable limitations: it applies to engines and therefore does not account for the influence of the airframe; it does not cover PM or CO_2; and it was developed to address local air quality issues and so does not consider total pollutant emissions produced over the whole flight cycle (Norman et al., 2003). Additional emission factors by aircraft subtype are available in Waldron and al. (2006) but were not considered for this uncertainty analysis.

Table 4: Aircraft emission factors

	GTOW	Fuel	NO_x	HC	CO
	kg	kg/LTO			
Jets					
A310	152 987	1 541	23.20	5.54	25.84
A320	77 000	802	10.83	1.92	17.59
A330	230 000	2 232	36.13	2.11	21.50
A340	276 500	2 020	35.37	18.75	50.56
B727	95 028	1 413	12.57	7.20	26.37
B737 100	49 190	920	7.97	0.58	4.82
B737 400	68 050	825	8.25	0.67	11.83
B747 100-300	377 842	3 414	55.94	37.25	78.23
B747 400	396 890	3 402	56.64	1.85	19.50
B757	115 680	1 253	19.73	1.23	12.55
B767 300 ER	186 880	1 617	26.03	0.88	6.08
B777	142 900	2 563	53.64	22.77	61.38
BAC1-11	33 800	682	4.93	21.39	37.74
BAe146	42 200	570	4.19	1.01	9.69
DC10-30	259 459	2 381	41.71	22.84	61.62
DC9	49 900	876	7.26	0.77	5.35
F100	43 390	744	5.79	1.42	13.68
F28	29 500	666	5.19	32.86	32.72
MD 82	67 800	1 003	12.34	1.92	6.52
Turboprops					
Antonov 26	19 686	137	0.196	6.935	10.110
ATR 42-320	14 097	116	1.026	0.000	0.866
ATR 72-200	17 560	139	1.490	0.000	0.728
BAe Jetstream 31	6 248	45	0.373	0.045	0.513
BAe Jetstream 41	8 674	62	0.470	0.089	0.819
Beech 1900C Airliner	6 027	60	0.255	0.626	2.211
Beech Super King Air 200B	4 684	53	0.247	0.128	0.759
Beech Super King Air 350	5 317	59	0.246	0.231	1.874
Cessna 208 Caravan	2 770	29	0.159	0.026	0.285
Dash 8 Q400	23 887	210	2.403	0.000	1.137
Dash 8 Q400 4580 hp	23 802	185	1.822	0.638	1.561
De Havilland Dash 7	17 270	142	0.766	0.188	1.489
De Havilland DHC-3 Turbo-Otter	2 817	32	0.174	0.016	0.263
Dornier 328-110	10 625	125	1.209	0.000	0.708
Embraer 110P2A	5 250	49	0.280	0.024	0.373
Fokker 27 Friendship	16 799	167	0.356	1.721	7.490
Fokker 50 Srs 100	16 852	125	1.262	0.000	0.727
Lockheed C-130H Hercules	44 905	278	1.927	0.873	1.884
Lockheed P-3B Orion	37 829	255	1.740	0.837	1.793
Reims F406 Caravan II	3 552	41	0.213	0.037	0.442
Saab 2000	18 824	146	1.036	0.036	0.825
Saab 2000 3740 hp	18 656	151	1.087	0.036	0.842
Saab 340B	11 043	75	0.499	0.224	0.427
Shorts 330	9 220	71	0.386	0.115	0.793
Shorts 360-300	10 848	84	0.407	0.680	3.193
Shorts SC.7 Srs3M-200	5 668	25	0.182	0.658	0.500
Swearingen Metro III	5 654	46	0.384	0.044	0.508

Limited emission factors (Table 5) for piston aircraft using aviation gasoline are available from the Swiss Federal Office of Civil Aviation (FOCA, 2006).

Table 5: Piston aircraft emission factors

	Fuel	**NO_x**	**HC**	**CO**
	kg/LTO			
Lycoming IO-360-A1B6 200hp	3.96	0.005	0.102	4.922
Lycoming IO-540-T4A5D 260hp	5.63	0.017	0.138	5.341
Lycoming O-320-E2A 150hp	3.18	0.028	0.047	2.397
Lycoming O-360-A3A 180hp	3.87	0.012	0.071	3.930
Lycoming O-540-J3C5D 235hp	4.74	0.003	0.150	6.060
Rotax 582 DCDI 64hp	1.30	0.001	0.575	1.078
Rotax 912 80hp	1.37	0.033	0.047	0.940
Rotax 912S 100hp	1.48	0.023	0.033	0.911
Rotax 914 114hp	2.79	0.026	0.071	2.314
TAE-125-01 Centurion 1.7 135hp	1.57	0.030	0.005	0.019
TCM IO-550-B 300hp	7.53	0.024	0.174	7.327
TCM TSIO-520-WB 325hp	10.80	0.023	0.122	9.665

2.3 Empirical results

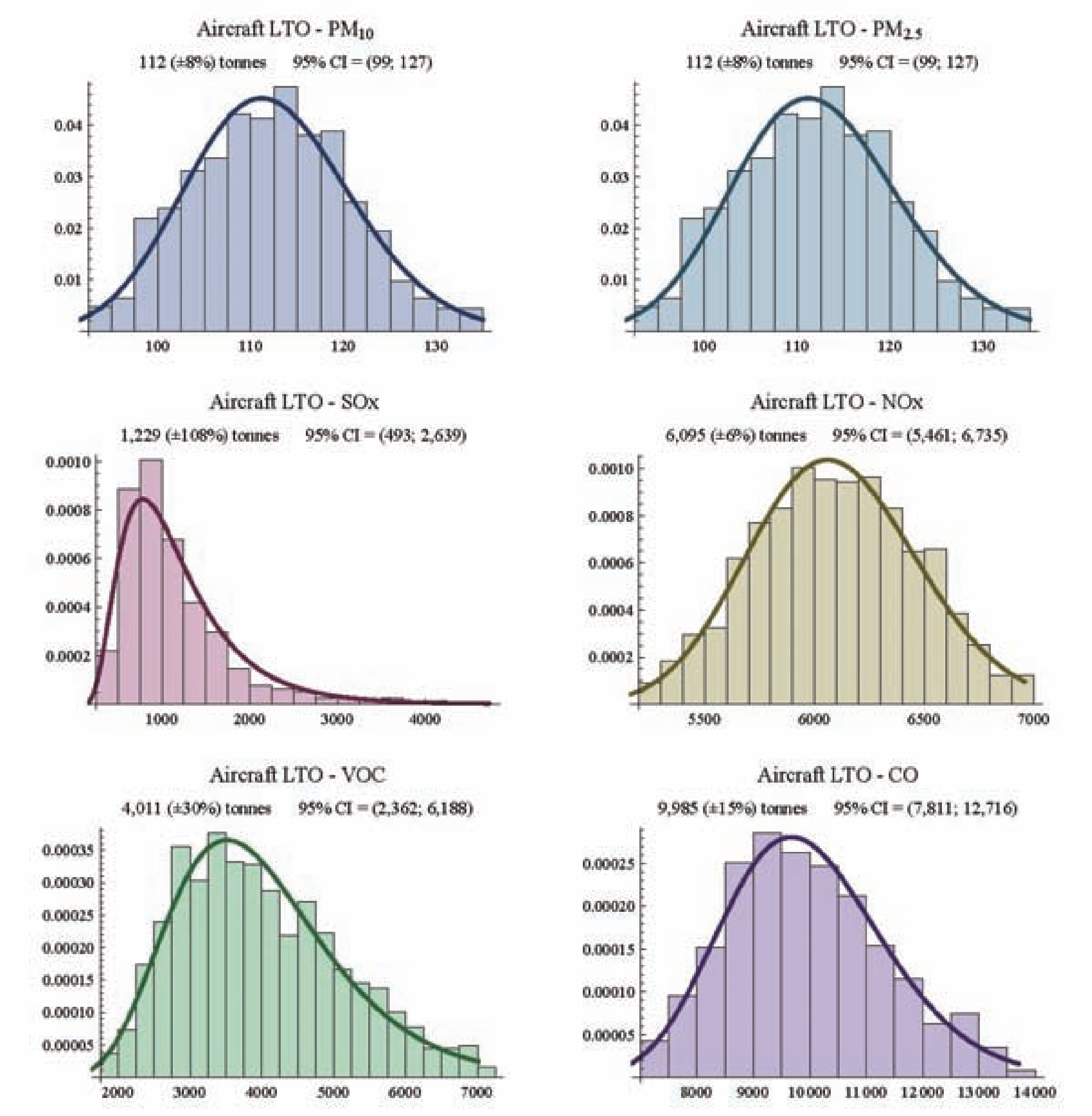

Figure 3: Monte Carlo – Aircraft LTO (metric tonnes)

3 Commercial marine vessels

This sub-sector covers CAC emissions from commercial marine vessels, but not land-based port support equipment, which is captured under off-road applications. The sub-sector is an aggregation of a number of classes of vessels that encompass freighters, tankers, tugs, ferries, passenger boats, fishing boats and container ships. SENES (2004) reviews the methodology currently used by Environment Canada to estimate emissions from commercial marine vessels. The current methodology does not take into consideration the International Maritime Organization (IMO) NO_x emissions reduction standards. NO_x emissions will be reduced by 15–20% for engines manufactured after the year 2000 (EEA, 2000).

3.1 Shipping in Canada

The current fuel-based approach derives emissions from Statcan's Shipping in Canada. There is no way to determine how much of the fuel available was actually consumed outside Canada's 200-mile limit, and hence should not contribute to ground-level ozone formation in Canada. The assumption is that for all fuel purchased in Canada but burned outside Canada, an equal amount was purchased outside Canada but burned within. Ocean-going vessels burn fuel in international waters, and by not being able to subtract that amount, it leads to an overestimation that cannot be quantified. Taylor (2007a) provides the best estimates available at this time (Table 17, marine transportation), with errors of more than 35% for all pollutants.

3.2 Vessel movements data

The current methodology for estimating emissions from commercial marine vessels is antiquated (Taylor, 2007a). Accurate data on vessel movements, origin, destination and shipping route archived by the Canadian Coast Guard should instead be used to estimate emissions using an activity-based, as opposed to the current fuel-based, methodology. Environment Canada is currently in the process of obtaining this information.

4 On-road vehicles

This sub-sector covers CAC emissions from vehicles licensed for use on road (paved and unpaved) to transport people and/or goods. Emissions of all CACs from this sub-sector result from the combustion of fossil fuels in internal engines, evaporation of those fuels through the fuel system and from tire/brake wear. MOBILE is a sophisticated model that requires a number of inputs to accurately estimate emission factors, which are then multiplied by vehicle kilometres traveled (VKT) to obtain emission estimates. Emission estimates are generated on a provincial/territorial level and monthly basis, then summed to get annual provincial/territorial level estimates.

In the past, mileage accumulation rates were derived from odometer readings of vehicles passing through the Ontario Drive Clean inspection program (Stewart Brown Associates, 2004b,a, 2005; Taylor, 2005c). Taylor (2007a) identified the need for a suitable, and complete, time-series of data for vehicle populations and mileage accumulation rates as an area for improvement. This report introduces a probabilistic framework to derive vehicle populations and VKT representative for each province, using aggregate data from the Statistics Canada Canadian Vehicle Survey.

4.1 MOBILE model

MOBILE is an EPA model for estimating pollution from on-road vehicles (Figure 4). MOBILE calculates emissions of hydrocarbons (HC), oxides of nitrogen (NO_x) and carbon monoxide (CO) from passenger cars, motorcycles, light-and heavy-duty trucks (Beardsley et al., 2001; Koupal and Glover, 2001; Glover et al., 2003; Koupal and Brzezinski, 2003). MOBILE is based on emissions testing of tens of thousands of vehicles (MSOD, 2002; Fulper, 2004). MOBILE estimates both exhaust and evaporative emissions, in the form of emission factors expressed as grams of pollutant per vehicle per hour (g/hr), or per vehicle mile travelled (g/mi).

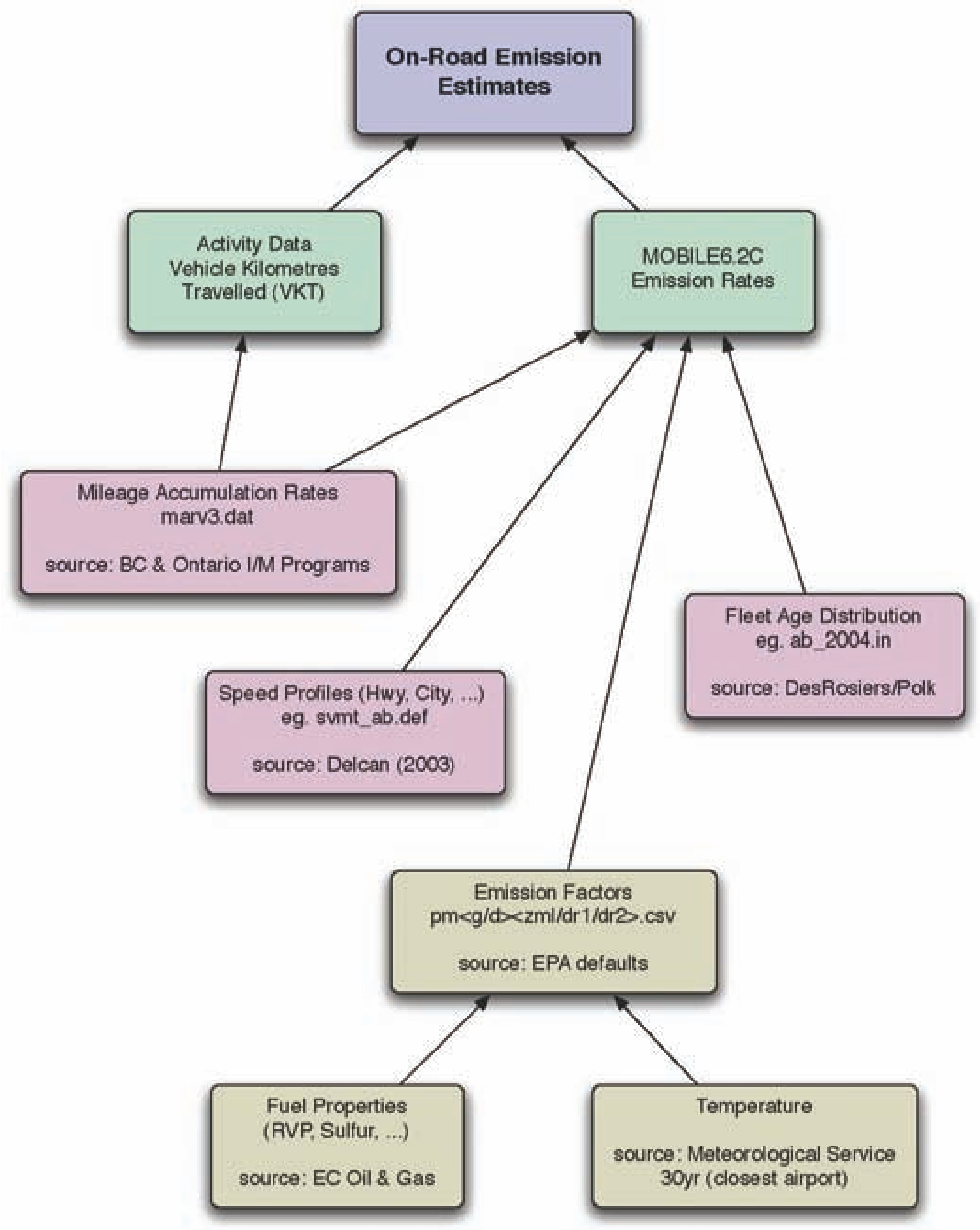

Figure 4: MOBILE model diagram

MOBILE was first developed as MOBILE1 in the late 1970s, and has been updated periodically to reflect improved data, changes in vehicle, engine and emission control system technologies, changes in applicable regulations and emission standards and test procedures, and improved understanding of in-use emission levels and the factors that influence them. The current official release, MOBILE6, was released for use in January 2002. This version added particulate matter (PM) to the list of estimated pollutants (Glover and Cumberworth, 2003).

This model accounts for the emission impacts of changes in vehicle emission standards, changes in vehicle populations and activity, and variation in local conditions such as temperature, humidity and fuel quality. Emission factors for a given vehicle category change over time to account for fleet turnover, as older vehicles built to less stringent emission standards get replaced by newer vehicles built in compliance with more stringent standards.

Since the 1988 model year, the Canadian and U.S. emissions standards have been in alignment for light and heavy-duty vehicles, and no changes to the MOBILE6.2 data[1] for these model years were made. However, for pre-1988 model years, standards were different, and the MOBILE6.2 data for these model years had to be modified for applicability in Canada (Gagnon and Taylor, 2003; Taylor, 2005a,b,d). The inputs for a run of the MOBILE6.2C model involve 9 100 vehicle subclasses.

$$\boldsymbol{\mathcal{I}} = \mathbf{R} \times \boldsymbol{\mathcal{M}} \times \mathbf{F} \times \mathbf{Y} \tag{1}$$

$$= \underbrace{\{AB, \ldots, YT\}}_{\text{13 regions}^2} \times \underbrace{\{LDV, \ldots, HDV8b\}}_{\text{14 MOBILE vehicle classes}} \times \underbrace{\{G, D\}}_{\text{2 fuel types}} \times \underbrace{\{0, -1, \ldots, -24\}}_{\text{25 model years}} \tag{2}$$

MOBILE6 needs minimum and maximum daily temperatures to perform several calculations: temperature corrections to exhaust NO_x, HC, and CO; diurnal, hot soak, running loss and resting loss portions of evaporative HC. Meteorological data comes

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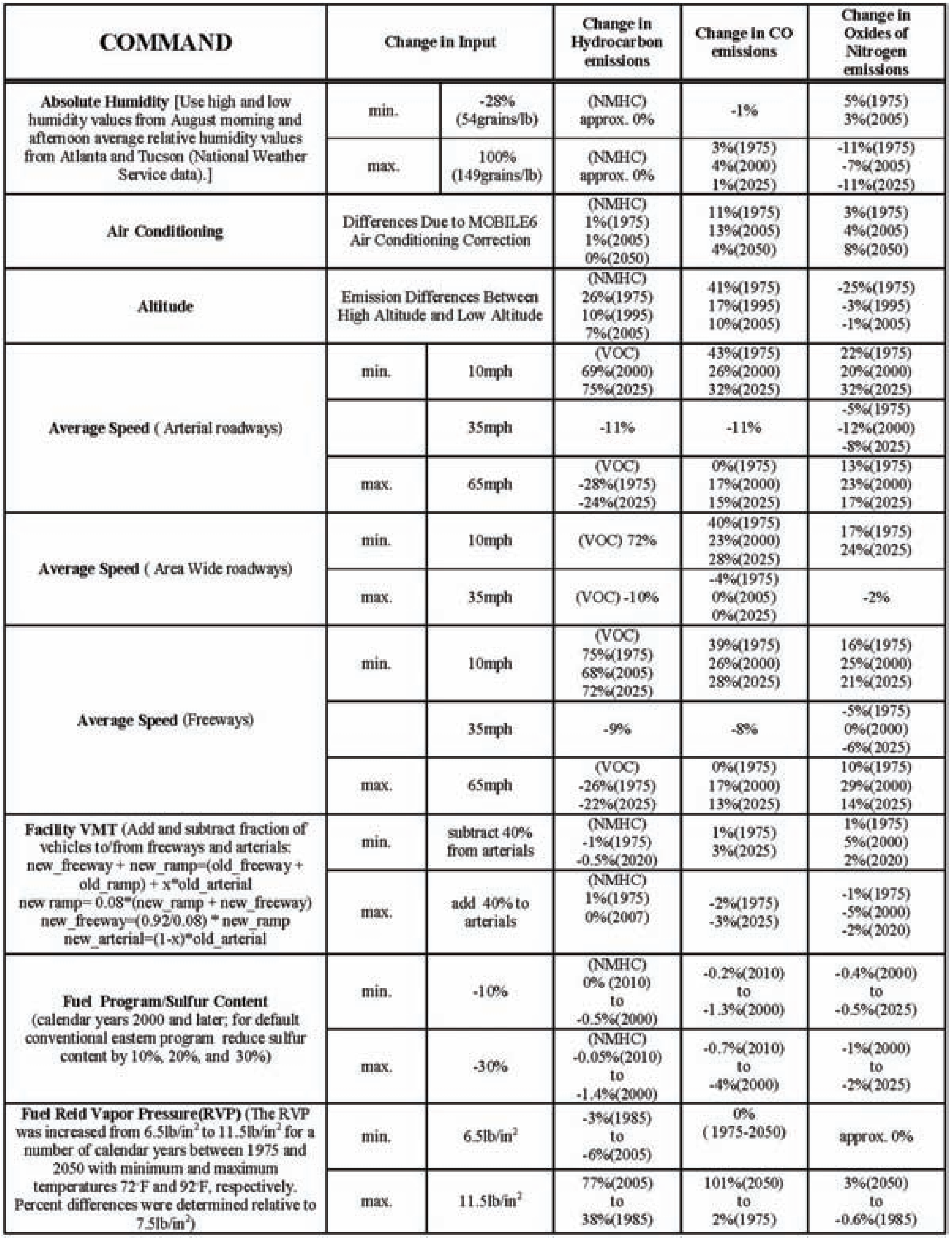
[1] Ten provinces and there territories.

from the Meteorological Service of Canada (MSC). For each province/ territory/region, the largest city by population is selected. For each of these cities, the largest airport (international if possible) is selected as the station from which to draw meteorological data. Airports are used because there is one in each city, and because they often contain the most complete and longest-running datasets. The meteorological data for the city is assigned to the entire province/territory/region.

Diesel and gasoline sulphur levels, in parts per million (ppm), are based on Guthrie et al. (2006). All other fuel characteristics, such as Reid Vapour Pressure (RVP) and oxygenates, are obtained from SENES (2002). MOBILE6 can also account for local and temporal variations in humidity, which significantly affect NO_x correction factors. The current Environment Canada methodology does not consider historical humidity data.

Prior knowledge of the relative importance of different MOBILE6 input parameters with respect to emission results can be an important factor in determining whether or not local data should be considered. Giannelli et al. (2002) present a systematic study of the relative importance of various MOBILE6 input parameters. Each parameter evaluated was varied, and the resulting MOBILE6 emissions were compared to emissions determined with default or some base value input (Table 6). These results were then subdivided into three categories: major effects, intermediate effects and minor effects on emissions. Vehicle age or registration distribution, average daily temperature, fuel RVP, and vehicle speed have the major effects, with changes in emissions of 20% or more relative to the emissions calculated with default input values. Absolute humidity, air conditioning, altitude, mileage accumulation, speed VMT and starts per day have intermediate effects with changes in emissions between 5% and 20%. Depending on the pollutant, remaining input parameters (Table 7) have minor effects, with changes in emissions of less than 5%.

Table 6: MOBILE sensitivity analysis

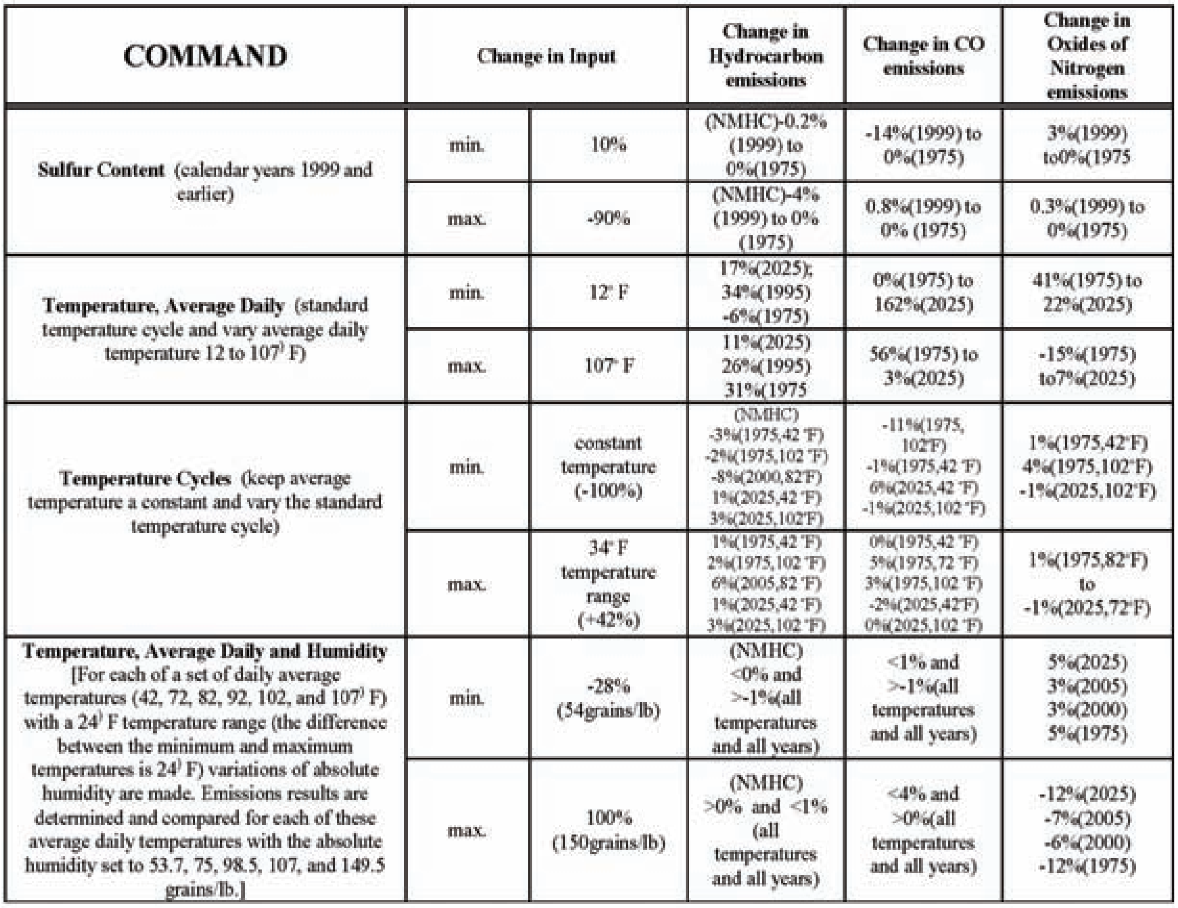


COMMAND	Change in Input		Change in Hydrocarbon emissions	Change in CO emissions	Change in Oxides of Nitrogen emissions
Absolute Humidity [Use high and low humidity values from August morning and afternoon average relative humidity values from Atlanta and Tucson (National Weather Service data).]	min.	-28% (54grains/lb)	(NMHC) approx. 0%	-1%	5%(1975) 3%(2005)
	max.	100% (149grains/lb)	(NMHC) approx. 0%	3%(1975) 4%(2000) 1%(2025)	-11%(1975) -7%(2005) -11%(2025)
Air Conditioning	Differences Due to MOBILE6 Air Conditioning Correction		(NMHC) 1%(1975) 1%(2005) 0%(2050)	11%(1975) 13%(2005) 4%(2050)	3%(1975) 4%(2005) 8%(2050)
Altitude	Emission Differences Between High Altitude and Low Altitude		(NMHC) 26%(1975) 10%(1995) 7%(2005)	41%(1975) 17%(1995) 10%(2005)	-25%(1975) -3%(1995) -1%(2005)
Average Speed (Arterial roadways)	min.	10mph	(VOC) 69%(2000) 75%(2025)	43%(1975) 26%(2000) 32%(2025)	22%(1975) 20%(2000) 32%(2025)
		35mph	-11%	-11%	-5%(1975) -12%(2000) -8%(2025)
	max.	65mph	(VOC) -28%(1975) -24%(2025)	0%(1975) 17%(2000) 15%(2025)	13%(1975) 23%(2000) 17%(2025)
Average Speed (Area Wide roadways)	min.	10mph	(VOC) 72%	40%(1975) 23%(2000) 28%(2025)	17%(1975) 24%(2025)
	max.	35mph	(VOC) -10%	-4%(1975) 0%(2005) 0%(2025)	-2%
Average Speed (Freeways)	min.	10mph	(VOC) 75%(1975) 68%(2005) 72%(2025)	39%(1975) 26%(2000) 28%(2025)	16%(1975) 25%(2000) 21%(2025)
		35mph	-9%	-8%	-5%(1975) 0%(2000) -6%(2025)
	max.	65mph	(VOC) -26%(1975) -22%(2025)	0%(1975) 17%(2000) 13%(2025)	10%(1975) 29%(2000) 14%(2025)
Facility VMT (Add and subtract fraction of vehicles to/from freeways and arterials: new_freeway + new_ramp=(old_freeway + old_ramp) + x*old_arterial new ramp= 0.08*(new_ramp + new_freeway) new_freeway=(0.92/0.08) * new_ramp new_arterial=(1-x)*old_arterial	min.	subtract 40% from arterials	(NMHC) -1%(1975) -0.5%(2020)	1%(1975) 3%(2025)	1%(1975) 5%(2000) 2%(2020)
	max.	add 40% to arterials	(NMHC) 1%(1975) 0%(2007)	-2%(1975) -3%(2025)	-1%(1975) -5%(2000) -2%(2020)
Fuel Program/Sulfur Content (calendar years 2000 and later; for default conventional eastern program reduce sulfur content by 10%, 20%, and 30%)	min.	-10%	(NMHC) 0% (2010) to -0.5%(2000)	-0.2%(2010) to -1.3%(2000)	-0.4%(2000) to -0.5%(2025)
	max.	-30%	(NMHC) -0.05%(2010) to -1.4%(2000)	-0.7%(2010) to -4%(2000)	-1%(2000) to -2%(2025)
Fuel Reid Vapor Pressure(RVP) (The RVP was increased from 6.5lb/in^2 to 11.5lb/in^2 for a number of calendar years between 1975 and 2050 with minimum and maximum temperatures 72°F and 92°F, respectively. Percent differences were determined relative to 7.5lb/in^2)	min.	6.5lb/in^2	-3%(1985) to -6%(2005)	0% (1975-2050)	approx. 0%
	max.	11.5lb/in^2	77%(2005) to 38%(1985)	101%(2050) to 2%(1975)	3%(2050) to -0.6%(1985)

Table 6: MOBILE sensitivity analysis (cont.)

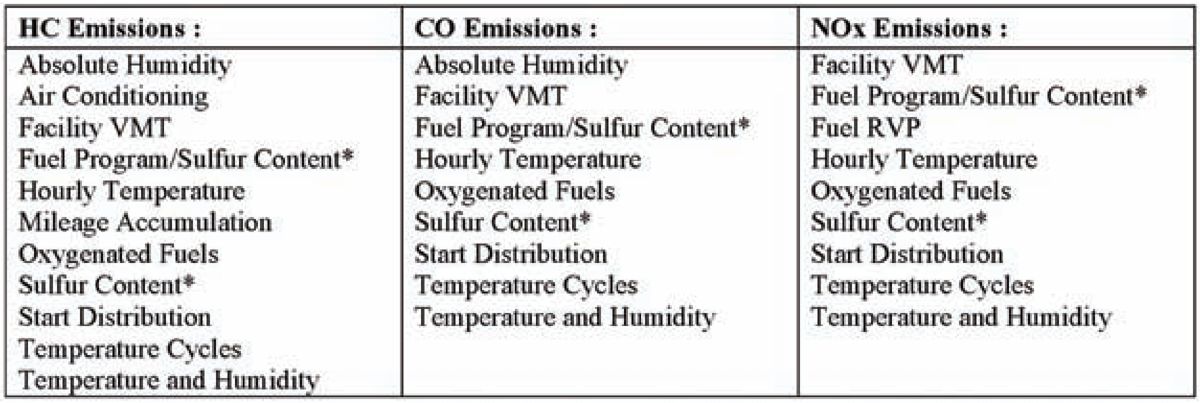
COMMAND	Change in Input		Change in Hydrocarbon emissions	Change in CO emissions	Change in Oxides of Nitrogen emissions
Mileage Accumulation(increase and decrease mileage accumulation relative to the MOBILE6 defaults)	min.	20% decrease	(NMHC) 3%(1980) 4%(2005) 3%(2015) 0.2%(2020)	–1.7%(1985) to -7.9%(2020)	3%(1990) to -12%(2020)
	max.	20% increase	(NMHC) 1%(1990) -1%(2000) 1%(2005) 3%(2020)	3%(1990) to 11%(2020)	-2%(1980) to 13%(2020)
Oxygenated Fuels (ether concentration from 1% to 2.7%; market share variations from 5% to 50%)	min.	5% mkt, 1%ether, 0% alcohol	(NMHC) approx. 0%	approx. 0%	0%
	max.	50% mkt, 0%ether, 2.7% alcohol	(NMHC) -2% (2000)to -3%(2020)	-5%(2000) to -3%(2020)	0%
Oxygenated Fuels (alcohol concentration from 0.7% to 3.5%; market share variations from 5% to 50%)	min.	50% mkt, 0%ether, 0.7% alcohol	(NMHC) approx. 1% (2000)to (2020)	<1% (2000) to (2020)	0%
	max.	50% mkt, 0%ether, 3.5% alcohol	(NMHC) -0.5% (2000)to - 1%(2020)	-5%(2000) to -2%(2020)	0%
Registration Distribution(decrease newer vehicle fractions and increase older vehicle fractions)	min.	5% age shift	(NMHC) 5%(1985) to 31%(2015)	3%(1980) to 21%(2000)	1%(1985) to 12%(2020)
	max.	20% age shift	(NMHC) 13%(1975) to 74%(2015)	9%(1975) 47%(1995) 22%(2020)	1%(1980) to 38%(2020)
Speed VMT (Arterial; -3% - null low speed vehicle fractions 9% - equal vehicle fractions for all speeds 14% - increase low speed vehicle fraction by 10% 21% - increase low speed vehicle fraction by 20% 29% - increase low speed vehicle fraction by 30%)	min.	-3% (free-flow/ all day non-rush hour speeds)	(NMHC) -3%	approx. -1%	-3% to -0.5%
	max.	29%(congested traffic flow ;i.e., 30% of rush hour "free-flow" vehicles at the lower speeds)	(NMHC) 35%(1975) 33%(1985) 39%(2050)	21%(1975) 13%(2005) 15%(2020)	5%(1975) to 8%(2050)
Speed VMT (Freeway; reduce fraction of vehicles from high speeds to lower speeds)	min.	-50% (equal distribution of speeds)	(NMHC) 12%(1975) 10%(2020) 11%(2050)	+3%(1975) -1%(2000) 0%(2050)	0%(1975) -1%(1995) -2%(2005) 0%(2050)
	max.	10%(most vehicles at the higher speeds)	(NMHC) -4%(1975) -3%(1985) -4%(2050)	-3%(1975) -2%(1995) -1%(2020)	approx. -1%
Starts Per Day(change the number of starts per day from -50% to +50% in increments of 10% for each vehicle type)	min.	-50%	(NMHC) -17%(2025) to -13%(1975)	-16%(1975) to -13%(2025)	-10%(1975) to -7%(2025)
	max.	50%	(NMHC) 17%(2025) to 14%(1975)	14%(2025) to 15%(1975)	10%(1975) to 7%(2025)
Start Distribution	compare emissions with default hourly start fractions to a constant fraction of starts for each hour of the day		(NMHC) 0%(1975) to 3%(2025)	1%(1975) to 3%(2025)	2%(1975) to 1%(2025)

Table 6: MOBILE sensitivity analysis (cont.)



COMMAND	Change in Input		Change in Hydrocarbon emissions	Change in CO emissions	Change in Oxides of Nitrogen emissions
Sulfur Content (calendar years 1999 and earlier)	min.	10%	(NMHC)-0.2% (1999) to 0%(1975)	-14%(1999) to 0%(1975)	3%(1999) to0%(1975
	max.	-90%	(NMHC)-4% (1999) to 0% (1975)	0.8%(1999) to 0% (1975)	0.3%(1999) to 0%(1975)
Temperature, Average Daily (standard temperature cycle and vary average daily temperature 12 to 107° F)	min.	12° F	17%(2025); 34%(1995) -6%(1975)	0%(1975) to 162%(2025)	41%(1975) to 22%(2025)
	max.	107° F	11%(2025) 26%(1995) 31%(1975	56%(1975) to 3%(2025)	-15%(1975) to7%(2025)
Temperature Cycles (keep average temperature a constant and vary the standard temperature cycle)	min.	constant temperature (-100%)	(NMHC) -3%(1975,42 °F) -2%(1975,102 °F) -8%(2000,82°F) 1%(2025,42 °F) 3%(2025,102°F)	-11%(1975, 102°F) -1%(1975,42 °F) 6%(2025,42 °F) -1%(2025,102 °F)	1%(1975,42°F) 4%(1975,102°F) -1%(2025,102°F)
	max.	34° F temperature range (+42%)	1%(1975,42 °F) 2%(1975,102 °F) 6%(2005,82 °F) 1%(2025,42 °F) 3%(2025,102 °F)	0%(1975,42 °F) 5%(1975,72 °F) 3%(1975,102 °F) -2%(2025,42°F) 0%(2025,102 °F)	1%(1975,82°F) to -1%(2025,72°F)
Temperature, Average Daily and Humidity [For each of a set of daily average temperatures (42, 72, 82, 92, 102, and 107° F) with a 24° F temperature range (the difference between the minimum and maximum temperatures is 24° F) variations of absolute humidity are made. Emissions results are determined and compared for each of these average daily temperatures with the absolute humidity set to 53.7, 75, 98.5, 107, and 149.5 grains/lb.]	min.	-28% (54grains/lb)	(NMHC) <0% and >-1%(all temperatures and all years)	<1% and >-1%(all temperatures and all years)	5%(2025) 3%(2005) 3%(2000) 5%(1975)
	max.	100% (150grains/lb)	(NMHC) >0% and <1% (all temperatures and all years)	<4% and >0%(all temperatures and all years)	-12%(2025) -7%(2005) -6%(2000) -12%(1975)

Table 7: MOBILE pollutants with minor effects



HC Emissions :	CO Emissions :	NOx Emissions :
Absolute Humidity Air Conditioning Facility VMT Fuel Program/Sulfur Content* Hourly Temperature Mileage Accumulation Oxygenated Fuels Sulfur Content* Start Distribution Temperature Cycles Temperature and Humidity	Absolute Humidity Facility VMT Fuel Program/Sulfur Content* Hourly Temperature Oxygenated Fuels Sulfur Content* Start Distribution Temperature Cycles Temperature and Humidity	Facility VMT Fuel Program/Sulfur Content* Fuel RVP Hourly Temperature Oxygenated Fuels Sulfur Content* Start Distribution Temperature Cycles Temperature and Humidity

4.2 Canadian vehicle survey

Censoring is important in survey sampling to protect the privacy of respondents. The Canadian Vehicle Survey (CVS) achieves censoring by aggregating response data into broad one- or two-dimensional categories (Tables 8–10). While a significant amount of information is destroyed in the process, we can still infer probabilistic properties of the individual variables. The aggregated CVS vehicle classes <4.5 tonnes (L), 4.5–15 tonnes (M), and >15 tonnes (H) are recursively subdivided into the more detailed 28 MOBILE vehicle classes (Figure 5).[2] At the same time, this probabilistic framework can be adjusted in the future should Environment Canada obtain higher resolution data.

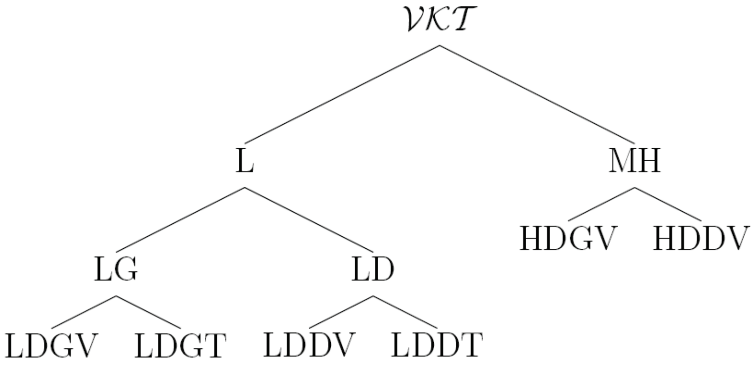


Figure 5: Mapping of CVS to MOBILE vehicle classes

For example, while the number of Alberta registrations in MOBILE vehicle classes LDGV to LDDT 34 for the current model year are unknown random variables, we at least can say that their sum

$$\begin{aligned}&\mathcal{M}(AB,LDGV,0) + \mathcal{M}(AB,LDGT1,0) + \mathcal{M}(AB,LDGT2,0) + \mathcal{M}(AB,LDGT3,0)\\&\quad + \mathcal{M}(AB,LDGT4,0) + \mathcal{M}(AB,LDDV,0) + \mathcal{M}(AB,LDDT12,0) + \mathcal{M}(AB,LDDT34,0) \qquad (3)\end{aligned}$$

is equal to the known quantity C(AB,L,0), which has value 133 386 as reported in CVS.

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[2] See equations 6 to 48 in Appendix A.3 for details.

Table 8: CVS Table 4-1

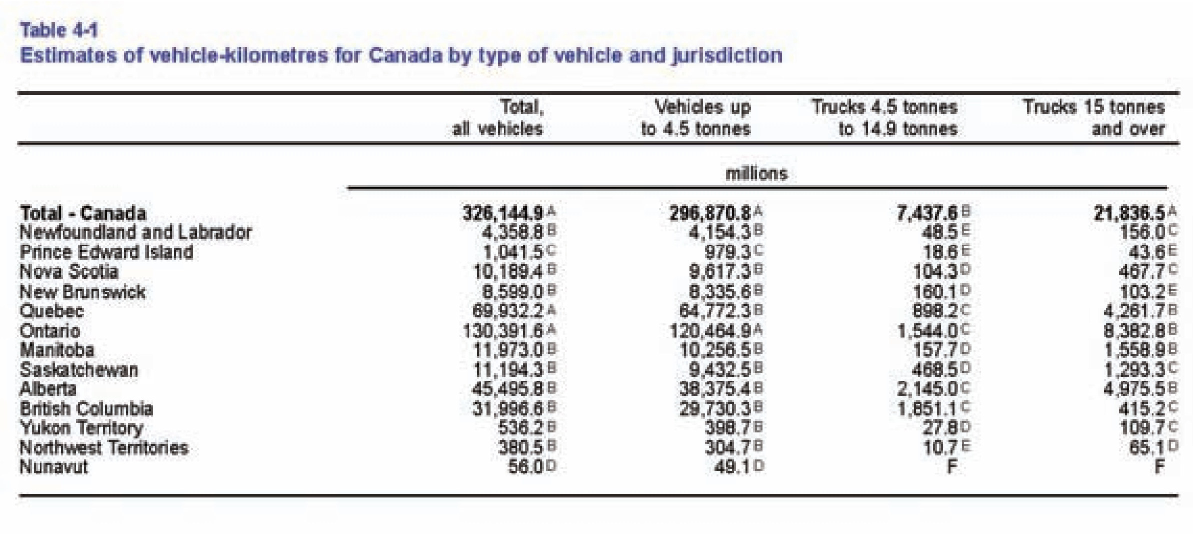


Table 4-1

Estimates of vehicle-kilometres for Canada by type of vehicle and jurisdiction

	Total, all vehicles	Vehicles up to 4.5 tonnes	Trucks 4.5 tonnes to 14.9 tonnes	Trucks 15 tonnes and over
	millions			
Total - Canada	**326,144.9**^{A}	**296,870.8**^{A}	**7,437.6**^{B}	**21,836.5**^{A}
Newfoundland and Labrador	4,358.8^{B}	4,154.3^{B}	48.5^{E}	156.0^{C}
Prince Edward Island	1,041.5^{C}	979.3^{C}	18.6^{E}	43.6^{E}
Nova Scotia	10,189.4^{B}	9,617.3^{B}	104.3^{D}	467.7^{C}
New Brunswick	8,599.0^{B}	8,335.6^{B}	160.1^{D}	103.2^{E}
Quebec	69,932.2^{A}	64,772.3^{B}	898.2^{C}	4,261.7^{B}
Ontario	130,391.6^{A}	120,464.9^{A}	1,544.0^{C}	8,382.8^{B}
Manitoba	11,973.0^{B}	10,256.5^{B}	157.7^{D}	1,558.9^{B}
Saskatchewan	11,194.3^{B}	9,432.5^{B}	468.5^{D}	1,293.3^{C}
Alberta	45,495.8^{B}	38,375.4^{B}	2,145.0^{C}	4,975.5^{B}
British Columbia	31,996.6^{B}	29,730.3^{B}	1,851.1^{C}	415.2^{C}
Yukon Territory	536.2^{B}	398.7^{B}	27.8^{D}	109.7^{C}
Northwest Territories	380.5^{B}	304.7^{B}	10.7^{E}	65.1^{D}
Nunavut	56.0^{D}	49.1^{D}	F	F

Table 9: CVS Table 4-2

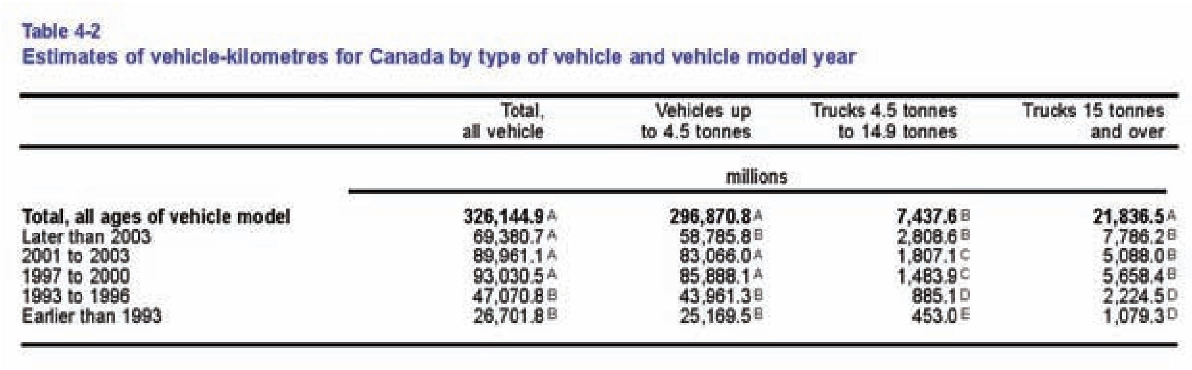


Table 4-2

Estimates of vehicle-kilometres for Canada by type of vehicle and vehicle model year

	Total, all vehicle	Vehicles up to 4.5 tonnes	Trucks 4.5 tonnes to 14.9 tonnes	Trucks 15 tonnes and over
	millions			
Total, all ages of vehicle model	**326,144.9**^{A}	**296,870.8**^{A}	**7,437.6**^{B}	**21,836.5**^{A}
Later than 2003	69,380.7^{A}	58,785.8^{B}	2,808.6^{B}	7,786.2^{B}
2001 to 2003	89,961.1^{A}	83,066.0^{A}	1,807.1^{C}	5,088.0^{B}
1997 to 2000	93,030.5^{A}	85,888.1^{A}	1,483.9^{C}	5,658.4^{B}
1993 to 1996	47,070.8^{B}	43,961.3^{B}	885.1^{D}	2,224.5^{D}
Earlier than 1993	26,701.8^{B}	25,169.5^{B}	453.0^{E}	1,079.3^{D}

Table 10: CVS Table 4-4

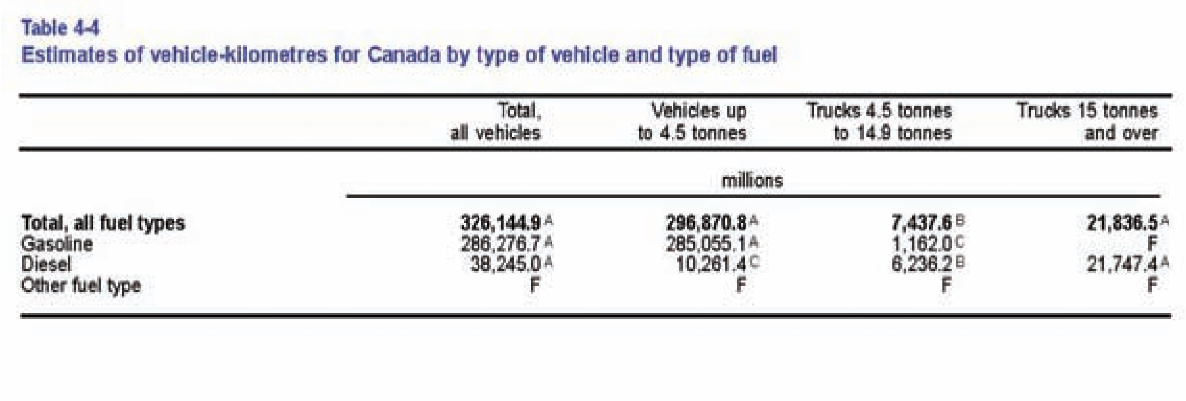


Table 4-4

Estimates of vehicle-kilometres for Canada by type of vehicle and type of fuel

	Total, all vehicles	Vehicles up to 4.5 tonnes	Trucks 4.5 tonnes to 14.9 tonnes	Trucks 15 tonnes and over
	millions			
Total, all fuel types	**326,144.9**^{A}	**296,870.8**^{A}	**7,437.6**^{B}	**21,836.5**^{A}
Gasoline	286,276.7^{A}	285,055.1^{A}	1,162.0^{C}	F
Diesel	38,245.0^{A}	10,261.4^{C}	6,236.2^{B}	21,747.4^{A}
Other fuel type	F	F	F	F

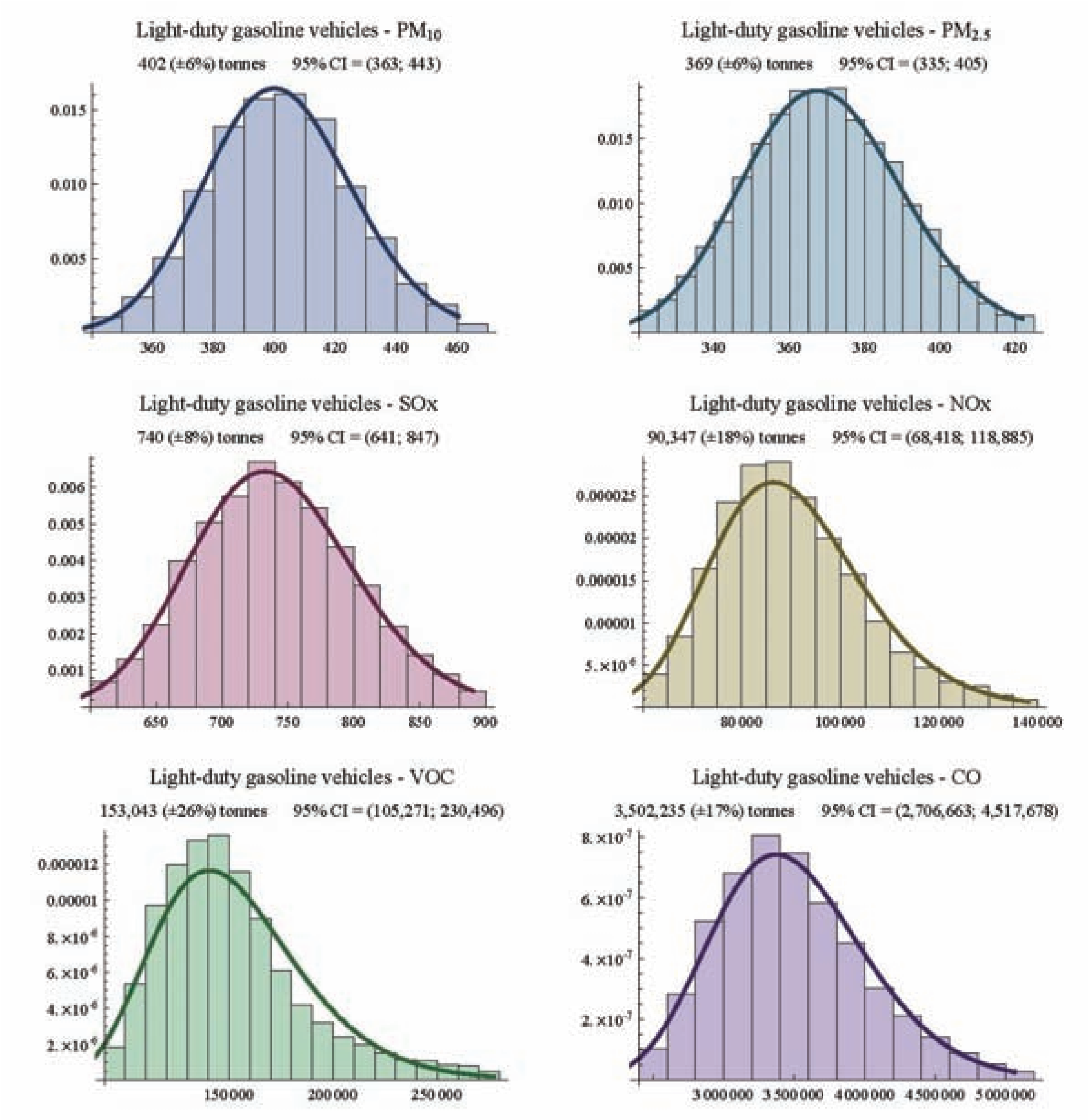
In the future, if Environment Canada obtains detailed registration data by province, MOBILE vehicle class and model year, then the random variables

$$\mathcal{M}(AB,LDGV,0), \ldots, \mathcal{M}(AB,LDDT34,0) \tag{4}$$

can be replaced in this probabilistic model by the known quantities.

$$M(AB,LDGV,0), \ldots, M(AB,LDDT34,0) \tag{5}$$

4.3 Empirical results


Light-duty gasoline vehicles - PM_{10}

402 (±6%) tonnes 95% CI = (363; 443)

Light-duty gasoline vehicles - $PM_{2.5}$

369 (±6%) tonnes 95% CI = (335; 405)

Light-duty gasoline vehicles - SOx

740 (±8%) tonnes 95% CI = (641; 847)

Light-duty gasoline vehicles - NOx

90,347 (±18%) tonnes 95% CI = (68,418; 118,885)

Light-duty gasoline vehicles - VOC

153,043 (±26%) tonnes 95% CI = (105,271; 230,496)

Light-duty gasoline vehicles - CO

3,502,235 (±17%) tonnes 95% CI = (2,706,663; 4,517,678)

Figure 6: Monte Carlo – Light-duty gasoline vehicles (metric tonnes)

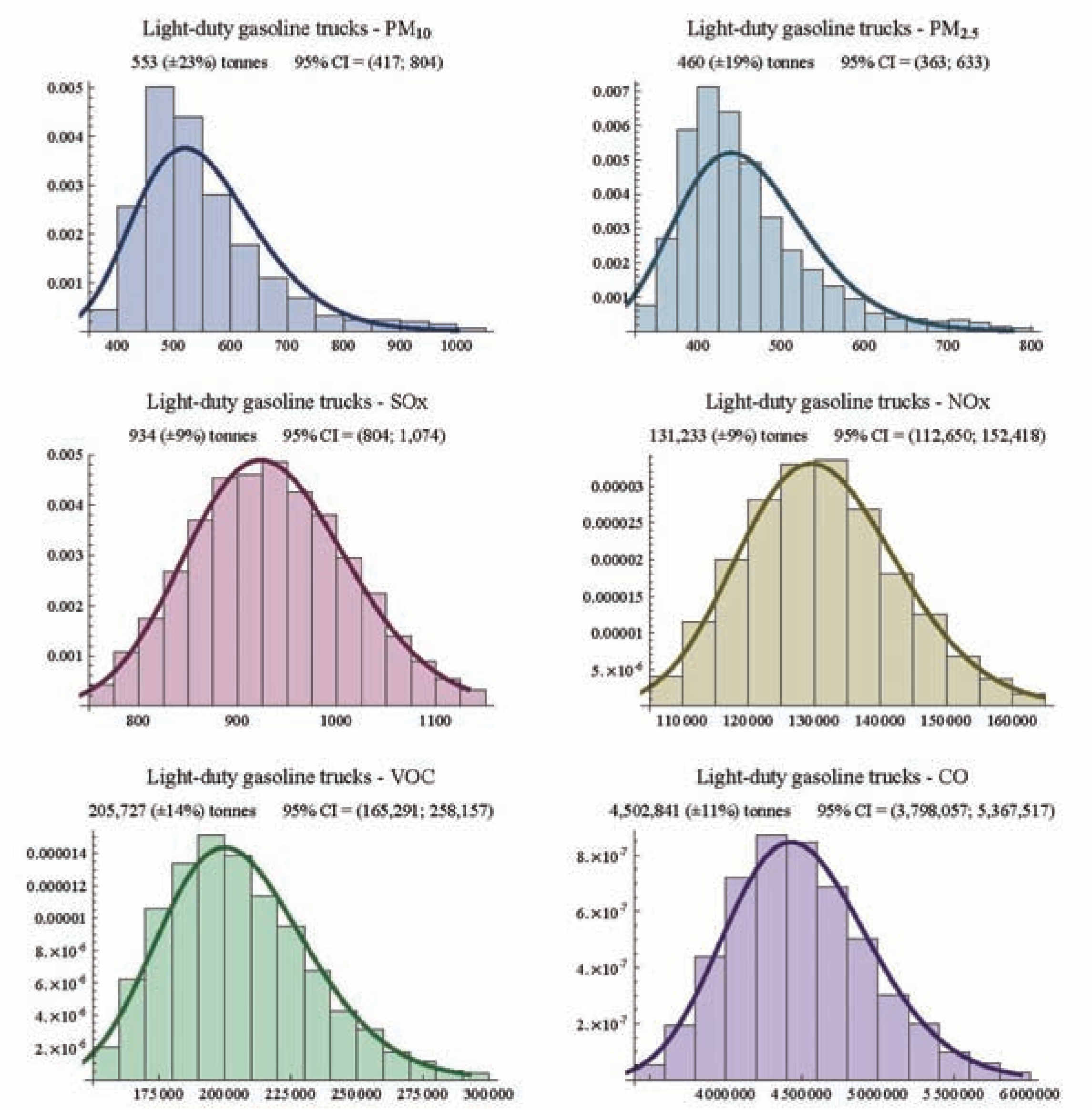
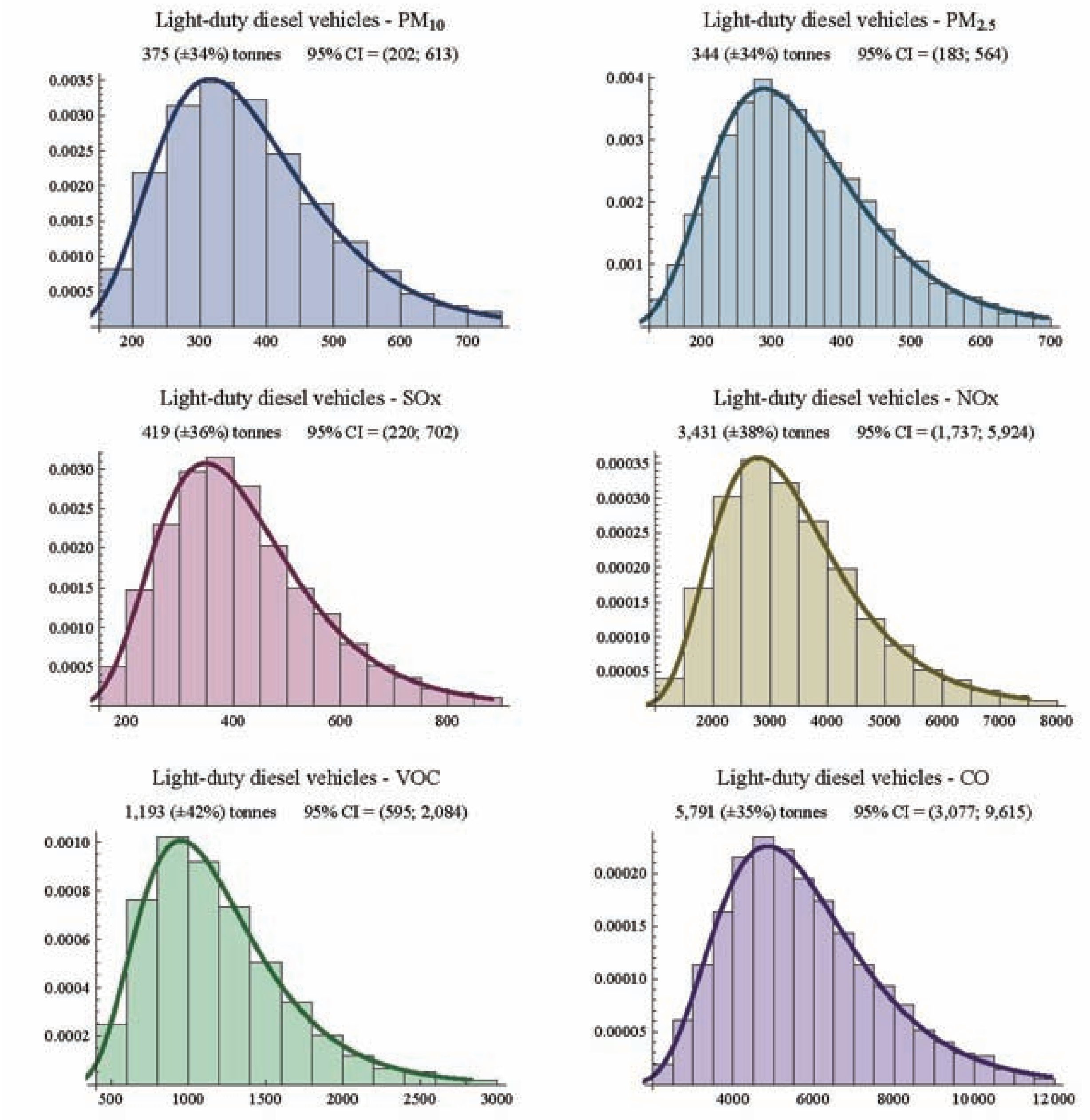


Figure 7: Monte Carlo – Light-duty gasoline trucks (metric tonnes)



Light-duty diesel vehicles - PM_{10}

375 (±34%) tonnes 95% CI = (202; 613)

Light-duty diesel vehicles - $PM_{2.5}$

344 (±34%) tonnes 95% CI = (183; 564)

Light-duty diesel vehicles - SOx

419 (±36%) tonnes 95% CI = (220; 702)

Light-duty diesel vehicles - NOx

3,431 (±38%) tonnes 95% CI = (1,737; 5,924)

Light-duty diesel vehicles - VOC

1,193 (±42%) tonnes 95% CI = (595; 2,084)

Light-duty diesel vehicles - CO

5,791 (±35%) tonnes 95% CI = (3,077; 9,615)

Figure 8: Monte Carlo – Light-duty diesel vehicles (metric tonnes)

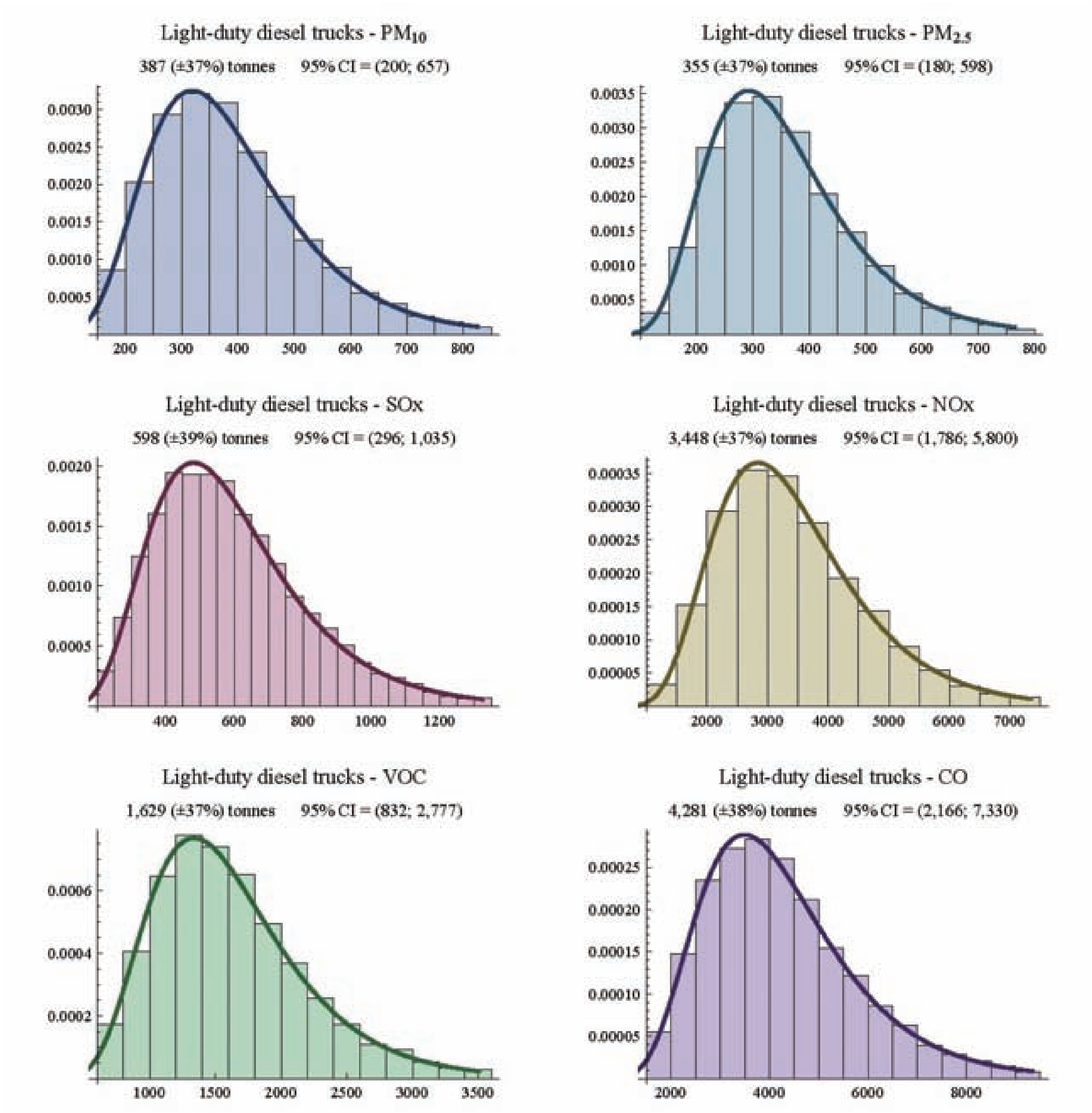


Figure 9: Monte Carlo – Light-duty diesel trucks (metric tonnes)

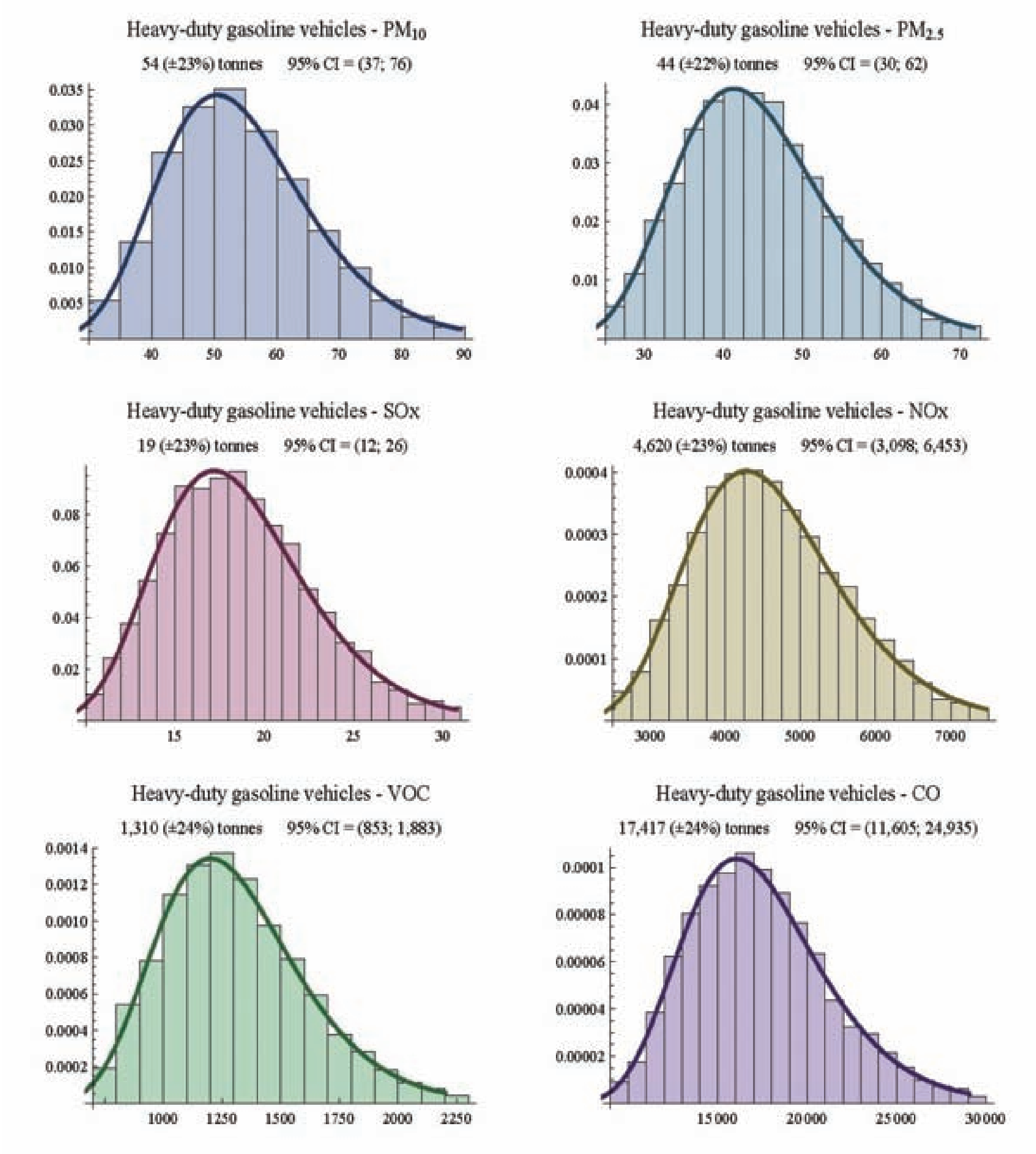
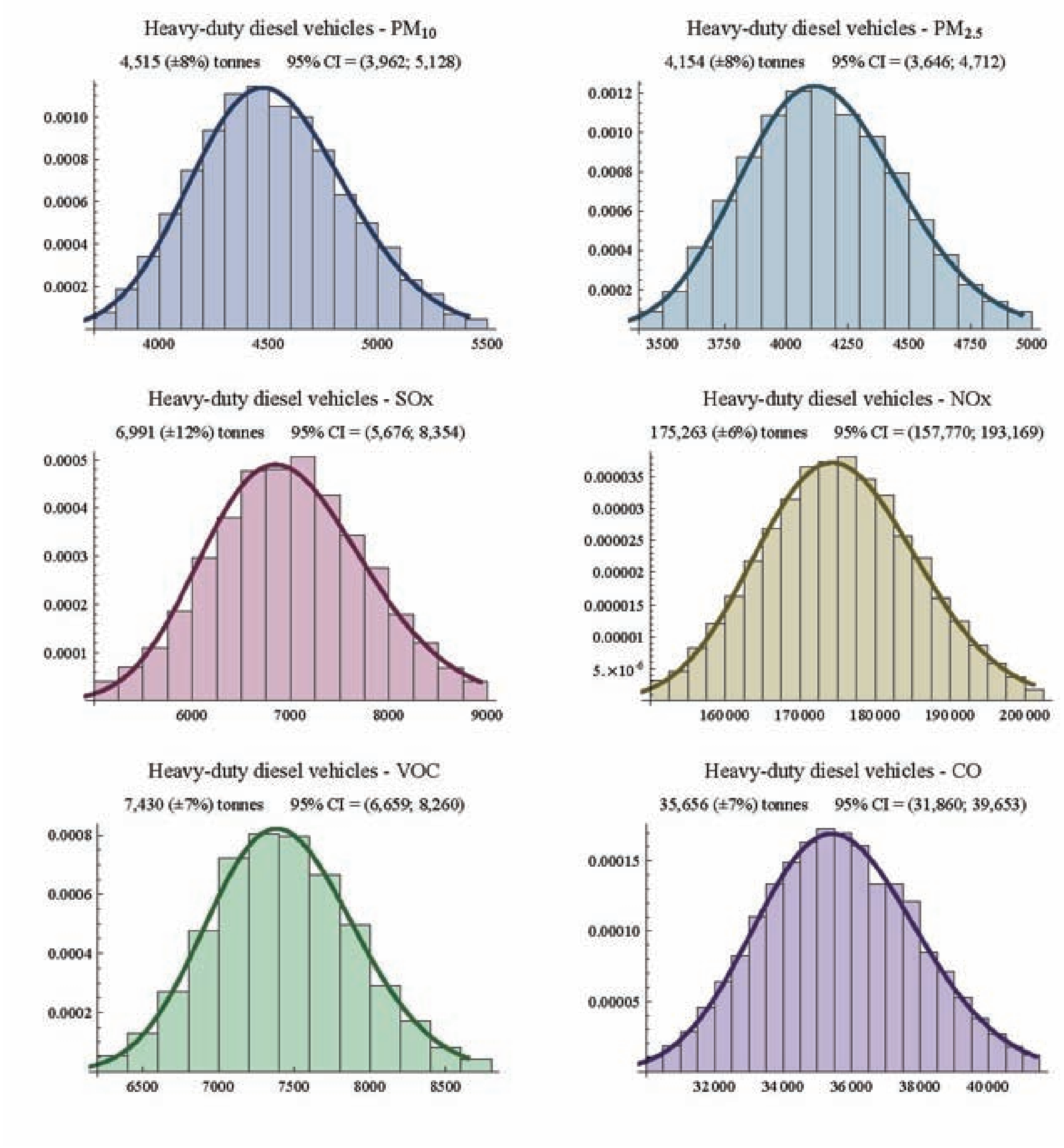


Figure 10: Monte Carlo – Heavy-duty gasoline vehicles (metric tonnes)



Heavy-duty diesel vehicles - PM_{10}

4,515 (±8%) tonnes 95% CI = (3,962; 5,128)

Heavy-duty diesel vehicles - $PM_{2.5}$

4,154 (±8%) tonnes 95% CI = (3,646; 4,712)

Heavy-duty diesel vehicles - SOx

6,991 (±12%) tonnes 95% CI = (5,676; 8,354)

Heavy-duty diesel vehicles - NOx

175,263 (±6%) tonnes 95% CI = (157,770; 193,169)

Heavy-duty diesel vehicles - VOC

7,430 (±7%) tonnes 95% CI = (6,659; 8,260)

Heavy-duty diesel vehicles - CO

35,656 (±7%) tonnes 95% CI = (31,860; 39,653)

Figure 11: Monte Carlo – Heavy-duty diesel vehicles (metric tonnes)

5 Off-road engines and machines

This sub-sector covers CAC emissions from engines, vehicles and machines not licensed for use on-road. Off-road applications include small spark-ignition engines such as lawnmowers and chainsaws; large spark-ignition engines such as those in forklifts; recreational vehicles and engines such as outboard engines, personal watercraft, snowmobiles and off-highway motorcycles; and off-road diesel engines such as those used in agricultural and construction equipment. While these machines may have various sources of power, only internal combustion engines are considered. Emission estimates are generated on a provincial/territorial level, then summed to get national level estimates.

5.1 NONROAD model

NONROAD is an EPA model for estimating emissions for all off-road (NONROAD, 2005; Harvey, 2006). The model includes more than 80 basic and 260 specific types of off-road applications identified by a source classification code (SCC), and further stratifies applications by horsepower rating and fuel types diesel, gasoline, liquefied petroleum gas (LPG) and compressed natural gas (CNG). Further information on the Canadian adaptation of the NONROAD model can be found in Cheminfo (2004) and Vaivads (2004a,b, 2005a,b, 2006).

Emission estimates from off-road applications are generated using a bottom-up approach (Figure 12). Activity factors are obtained by multiplying hours per year by a load factor and rated power for each SCC. Emission factors account for the age distribution of equipment and the effects of deterioration and maintenance over time. Meteorological and fuel data collected for input into MOBILE (see Table 6, section 4.1 for details) is also used for input into NONROAD. As in MOBILE, NONROAD needs minimum/maximum daily temperatures and fuel characteristics to compute correction factors. NONROAD also applies conversion factors for HC to VOC (EPA, 2005a), with fraction of $PM_{2.5}$ to PM_{10} taken as .92 for gasoline and .97 for diesel.

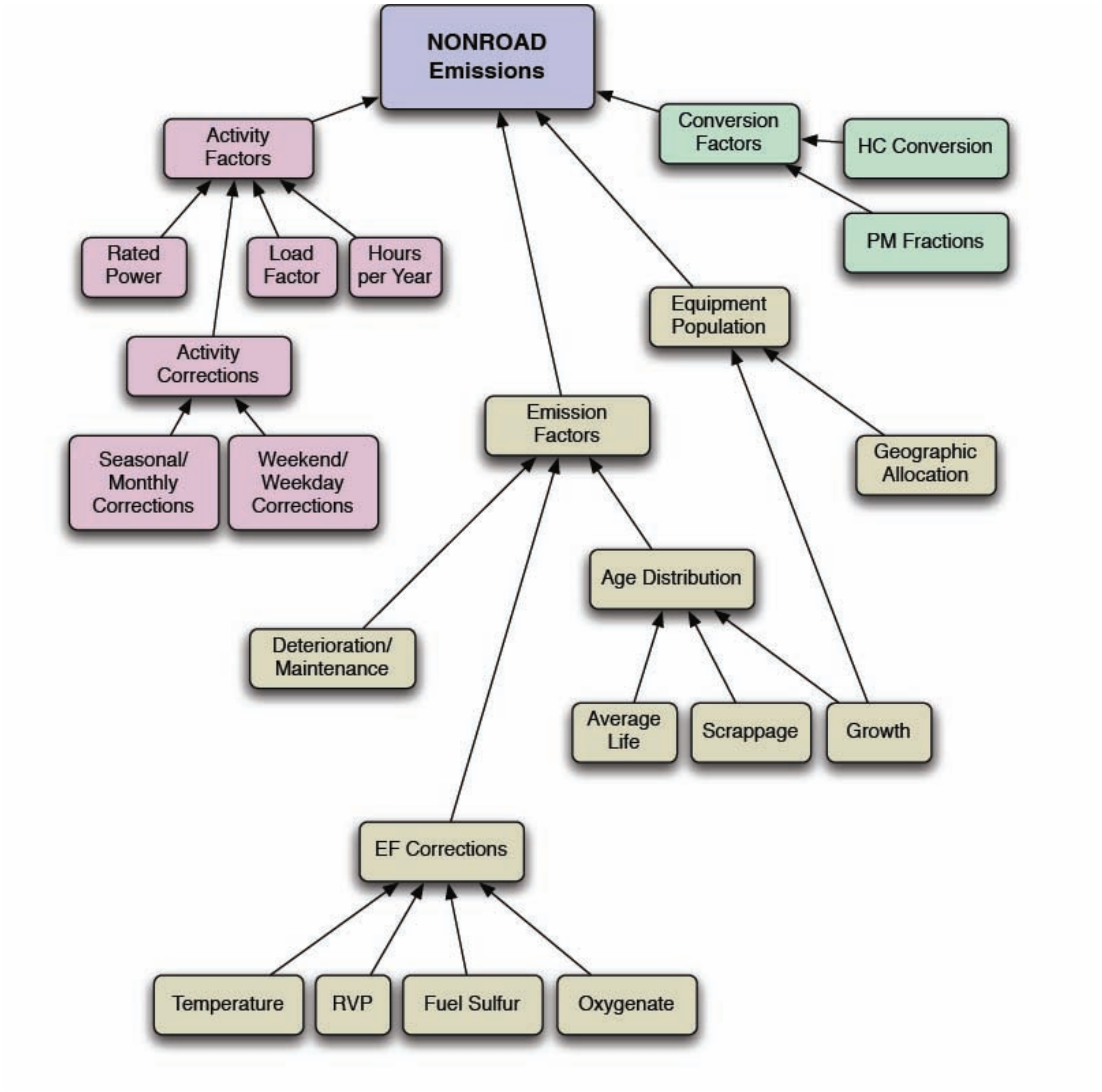


Figure 12: NONROAD model diagram

Chi (2004) conducted a sensitivity analysis of the NONROAD model, and determined input variables with significant effects on emissions. Results showed estimates to be significantly sensitive to increases in equipment population, activity, load factor and emission factor. Variances in ambient temperature, fuel RVP, fuel sulphur (except for SO_x estimates) and average useful life have smaller effects.

5.2 Fuel consumed estimates

Table 11 summarizes top-down probabilistic fuel estimates used in this uncertainty analysis. Gasoline and diesel fuel consumed estimates from Statcan CVS (2005), with quality indicator from CANSIM (2008), are subtracted from Statcan RESD (2005) census-based fuel sales data.

Table 11: NONROAD top-down fuel estimates

	2002	2003	2004	2005	2006
	megalitres				
Total - gasoline sales	**39,599^{A}**	**40,229^{A}**	**40,993^{A}**	**40,834^{A}**	**40,914^{A}**
Road transport and urban transit	844^{A}	890^{A}	998^{A}	1,105^{A}	1,083^{A}
Retail pump sales	34,985^{A}	35,785^{A}	36,576^{A}	36,170^{A}	36,254^{A}
Agriculture	1,501^{A}	1,528^{A}	1,441^{A}	1,475^{A}	1,499^{A}
Public administration	197^{A}	221^{A}	236^{A}	222^{A}	227^{A}
Commercial and other institutional	2,073^{A}	1,805^{A}	1,743^{A}	1,862^{A}	1,851^{A}
Substract: CVS gasoline estimate	**32,681^{A}**	**32,637^{A}**	**31,045^{D}**	**29,678^{E}**	**31,111^{D}**
NONROAD gasoline estimate	**6,918^{A}**	**7,592^{A}**	**9,948^{D}**	**11,156^{E}**	**9,802^{D}**
Total - diesel sales	**16,350^{A}**	**17,594^{A}**	**18,578^{A}**	**19,484^{A}**	**19,577^{A}**
Road transport and urban transit	6,027^{A}	6,478^{A}	6,576^{A}	6,924^{A}	6,890^{A}
Retail pump sales	3,680^{A}	3,943^{A}	4,617^{A}	4,639^{A}	4,681^{A}
Agriculture	2,183^{A}	2,258^{A}	2,271^{A}	2,271^{A}	2,370^{A}
Public administration	584^{A}	690^{A}	709^{A}	802^{A}	758^{A}
Commercial and other institutional	3,876^{A}	4,226^{A}	4,405^{A}	4,848^{A}	4,877^{A}
Substract: CVS diesel estimate	**10,262^{B}**	**9,884^{B}**	**9,455^{B}**	**10,135^{B}**	**10,075^{B}**
NONROAD diesel estimate	**6,088^{B}**	**7,710^{B}**	**9,123^{B}**	**9,349^{B}**	**9,501^{B}**

5.3 Emission factors

EPA (2004, NR-009c) describes NONROAD exhaust emission factors, crankcase estimates and brake specific fuel consumption (BSFC) estimates used for compression-ignition (diesel) engines. Emission factors for spark-ignition (SI) engines powered by gasoline, CNG and LPG are covered in EPA (2005b, NR-010e). Frey and Bammi (2002a, 2003) report uncertainties of 24–77% for NO_x and HC emissions from lawn and garden engines, and 15–49% from construction, farm and industrial (CFI) engines (Figures 13 and 14).

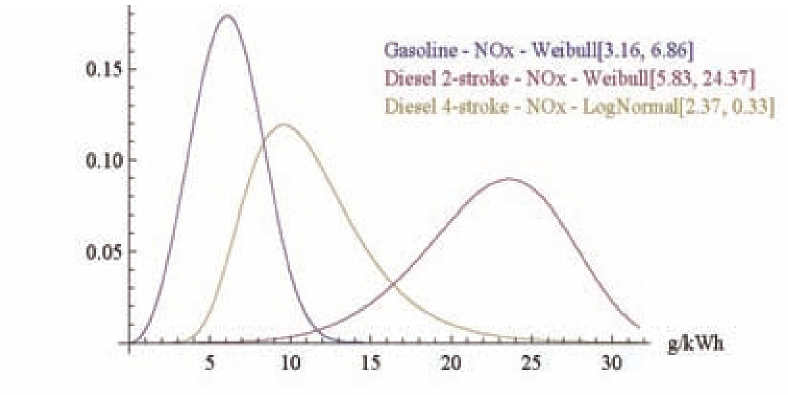


Figure 13: CFI engines – NO_x emission factors

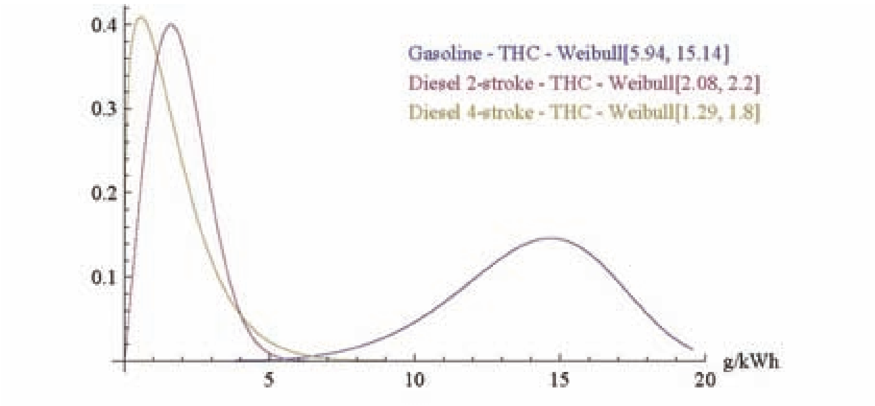


Figure 14: CFI engines – THC emission factors

5.4 Empirical results

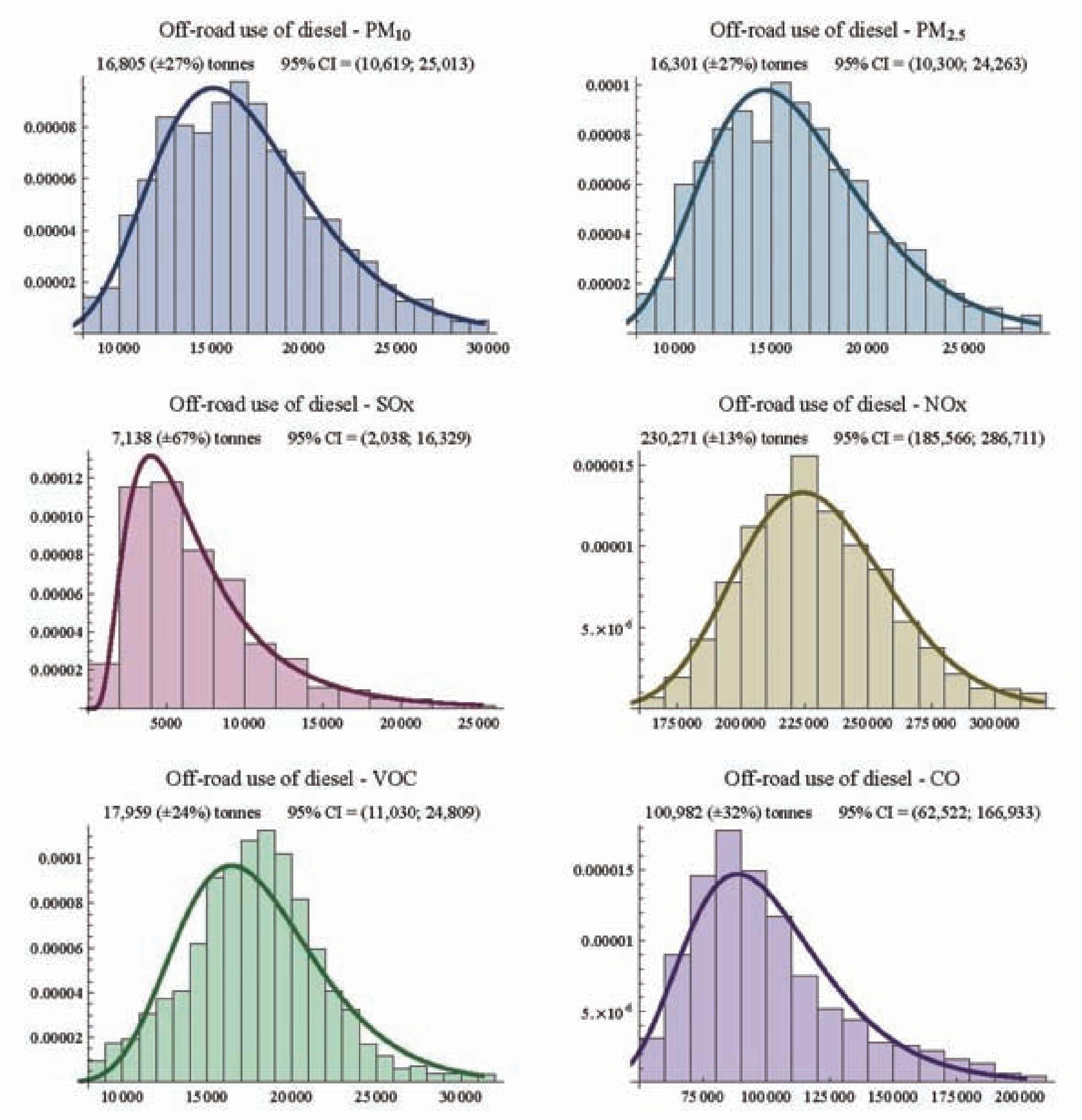
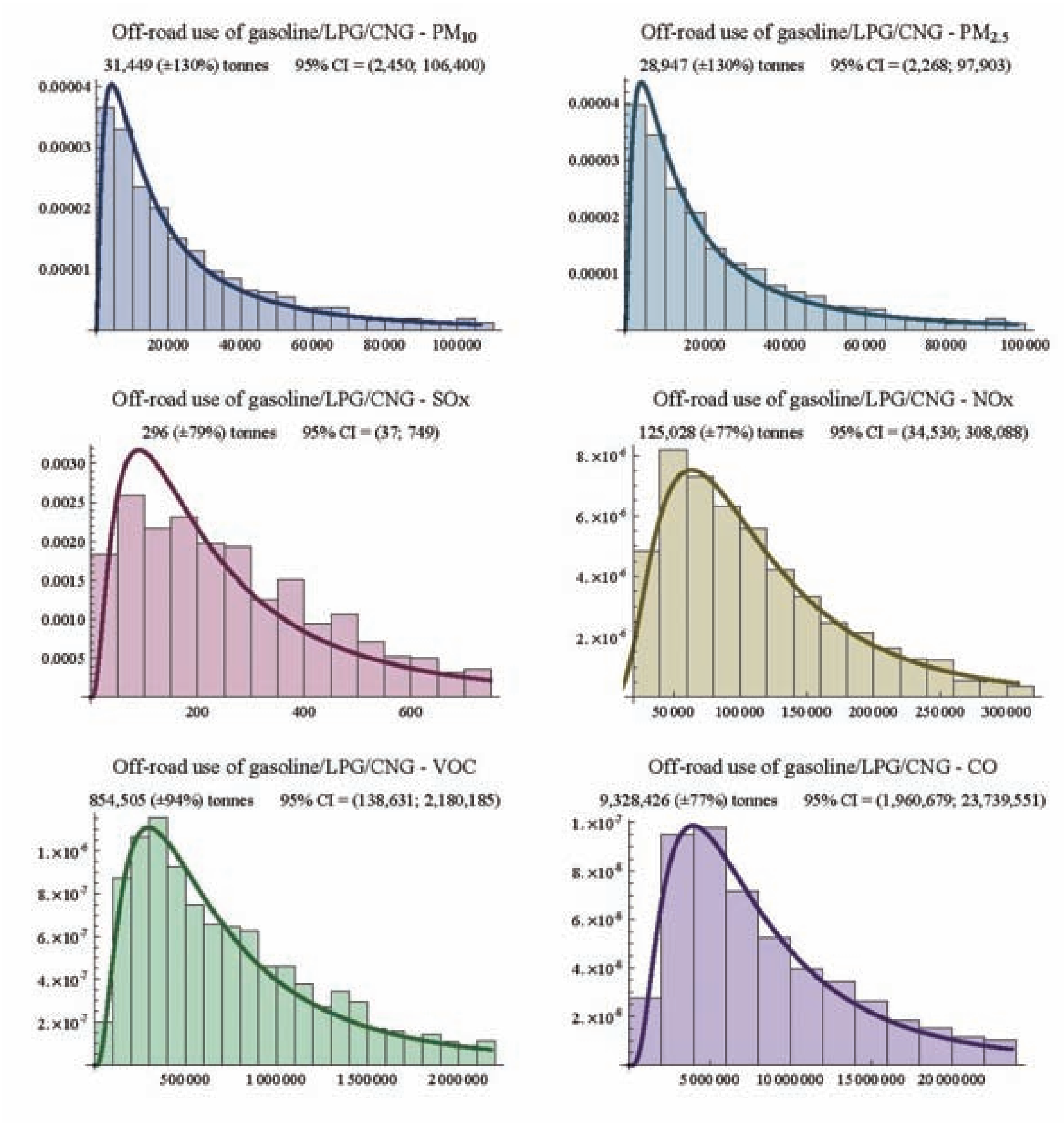


Figure 15: Monte Carlo – Off-road use of diesel (metric tonnes)



Off-road use of gasoline/LPG/CNG - PM_{10}

31,449 (±130%) tonnes 95% CI = (2,450; 106,400)

Off-road use of gasoline/LPG/CNG - $PM_{2.5}$

28,947 (±130%) tonnes 95% CI = (2,268; 97,903)

Off-road use of gasoline/LPG/CNG - SOx

296 (±79%) tonnes 95% CI = (37; 749)

Off-road use of gasoline/LPG/CNG - NOx

125,028 (±77%) tonnes 95% CI = (34,530; 308,088)

Off-road use of gasoline/LPG/CNG - VOC

854,505 (±94%) tonnes 95% CI = (138,631; 2,180,185)

Off-road use of gasoline/LPG/CNG - CO

9,328,426 (±77%) tonnes 95% CI = (1,960,679; 23,739,551)

Figure 16: Monte Carlo – Off-road use of gasoline/LPG/CNG (metric tonnes)

6 Locomotives

This sub-sector covers CAC emissions from locomotives, but not rail support equipment (captured under off-road applications). Almost all locomotives in North America come from two manufacturers: General Electric (Transportation Systems) and General Motors (Electromotive Division). New locomotives purchased by railroads have a lifetime of 30 to 40 years. The locomotives are remanufactured periodically to retain the performance of the engines (Sierra Research, 2004b).

Most locomotives are diesel-electric, in which a diesel engine powers electric motors that drive the wheels. Because these engines do not drive the wheels directly, engine speed is independent of the speed of the locomotive. Instead, the engine operates at a series of steady-state points, known as notch settings (Sierra Research, 2004b).

6.1 Emission factors

In the past, emission factors and activity levels were estimated and/or generated by the Railway Association of Canada (RAC) (LEM, 2000, 2002a,b, 2003, 2005, 2006). This was the only sub-sector for which Environment Canada did not have full transparency and control of the estimates or input parameters. As part of this report, emission factors (tables 13-16) covering most of the locomotive fleet in Canada were obtained from various sources (Dunn and Eggleton, 2002; Fritz, 2004; Moshiri, 2006).

Emission measurements from locomotives are made at each notch setting, and the average emissions for the locomotive are computed from a duty cycle representing time spent at each notch setting, which differ for freight, passenger and yard/switching operations. Typically, there are eight notches for power settings, one or two idle settings, and one or two settings for dynamic braking (DB) (Sierra Research, 2004b). Table 12 shows published duty cycles from the EPA and RAC.

Brake horsepower (bhp) is the measure of an engine's horsepower without losses caused by the gearbox, generator, differential, water pump and other auxiliary components such as alternator, power steering and AC compressor (Wikipedia, 2008). Thus the prefix brake refers to where the power is measured: at the engine's output shaft, as on an engine dynamometer. Actual horsepower delivered to the wheels is less. The term brake refers to the original use of a hand brake to measure torque during the test, which is multiplied by the engine RPM and a scaling constant to give horsepower.

Table 12: Duty cycle by locomotive service

	DB	Idle	N1	N2	N3	N4	N5	N6	N7	N8
	Percent of engine operating time									
EPA Line-haul	12.5	38.0	6.5	6.5	5.2	4.4	3.8	3.9	3.0	16.2
EPA Passenger	6.2	47.4	7.0	5.1	5.7	4.7	4.0	2.9	1.4	15.6
EPA Switch	0.0	59.8	12.4	12.3	5.8	3.6	3.6	1.5	0.2	0.8
RAC Freight	5.1	58.1	3.9	5.0	4.4	3.7	3.3	3.0	1.5	12.0
RAC Passenger	0.0	69.6	0.4	4.8	2.1	1.4	1.2	0.8	0.2	19.5
RAC Switching	0.0	83.0	4.1	4.0	3.6	2.0	1.0	0.5	0.3	1.5

Emissions for each notch setting are measured in terms of an emissions rate, e.g. grams per brake-horsepower hour (g/bhp-hr). The power setting in horsepower, and the fuel rate in pounds or gallons per hour, are also measured (Sierra Research, 2004b). All sulphur in the fuel is assumed to be converted to SO_x during combustion (Sierra Research, 2004a), and therefore SO_x emissions are a direct function of sulphur content in fuel consumed. NO_x correction factors for engine intake air temperature and ambient air humidity are applied to emission testing results as specified by EPA in 40 Code of Federal Regulations (CFR) (Moshiri, 2006). However, NO_x correction factors to account for varying atmospheric conditions during a given year are not considered. This most likely contributes additional uncertainty, which is not quantified in this report.

Table 13: Locomotives NO_x emission factors (by notch)

	Fleet	DB	Idle	N1	N2	N3	N4	N5	N6	N7	N8
		NO_x (grams/litre)									
Freight Train											
SD-40-2, 16-645E3, 3000hp	590	59.6	67.8	77.2	61.9	61.0	60.3	60.5	56.7	54.7	55.1
AC4400CW, 16-7FDL, 4400hp	376	61.6	28.5	36.7	41.1	55.1	62.5	41.6	42.1	40.1	35.4
Dash 9-44CM, 16-7FDL, 4400hp	222	61.6	28.5	36.7	41.1	55.1	62.5	41.6	42.1	40.1	35.4
SD-75, 16-710G3C, 4300hp	177	58.2	17.0	16.8	17.5	17.6	22.5	30.6	21.6	17.7	20.6
GP-38, 16-645, 2000hp	130	49.8	71.4	60.7	57.9	65.9	68.7	70.3	75.0	76.4	74.5
GP-38-2, 16-645, 2000hp	81	49.8	71.4	60.7	57.9	65.9	68.7	70.3	75.0	76.4	74.5
ES44AC, 12-GEVO, 4360hp	67	41.3	46.0	43.1	36.1	29.3	30.3	33.2	36.8	38.2	35.8
SD-60, 16-710G3, 3800hp	61	43.4	90.9	63.9	60.5	55.9	56.5	55.8	61.8	69.4	62.9
SD-90, 16-710G3C, 4300hp	61	58.2	17.0	16.8	17.5	17.6	22.5	30.6	21.6	17.7	20.6
Dash 8-40CM, 16-7FDL, 4000hp	56	56.0	25.9	33.4	37.3	50.1	56.8	37.8	38.3	36.5	32.2
SD-50, 16-645F3B, 3600hp	56	55.4	71.9	47.9	68.7	62.5	61.2	60.4	67.5	69.9	67.1
GP-38, 16-645, 2000hp	47	49.8	71.4	60.7	57.9	65.9	68.7	70.3	75.0	76.4	74.5
SD-40-1, 16-645E3, 3000hp	43	59.6	67.8	77.2	61.9	61.0	60.3	60.5	56.7	54.7	55.1
Dash 8-40CM, 16-7FDL, 4400hp	25	61.6	28.5	36.7	41.1	55.1	62.5	41.6	42.1	40.1	35.4
SD-70, 16-710G3B, 4000hp	25	47.6	47.6	46.3	46.0	50.8	53.5	55.3	65.0	75.2	66.7
GP-40, 16-645, 3000hp	14	74.7	107.0	91.1	86.9	98.9	103.0	105.0	113.0	115.0	112.0
B39-8, 16-FDL16, 3900hp	12	20.9	26.3	30.9	33.0	41.8	48.0	63.1	68.2	71.1	65.9
C30-7, 16-7FDL, 3000hp	12	42.0	19.4	25.0	28.0	37.6	42.6	28.4	28.7	27.4	24.1
SD-40, 16-645D3A, 2250hp	10	44.6	62.5	47.5	46.7	45.2	44.7	43.7	41.5	41.1	47.6
GP-40-2, 16-645, 3000hp	8	74.7	107.0	91.1	86.9	98.9	103.0	105.0	113.0	115.0	112.0
weighted average		*57.2*	*49.2*	*51.6*	*48.4*	*53.4*	*56.6*	*51.2*	*50.4*	*49.3*	*47.5*
Switching											
GP-9, 16-645, 1750hp	190	43.6	62.4	53.1	50.7	57.7	60.1	61.5	65.7	66.8	65.2
GP-9, 16-645, 1800hp	163	44.8	64.2	54.7	52.2	59.3	61.8	63.3	67.5	68.7	67.1
GMD1, 12-645, 1200hp	41	62.5	55.6	44.3	42.8	50.1	57.6	62.4	62.9	60.6	55.9
GP-38, 16-645, 2000hp	29	49.8	71.4	60.7	57.9	65.9	68.7	70.3	75.0	76.4	74.5
SD-40-2, 16-645, 3000hp	25	74.7	107.0	91.1	86.9	98.9	103.0	105.0	113.0	115.0	112.0
GP-9, 16-645, 1700hp	17	42.4	60.7	51.6	49.3	56.0	58.4	59.8	63.8	64.9	63.3
GP-38-2, 16-645, 2000hp	9	49.8	71.4	60.7	57.9	65.9	68.7	70.3	75.0	76.4	74.5
weighted average		*47.8*	*65.5*	*55.5*	*53.0*	*60.4*	*63.3*	*65.2*	*69.2*	*70.2*	*68.2*
Passenger Train											
F59PH, 12-710G3, 3000hp	61	36.2	57.6	55.7	61.3	58.1	51.8	47.2	43.0	46.9	45.9
FP40PH2, 16-645E3C, 3000hp	54	59.6	67.8	77.2	61.9	61.0	60.3	60.5	56.7	54.7	55.1
P42DC, 16-7FDL, 4250hp	21	59.5	27.6	35.5	39.7	53.2	60.4	40.2	40.7	38.8	34.2
weighted average		*49.1*	*57.0*	*61.1*	*58.2*	*58.5*	*56.5*	*51.4*	*48.1*	*48.7*	*47.7*

Table 14: Locomotives CO emission factors (by notch)

	Fleet	DB	Idle	N1	N2	N3	N4	N5	N6	N7	N8
		CO (grams/litre)									
Freight Train											
SD-40-2, 16-645E3, 3000hp	590	10.43	27.56	12.68	4.13	3.01	2.41	4.46	7.03	10.45	9.93
AC4400CW, 16-7FDL, 4400hp	376	18.02	8.3	2.17	2.19	4.34	7.59	9.46	8.94	8.02	8.15
Dash 9-44CM, 16-7FDL, 4400hp	222	18.02	8.3	2.17	2.19	4.34	7.59	9.46	8.94	8.02	8.15
SD-75, 16-710G3C, 4300hp	177	15.61	2.95	0.76	0.63	0.63	0.79	1.14	3.07	8.09	6.54
GP-38, 16-645, 2000hp	130	12.43	16.2	8.03	5.74	3.48	2.65	2.5	2.98	4.57	8.52
GP-38-2, 16-645, 2000hp	81	12.43	16.2	8.03	5.74	3.48	2.65	2.5	2.98	4.57	8.52
ES44AC, 12-GEVO, 4360hp	67	7.76	5.22	3.92	4.36	4.45	3.44	2.03	1.44	1.44	0.7
SD-60, 16-710G3, 3800hp	61	4.54	7.94	2.66	2.1	1.85	4.28	6.81	7.85	4.08	3.86
SD-90, 16-710G3C, 4300hp	61	15.61	2.95	0.76	0.63	0.63	0.79	1.14	3.07	8.09	6.54
Dash 8-40CM, 16-7FDL, 4000hp	56	16.39	7.55	1.97	1.99	3.94	6.9	8.6	8.13	7.29	7.41
SD-50, 16-645F3B, 3600hp	56	9.25	18.73	9.43	3.69	3.79	3.49	5.92	6.4	7.04	6.63
GP-38, 16-645, 2000hp	47	12.43	16.2	8.03	5.74	3.48	2.65	2.5	2.98	4.57	8.52
SD-40-1, 16-645E3, 3000hp	43	10.43	27.56	12.68	4.13	3.01	2.41	4.46	7.03	10.45	9.93
Dash 8-40CM, 16-7FDL, 4400hp	25	18.02	8.3	2.17	2.19	4.34	7.59	9.46	8.94	8.02	8.15
SD-70, 16-710G3B, 4000hp	25	5.84	5.84	3.08	2.7	1.98	6.48	10.18	10.34	5.39	5.49
GP-40, 16-645, 3000hp	14	18.64	24.3	12.05	8.61	5.23	3.98	3.75	4.47	6.86	12.77
B39-8, 16-FDL16, 3900hp	12	28.95	41.83	8.58	6.57	6.72	8.97	10.58	11.6	9.53	7.56
C30-7, 16-7FDL, 3000hp	12	12.29	5.66	1.48	1.49	2.96	5.17	6.45	6.1	5.47	5.56
SD-40, 16-645D3A, 2250hp	10	10.47	24.46	11.62	4.46	3.51	3.07	4.24	7.79	12.96	17.69
GP-40-2, 16-645, 3000hp	8	18.64	24.3	12.05	8.61	5.23	3.98	3.75	4.47	6.86	12.77
weighted average		*13.58*	*15.1*	*6.4*	*3.25*	*3.29*	*4.17*	*5.59*	*6.54*	*7.94*	*8.17*
Switching											
GP-9, 16-645, 1750hp	190	10.87	14.17	7.03	5.02	3.05	2.32	2.19	2.61	4	7.45
GP-9, 16-645, 1800hp	163	11.18	14.58	7.23	5.17	3.14	2.39	2.25	2.68	4.12	7.66
GMD1, 12-645, 1200hp	41	6.41	10.2	6.52	4.53	2.98	2.09	1.84	2.37	5.78	13.28
GP-38, 16-645, 2000hp	29	12.43	16.2	8.03	5.74	3.48	2.65	2.5	2.98	4.57	8.52
SD-40-2, 16-645, 3000hp	25	18.64	24.3	12.05	8.61	5.23	3.98	3.75	4.47	6.86	12.77
GP-9, 16-645, 1700hp	17	10.56	13.77	6.83	4.88	2.96	2.25	2.13	2.53	3.89	7.24
GP-38-2, 16-645, 2000hp	9	12.43	16.2	8.03	5.74	3.48	2.65	2.5	2.98	4.57	8.52
weighted average		*11.12*	*14.65*	*7.39*	*5.27*	*3.22*	*2.43*	*2.28*	*2.74*	*4.39*	*8.39*
Passenger Train											
F59PH, 12-710G3, 3000hp	61	4.54	6.72	2.36	2.83	1.38	1.8	3.65	5.88	4.34	4.06
FP40PH2, 16-645E3C, 3000hp	54	10.43	27.56	12.68	4.13	3.01	2.41	4.46	7.03	10.45	9.93
P42DC, 16-7FDL, 4250hp	21	17.41	8.02	2.09	2.11	4.19	7.33	9.14	8.64	7.75	7.87
weighted average		*8.87*	*15.19*	*6.42*	*3.24*	*2.46*	*2.89*	*4.82*	*6.76*	*7.29*	*6.98*

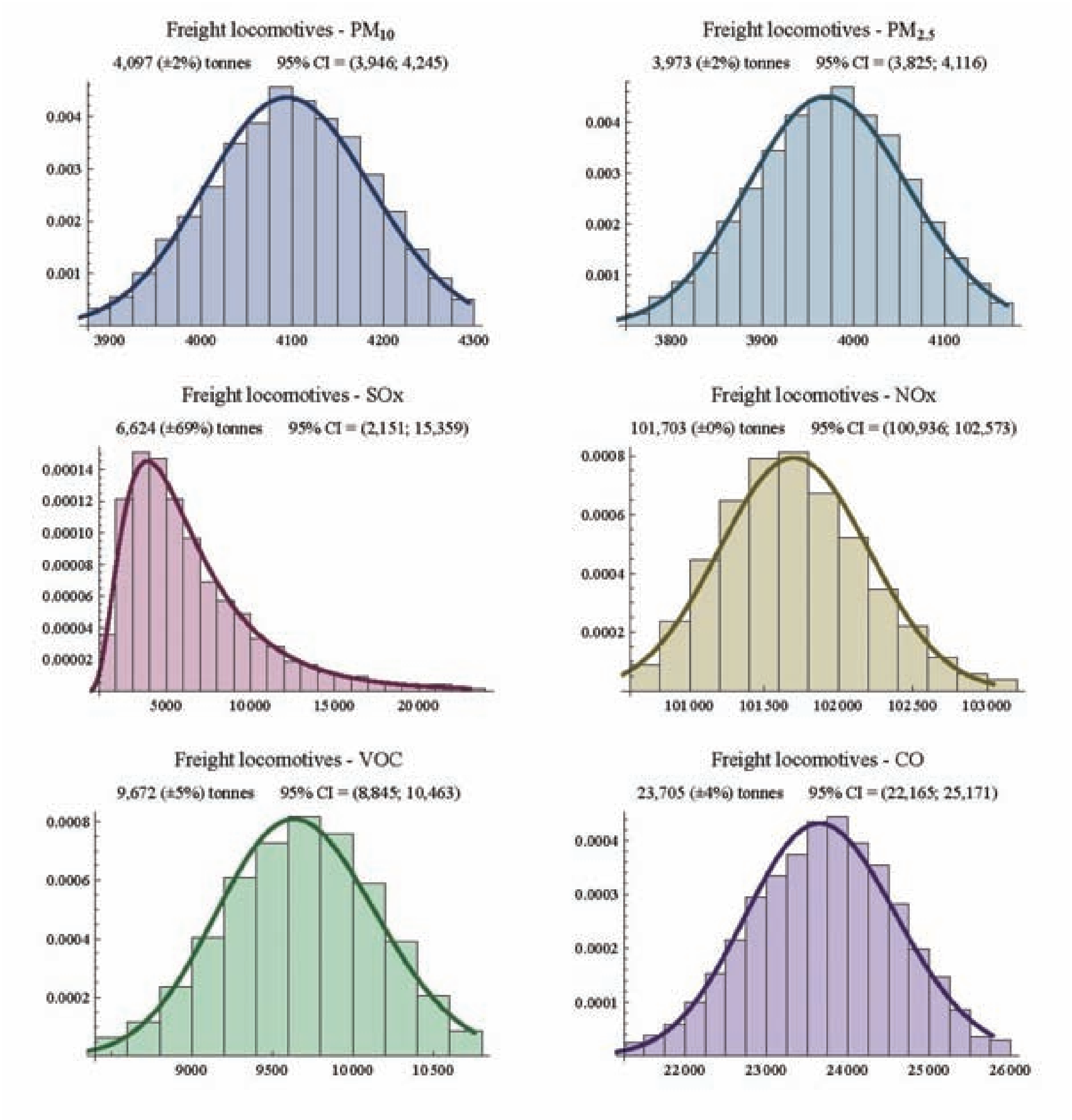
Table 15: Locomotives HC emission factors (by notch)

	Fleet	DB	Idle	N1	N2	N3	N4	N5	N6	N7	N8
		HC (grams/litre)									
Freight Train											
SD-40-2, 16-645E3, 3000hp	590	4.60	9.07	6.01	2.43	1.81	1.66	1.57	1.61	1.74	1.84
AC4400CW, 16-7FDL, 4400hp	376	7.55	4.75	1.51	1.19	1.33	1.15	0.92	0.91	0.86	0.81
Dash 9-44CM, 16-7FDL, 4400hp	222	7.55	4.75	1.51	1.19	1.33	1.15	0.92	0.91	0.86	0.81
SD-75, 16-710G3C, 4300hp	177	6.08	0.24	0.12	0.11	0.09	0.13	0.13	0.13	0.12	0.16
GP-38, 16-645, 2000hp	130	4.78	7.10	4.05	2.01	1.53	1.45	1.54	1.52	1.68	1.73
GP-38-2, 16-645, 2000hp	81	4.78	7.10	4.05	2.01	1.53	1.45	1.54	1.52	1.68	1.73
ES44AC, 12-GEVO, 4360hp	67	4.85	4.40	2.07	2.06	1.53	1.31	1.02	0.94	0.79	0.77
SD-60, 16-710G3, 3800hp	61	4.83	7.44	2.72	2.03	1.54	1.43	1.34	1.37	1.49	1.63
SD-90, 16-710G3C, 4300hp	61	6.08	0.24	0.12	0.11	0.09	0.13	0.13	0.13	0.12	0.16
Dash 8-40CM, 16-7FDL, 4000hp	56	6.86	4.32	1.37	1.08	1.21	1.04	0.83	0.83	0.78	0.74
SD-50, 16-645F3B, 3600hp	56	5.05	7.99	4.16	2.40	1.77	1.60	1.56	1.51	1.68	1.71
GP-38, 16-645, 2000hp	47	4.78	7.10	4.05	2.01	1.53	1.45	1.54	1.52	1.68	1.73
SD-40-1, 16-645E3, 3000hp	43	4.60	9.07	6.01	2.43	1.81	1.66	1.57	1.61	1.74	1.84
Dash 8-40CM, 16-7FDL, 4400hp	25	7.55	4.75	1.51	1.19	1.33	1.15	0.92	0.91	0.86	0.81
SD-70, 16-710G3B, 4000hp	25	6.98	6.98	2.96	2.07	1.42	1.21	1.13	1.19	1.26	1.36
GP-40, 16-645, 3000hp	14	7.17	10.65	6.07	3.01	2.30	2.17	2.31	2.28	2.52	2.60
B39-8, 16-FDL16, 3900hp	12	21.92	40.64	5.38	3.43	2.30	1.46	1.42	1.53	1.53	1.41
C30-7, 16-7FDL, 3000hp	12	5.15	3.24	1.03	0.81	0.91	0.78	0.62	0.62	0.58	0.55
SD-40, 16-645D3A, 2250hp	10	5.55	8.24	5.30	3.03	2.35	1.86	1.86	1.68	1.76	1.81
GP-40-2, 16-645, 3000hp	8	7.17	10.65	6.07	3.01	2.30	2.17	2.31	2.28	2.52	2.60
weighted average		*5.93*	*6.29*	*3.27*	*1.68*	*1.40*	*1.26*	*1.16*	*1.16*	*1.21*	*1.24*
Switching											
GP-9, 16-645, 1750hp	190	4.19	6.21	3.54	1.76	1.34	1.26	1.35	1.33	1.47	1.51
GP-9, 16-645, 1800hp	163	4.30	6.39	3.64	1.81	1.38	1.30	1.39	1.37	1.51	1.56
GMD1, 12-645, 1200hp	41	2.66	5.58	3.33	1.80	1.27	1.14	1.21	1.32	1.44	1.55
GP-38, 16-645, 2000hp	29	4.78	7.10	4.05	2.01	1.53	1.45	1.54	1.52	1.68	1.73
SD-40-2, 16-645, 3000hp	25	7.17	10.65	6.07	3.01	2.30	2.17	2.31	2.28	2.52	2.60
GP-9, 16-645, 1700hp	17	4.07	6.03	3.44	1.71	1.30	1.23	1.31	1.29	1.43	1.47
GP-38-2, 16-645, 2000hp	9	4.78	7.10	4.05	2.01	1.53	1.45	1.54	1.52	1.68	1.73
weighted average		*4.30*	*6.52*	*3.73*	*1.86*	*1.41*	*1.33*	*1.41*	*1.40*	*1.55*	*1.61*
Passenger Train											
F59PH, 12-710G3, 3000hp	61	5.51	3.83	1.39	1.13	0.97	1.04	1.09	1.20	1.60	1.40
FP40PH2, 16-645E3C, 3000hp	54	4.60	9.07	6.01	2.43	1.81	1.66	1.57	1.61	1.74	1.84
P42DC, 16-7FDL, 4250hp	21	7.29	4.59	1.46	1.15	1.28	1.11	0.88	0.88	0.83	0.79
weighted average		*5.42*	*6.03*	*3.24*	*1.65*	*1.35*	*1.30*	*1.25*	*1.31*	*1.53*	*1.48*

Table 16: Locomotives PM emission factors (by notch)

	Fleet	DB	Idle	N1	N2	N3	N4	N5	N6	N7	N8
		PM (grams/litre)									
Freight Train											
SD-40-2, 16-645E3, 3000hp	590	1.59	2.73	1.65	1.63	1.53	1.32	1.26	1.36	1.26	1.31
AC4400CW, 16-7FDL, 4400hp	376	3.42	2.29	1.64	0.53	1.94	1.00	1.30	0.91	0.82	0.73
Dash 9-44CM, 16-7FDL, 4400hp	222	3.42	2.29	1.64	0.53	1.94	1.00	1.30	0.91	0.82	0.73
SD-75, 16-710G3C, 4300hp	177	3.64	0.78	2.34	2.26	3.38	2.93	2.19	2.68	2.92	4.01
GP-38, 16-645, 2000hp	130	1.28	2.17	1.03	1.47	1.51	1.17	1.11	1.35	1.19	1.30
GP-38-2, 16-645, 2000hp	81	1.28	2.17	1.03	1.47	1.51	1.17	1.11	1.35	1.19	1.30
ES44AC, 12-GEVO, 4360hp	67	2.00	1.55	0.78	0.87	0.76	0.55	0.68	0.50	0.43	0.35
SD-60, 16-710G3, 3800hp	61	1.74	2.60	1.34	1.53	1.54	1.36	1.34	1.53	1.34	1.39
SD-90, 16-710G3C, 4300hp	61	3.64	0.78	2.34	2.26	3.38	2.93	2.19	2.68	2.92	4.01
Dash 8-40CM, 16-7FDL, 4000hp	56	3.11	2.09	1.49	0.48	1.76	0.90	1.18	0.83	0.74	0.66
SD-50, 16-645F3B, 3600hp	56	1.59	2.72	1.65	1.63	1.53	1.32	1.26	1.36	1.26	1.31
GP-38, 16-645, 2000hp	47	1.28	2.17	1.03	1.47	1.51	1.17	1.11	1.35	1.19	1.30
SD-40-1, 16-645E3, 3000hp	43	1.59	2.73	1.65	1.63	1.53	1.32	1.26	1.36	1.26	1.31
Dash 8-40CM, 16-7FDL, 4400hp	25	3.42	2.29	1.64	0.53	1.94	1.00	1.30	0.91	0.82	0.73
SD-70, 16-710G3B, 4000hp	25	1.79	1.79	0.85	1.05	1.35	1.69	1.64	1.47	1.40	1.47
GP-40, 16-645, 3000hp	14	1.92	3.26	1.55	2.21	2.26	1.76	1.66	2.02	1.79	1.96
B39-8, 16-FDL16, 3900hp	12	9.74	19.38	3.10	2.18	2.26	1.70	1.08	1.01	1.03	0.97
C30-7, 16-7FDL, 3000hp	12	2.33	1.56	1.12	0.36	1.32	0.68	0.89	0.62	0.56	0.50
SD-40, 16-645D3A, 2250hp	10	2.80	3.23	2.95	2.75	2.66	2.62	2.58	2.56	2.55	2.54
GP-40-2, 16-645, 3000hp	8	1.92	3.26	1.55	2.21	2.26	1.76	1.66	2.02	1.79	1.96
weighted average		*2.46*	*2.33*	*1.61*	*1.29*	*1.86*	*1.37*	*1.35*	*1.35*	*1.28*	*1.41*
Switching											
GP-9, 16-645, 1750hp	190	1.12	1.90	0.90	1.29	1.32	1.03	0.97	1.18	1.04	1.14
GP-9, 16-645, 1800hp	163	1.15	1.96	0.93	1.32	1.36	1.06	1.00	1.21	1.07	1.17
GMD1, 12-645, 1200hp	41	1.03	1.75	0.82	1.17	1.21	0.94	0.89	1.08	0.96	1.04
GP-38, 16-645, 2000hp	29	1.28	2.17	1.03	1.47	1.51	1.17	1.11	1.35	1.19	1.30
SD-40-2, 16-645, 3000hp	25	1.92	3.26	1.55	2.21	2.26	1.76	1.66	2.02	1.79	1.96
GP-9, 16-645, 1700hp	17	1.09	1.85	0.88	1.25	1.28	1.00	0.94	1.14	1.02	1.11
GP-38-2, 16-645, 2000hp	9	1.28	2.17	1.03	1.47	1.51	1.17	1.11	1.35	1.19	1.30
weighted average		*1.18*	*2.00*	*0.95*	*1.35*	*1.39*	*1.08*	*1.02*	*1.24*	*1.10*	*1.20*
Passenger Train											
F59PH, 12-710G3, 3000hp	61	0.92	1.18	0.63	1.35	1.36	1.07	1.00	1.19	1.07	1.17
FP40PH2, 16-645E3C, 3000hp	54	1.59	2.73	1.65	1.63	1.53	1.32	1.26	1.36	1.26	1.31
P42DC, 16-7FDL, 4250hp	21	3.30	2.22	1.59	0.51	1.87	0.96	1.25	0.88	0.79	0.71
weighted average		*1.55*	*1.96*	*1.18*	*1.33*	*1.51*	*1.15*	*1.14*	*1.21*	*1.10*	*1.16*

6.2 Empirical results



Freight locomotives - PM_{10}

4,097 (±2%) tonnes 95% CI = (3,946; 4,245)

Freight locomotives - $PM_{2.5}$

3,973 (±2%) tonnes 95% CI = (3,825; 4,116)

Freight locomotives - SOx

6,624 (±69%) tonnes 95% CI = (2,151; 15,359)

Freight locomotives - NOx

101,703 (±0%) tonnes 95% CI = (100,936; 102,573)

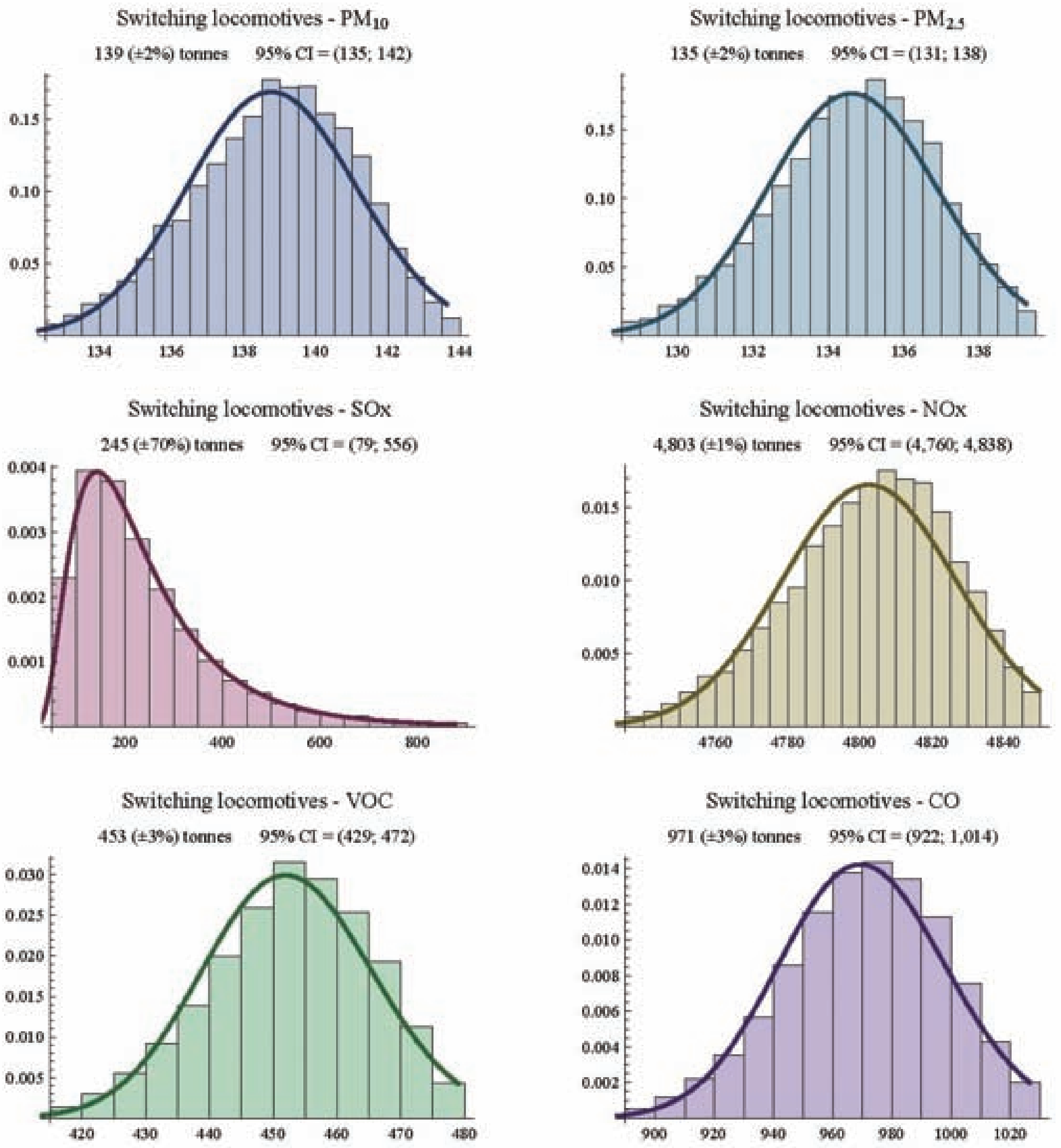
Freight locomotives - VOC

9,672 (±5%) tonnes 95% CI = (8,845; 10,463)

Freight locomotives - CO

23,705 (±4%) tonnes 95% CI = (22,165; 25,171)

Figure 17: Monte Carlo – Freight locomotives (metric tonnes)


Switching locomotives - PM_{10}

139 (±2%) tonnes 95% CI = (135; 142)

Switching locomotives - $PM_{2.5}$

135 (±2%) tonnes 95% CI = (131; 138)

Switching locomotives - SOx

245 (±70%) tonnes 95% CI = (79; 556)

Switching locomotives - NOx

4,803 (±1%) tonnes 95% CI = (4,760; 4,838)

Switching locomotives - VOC

453 (±3%) tonnes 95% CI = (429; 472)

Switching locomotives - CO

971 (±3%) tonnes 95% CI = (922; 1,014)

Figure 18: Monte Carlo – Switching locomotives (metric tonnes)

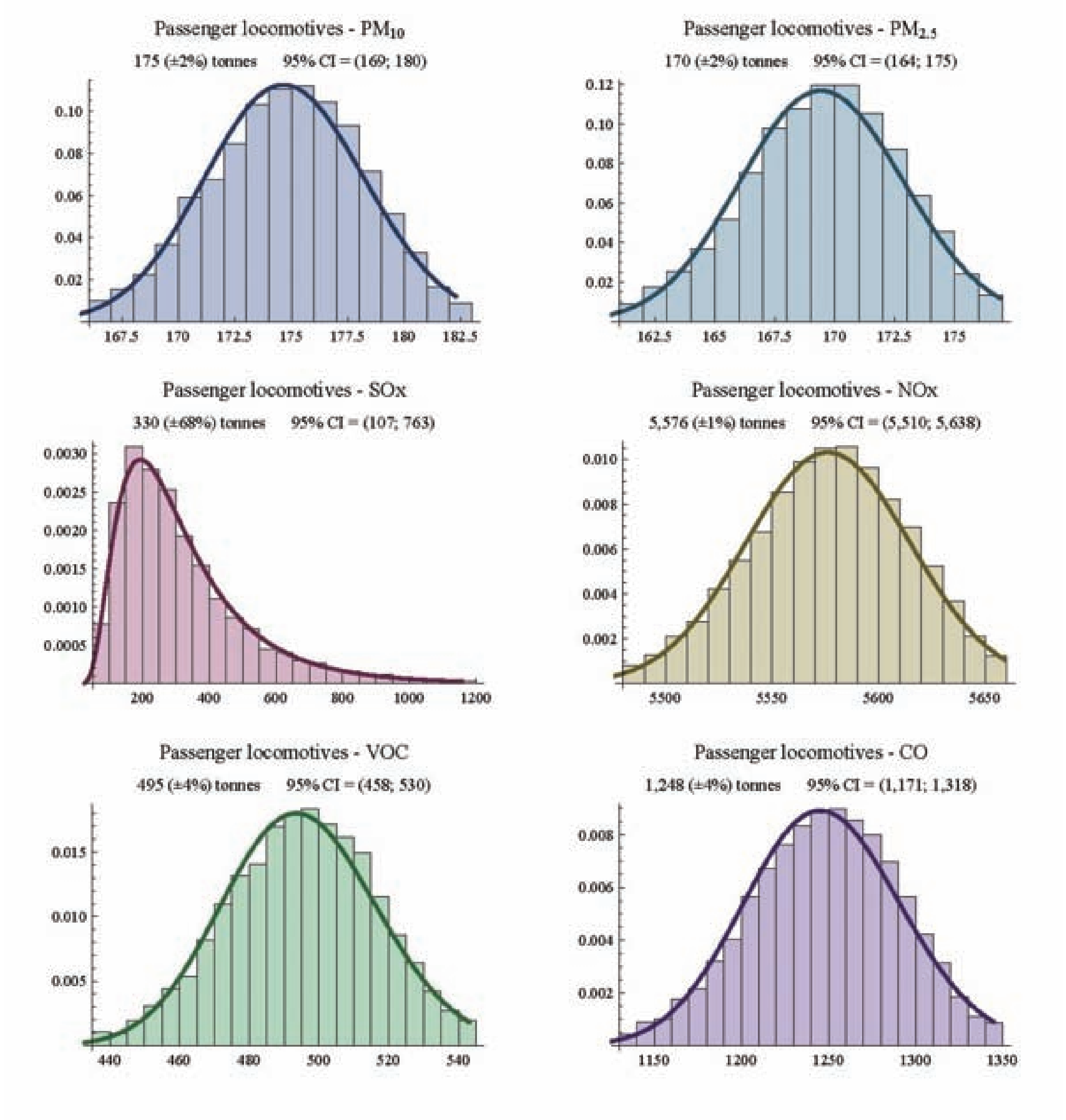


Figure 19: Monte Carlo – Passenger locomotives (metric tonnes)

7 Conclusion

The principal findings of this report are:

- Estimation methodologies are closely aligned between various countries, including the EPA in the United States, the European Environment Agency (EEA) and Environment Canada. Therefore, meaningful country-by-country comparisons are possible. This report complements models and data obtained from both the EPA and the EEA. Methodologies for the estimation of GHG emissions overlap significantly with those for CACs.
- Off-road engines now account for more emissions of most pollutants than all on-road vehicles in Canada. CO emissions from off-road engines could be as high as 23.7 megatonnes, while CO emissions from on-road vehicles are at most 9.7 megatonnes. VOC emissions from off-road engines are also considerably higher with an upper confidence bound of 2.2 megatonnes, while on-road vehicles contribute less than 481 kilotonnes.
- Poor quality of activity data for off-road engines leads to considerable uncertainty in the emission estimates, with errors of more than 35% for most pollutants. This uncertainty also originates in the small sample sizes of emission testing for off-road engines.
- Emission estimates from locomotives are the most accurate of any mobile source, with errors under 5% for all pollutants, except SO_x (see below). Accuracy follows from a complete accounting of the locomotive fleet by the RAC, together with comprehensive emission testing data for over 90% of locomotive models in operation on railroads in Canada.
- Using a bottom-up approach, uncertainty of SO_x estimates for all mobile sources is related to the highly variable sulphur content of various fuels from local refineries and from the same refinery over time (see Guthrie et al. (2006) for details). A top-down fuel-based sulphur balance approach would yield considerably more accurate national estimates.
- Insufficient information on methodologies to estimate emissions of ammonia, NH_3, limited to a single report (Coe et al., 1996), did not allow this pollutant to be considered for this uncertainty analysis.

- CAC emissions from off-road mobile sources involved in oil sands activities in Alberta (Taylor, 2007b) were not considered for this report.

Table 17 summarizes Monte Carlo empirical results from figures 3, 6–11 and 15–19, with uncertainty reported using a modified version of Statistics Canada's letter-scale quality indicator (see Table 2).

Table 17: CAC 2005 estimates (with quality indicator)

	PM$_{10}$	PM$_{2.5}$	SO$_x$	NO$_x$	VOC	CO
	metric tonnes					
Total - aircraft	**995**^{F}	**995**^{F}	**4,841**^{F}	**61,442**^{F}	**8,218**^{F}	**46,357**^{F}
LTO	112^{B}	112^{B}	1,215^{F}	6,123^{B}	4,060^{E}	9,931^{C}
Cruise	883^{F}	883^{F}	3,626^{F}	55,319^{F}	4,158^{F}	36,426^{F}
Marine transportation	**5,820**^{F}	**5,565**^{F}	**32,359**^{F}	**117,096**^{F}	**8,035**^{F}	**9,572**^{F}
Total - on-road vehicles	**6,286**^{B}	**5,726**^{B}	**9,700**^{B}	**408,341**^{B}	**370,331**^{C}	**8,068,222**^{B}
Light-duty gasoline vehicles	402^{B}	369^{B}	740^{B}	90,347^{D}	153,043^{E}	3,502,235^{D}
Light-duty gasoline trucks	553^{E}	460^{D}	934^{B}	131,233^{B}	205,727^{C}	4,502,841^{C}
Light-duty diesel vehicles	375^{E}	344^{E}	419^{F}	3,431^{F}	1,193^{F}	5,791^{F}
Light-duty diesel trucks	387^{F}	355^{F}	598^{F}	3,448^{F}	1,629^{F}	4,281^{F}
Heavy-duty gasoline vehicles	54^{E}	44^{E}	19^{E}	4,620^{E}	1,310^{E}	17,417^{E}
Heavy-duty diesel vehicles	4,515^{B}	4,154^{B}	6,991^{C}	175,263^{B}	7,430^{B}	35,656^{B}
Total - off-road engines	**48,254**^{F}	**45,248**^{F}	**7,434**^{F}	**355,299**^{E}	**872,464**^{F}	**9,429,408**^{F}
Off-road use of diesel	16,805^{E}	16,301^{E}	7,138^{F}	230,271^{C}	17,959^{E}	100,982^{E}
Off-road use of gasoline	31,449^{F}	28,947^{F}	296^{F}	125,028^{F}	854,505^{F}	9,328,426^{F}
Total - locomotives	**4,411**^{A}	**4,277**^{A}	**7,199**^{F}	**112,082**^{A}	**10,620**^{A}	**25,923**^{A}
Freight	4,097^{A}	3,973^{A}	6,624^{F}	101,703^{A}	9,672^{B}	23,705^{A}
Switching	139^{A}	135^{A}	245^{F}	4,803^{A}	453^{A}	971^{A}
Passenger	175^{A}	170^{A}	330^{F}	5,576^{A}	495^{A}	1,248^{A}

Table 18 summarizes potential improvements:

- Higher-resolution activity data from NAV Canada, Canadian Coast Guard and CVS would increase accuracy of estimates for all pollutants.
- By far the least understood and most complex pollutant to estimate from aircraft is PM (Patterson, 2005; Taylor, 2007a). Recent research on aircraft emissions has focused on this issue (Wey et al., 2007; Corporan et al., 2008; Agrawal et al., 2008).
- Environment Canada unsuccessfully attempted to obtain a recent version of the Mobile Source Observation Database (MSOD) from the EPA for this report. Future acquisition of this very large dataset containing millions of high-resolution emission testing results would greatly enhance the accuracy of estimates for on-road vehicles and off-road engines.
- Improper, or lack of, NO_x correction factors for off-road engines and locomotives contribute significant uncertainty for estimates of this pollutant (see Appendix A.2.3 for details), which has not been quantified in this report.

Table 18: Activity data and emission factors – potential improvements

	Activity data	Emission factors
Aircraft	NAV CANADA movements by aircraft type	PM factors
Commercial marine	Canadian Coast Guard vessel movements data	NO_x correction for humidity
On-road vehicles	CVS micro data	MSOD
Off-road engines	–	MSOD
Locomotives	–	NO_x correction for humidity and temperature

A Appendix

A.1 Statistical distributions

A random variable is a function whose output is random and to which a probability distribution is assigned. This report classifies random variables into four types (Table 19).

Table 19: Types of random variables

	uncertainty	random variable	distribution
TYPE I	known	A	$\delta(A)$[3]
TYPE II	uncertain	$\mathcal{A}$	eg. $\mathcal{A} \sim \mathrm{N}(\mu, \sigma), \ldots$
TYPE III	↓	$\mathcal{A}_1 + \cdots + \mathcal{A}_n = B$	$\boldsymbol{\mathcal{A}} \sim \mathrm{Dirichlet}(\alpha_1, \ldots, \alpha_n) \cdot B$
TYPE IV	more uncertain	$\mathcal{A}_1 + \cdots + \mathcal{A}_n = \mathcal{B}$	$\boldsymbol{\mathcal{A}} \sim \mathrm{Dirichlet}(\alpha_1, \ldots, \alpha_n) \cdot \mathcal{B}$

A.1.1 Normal distribution

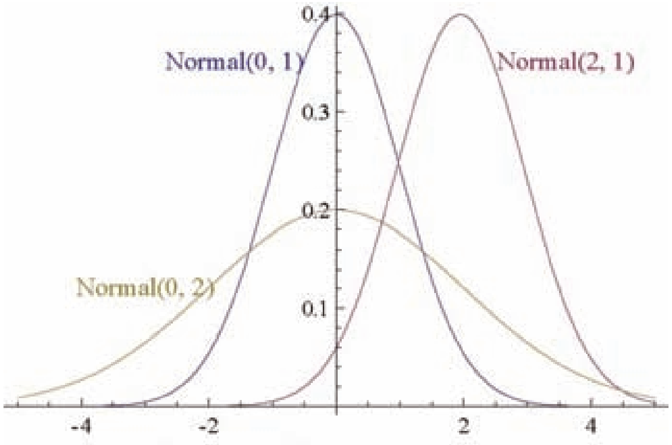


Figure 20: Normal distribution

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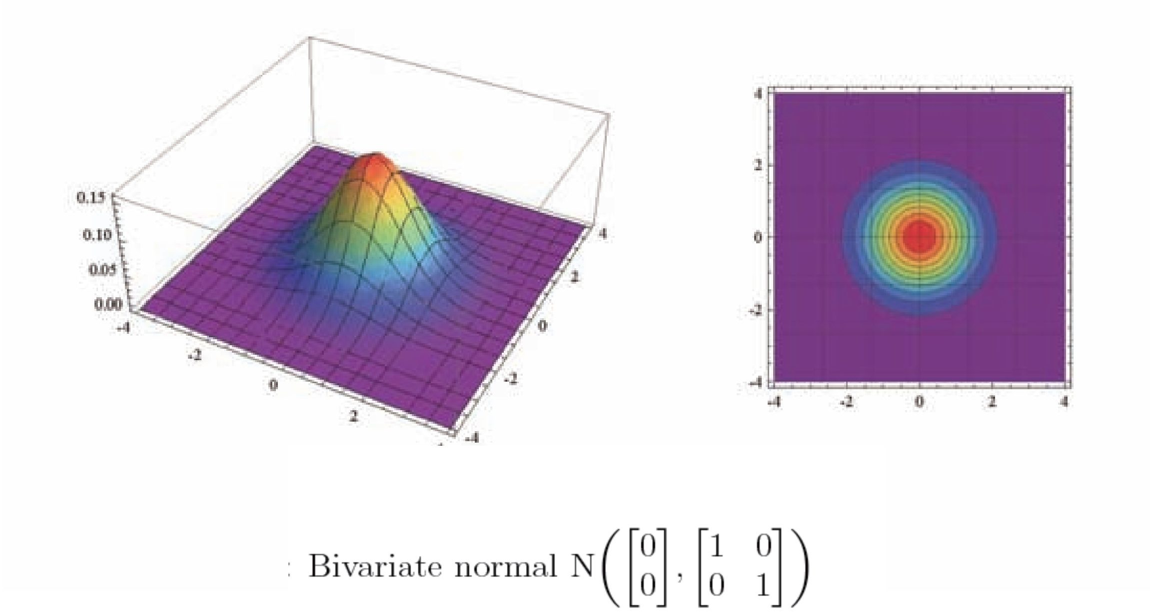
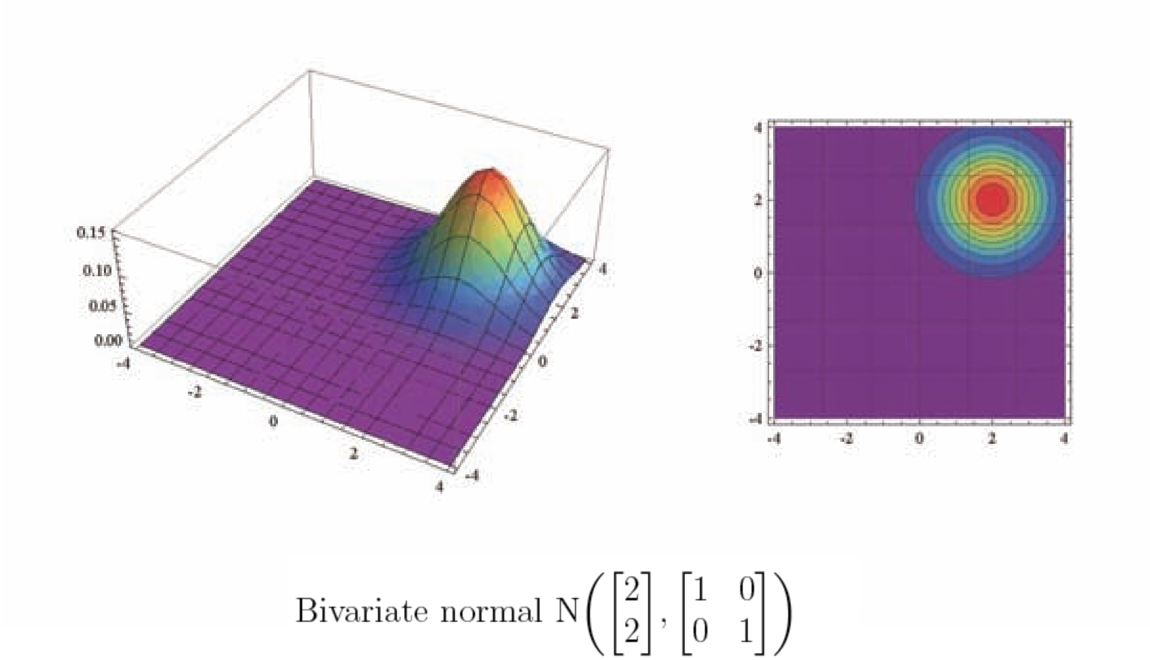
[3] Takes value A with probability 1. δ(A) is known as the delta, or point-mass, distribution at A.

A.1.2 Multivariate normal distribution



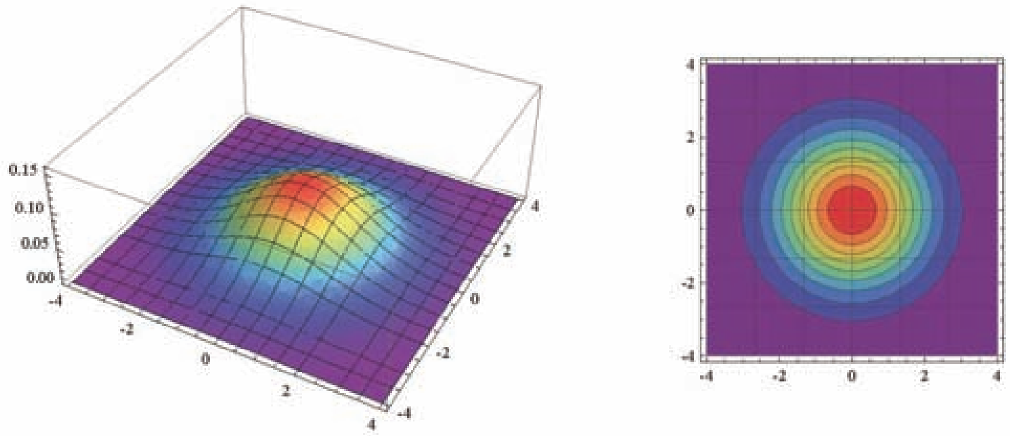
: Bivariate normal $\mathrm{N}\left(\begin{bmatrix}0\\0\end{bmatrix},\begin{bmatrix}1&0\\0&1\end{bmatrix}\right)$

Figure 21: Bivariate normal distribution (example 1)



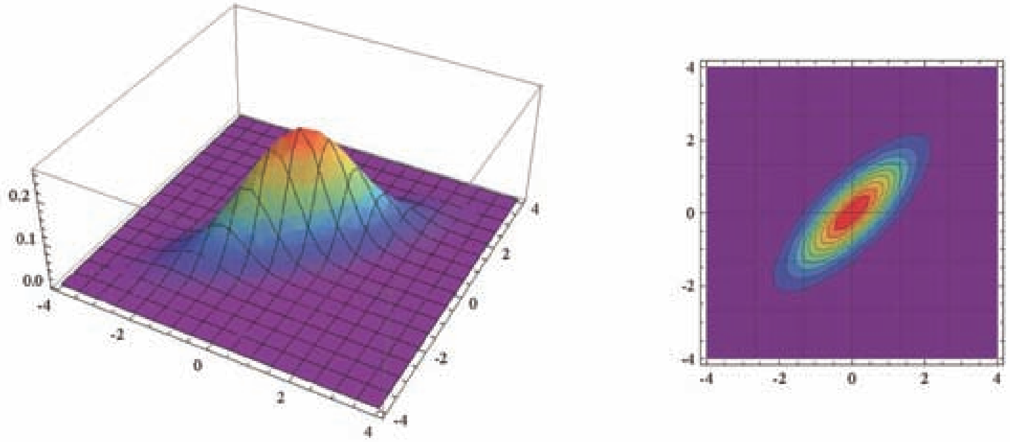
Bivariate normal $\mathrm{N}\left(\begin{bmatrix}2\\2\end{bmatrix},\begin{bmatrix}1&0\\0&1\end{bmatrix}\right)$

Figure 22: Bivariate normal distribution (example 2)



$$\text{Bivariate normal } \mathrm{N}\left(\begin{bmatrix}0\\0\end{bmatrix}, \begin{bmatrix}2 & 0\\0 & 2\end{bmatrix}\right)$$

Figure 23: Bivariate normal distribution (example 3)



$$\text{Bivariate normal } \mathrm{N}\left(\begin{bmatrix}0\\0\end{bmatrix}, \begin{bmatrix}1 & .5\\.5 & 1\end{bmatrix}\right)$$

Figure 24: Bivariate normal distribution (example 4)

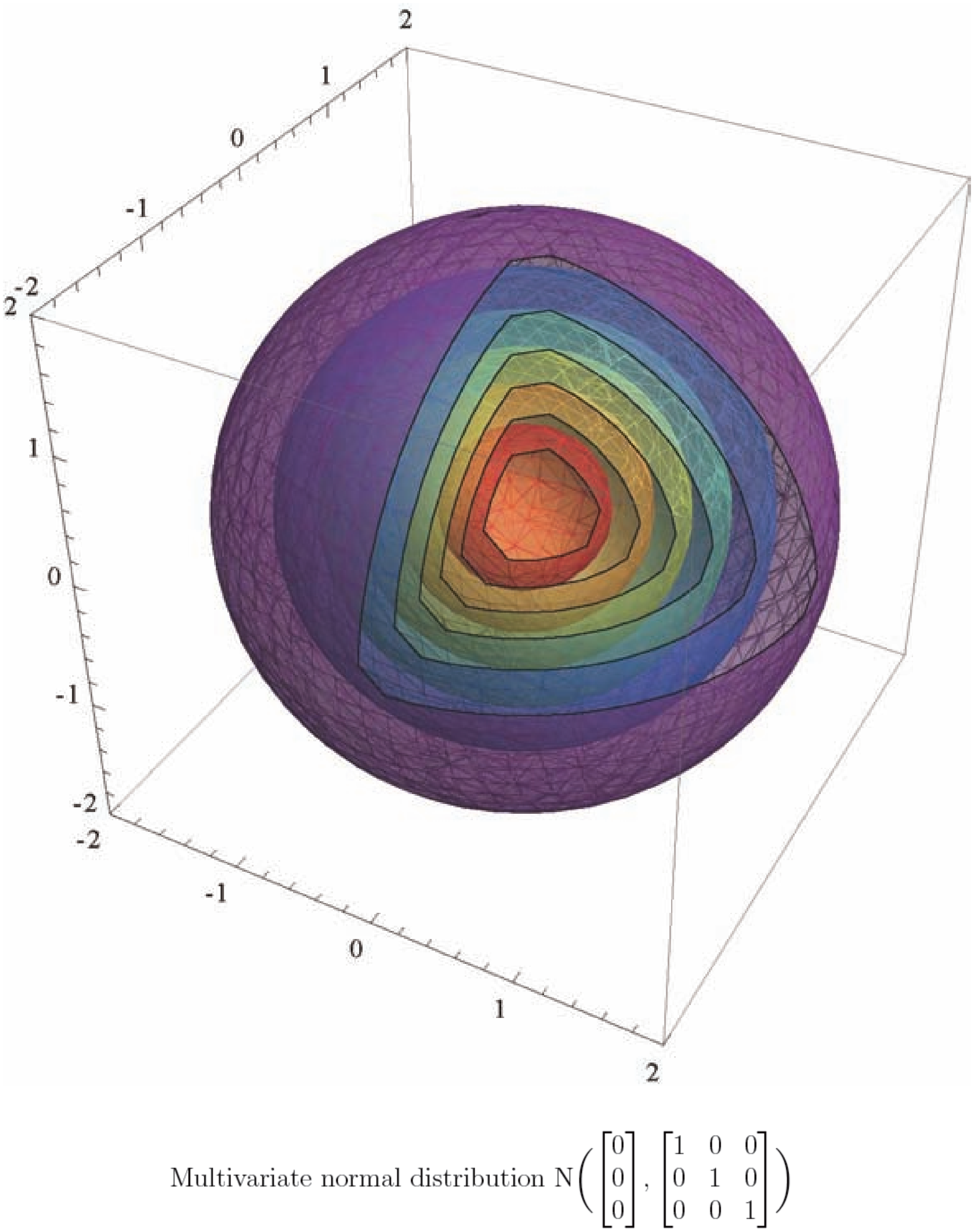


Figure 25: Multivariate normal distribution

A.1.3 Lognormal distribution

In probability and statistics, the lognormal distribution is the single-tailed probability distribution of any random variable whose logarithm is normally distributed (Wikipedia, 2008). If Y is a random variable with a normal distribution, then X = exp(Y) has a lognormal distribution; likewise, if X is lognormally distributed, then log(X) is normally distributed. The base of the logarithmic function does not matter: if log(X) is normally distributed, then so is $\log_b(X)$, for any two positive numbers a, b ≠1. A variable might be modelled as lognormal, if it could be thought of as the multiplicative product of many small independent factors.

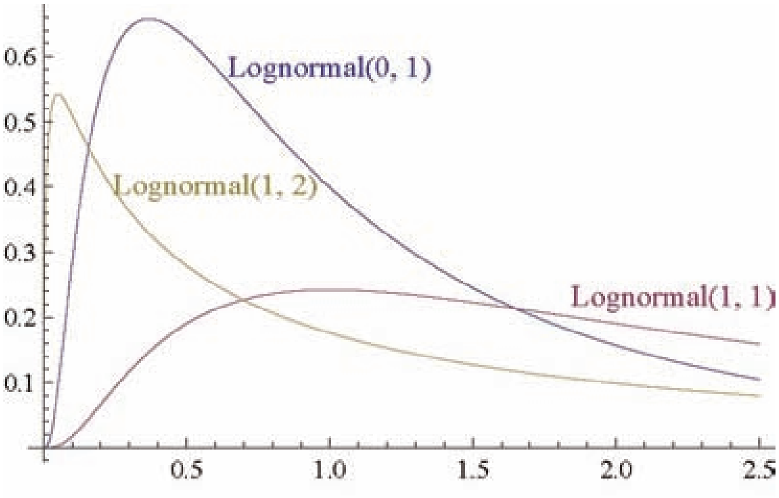


Figure 26: Lognormal distribution

The Weibull distribution is a skewed cousin to the lognormal in the exponential family. This distribution is often used in uncertainty analysis due to its flexibility; it can mimic the behaviour of other statistical distributions such as the normal, lognormal and exponential.

A.1.4 Uniform distribution

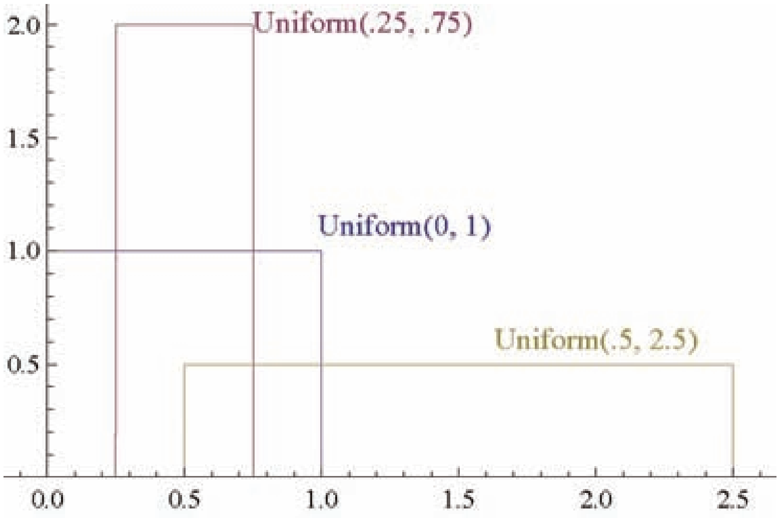


Figure 27: Uniform distribution

A.1.5 Beta distribution

Beta distributions are versatile, and a variety of uncertainties can be usefully modelled by them, especially when the random variables involve percentages.

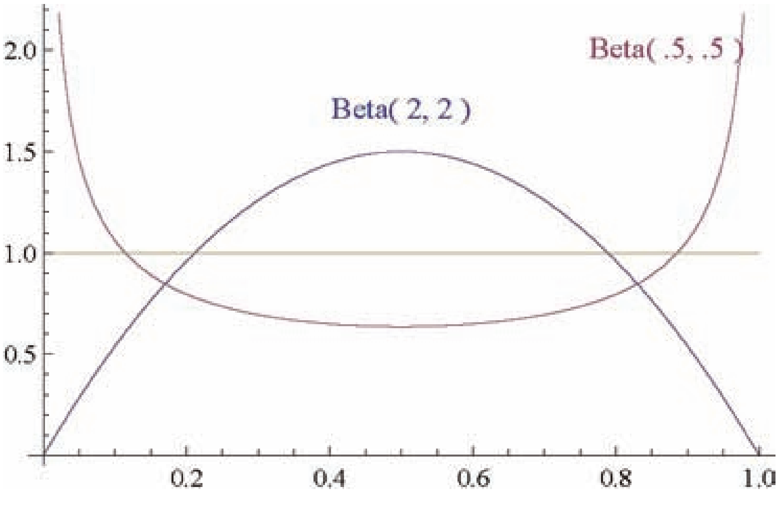


Figure 28: Beta distribution

A.1.6 Dirichlet distribution

In probability and statistics, the Dirichlet distribution is the multivariate generalization of the beta distribution, and it is best known as the conjugate prior of the multinomial distribution in Bayesian inference.

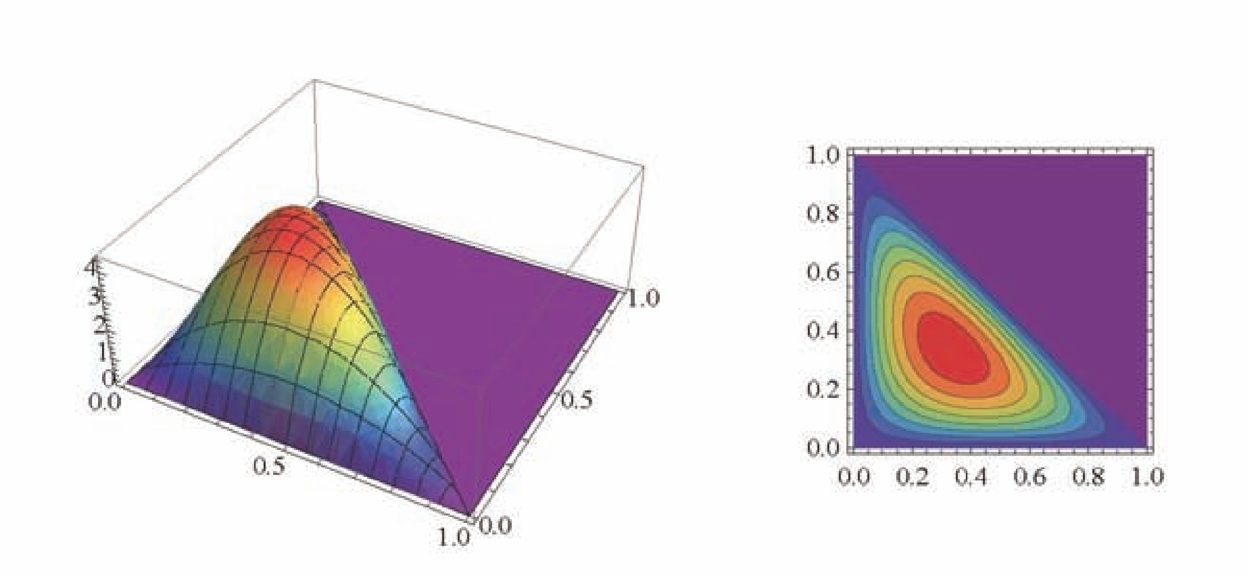


Figure 29: Dirichlet distribution

Wikipedia (2008) provides an intuitive interpretation of the parameters. One example use of the Dirichlet distribution is if one wanted to cut strings (each of initial length 1.0) into K pieces with different lengths, where each piece had a designated average length, but allowing some variation in the relative sizes of the pieces. The α/α_0 values specify the mean lengths of the cut pieces of string resulting from the distribution. The variance around this mean varies inversely with α_0.

A.2 Monte Carlo uncertainty analysis

A.2.1 Monte Carlo MOBILE perl script

- *monte_carlo_mobile_canada()* is the main loop of this script. It will keep running until the program is stopped manually using ctrl-c. Two independent runs of the model are executed in parallel threads to double performance on dual-processor machines. This code can easily be modified for an arbitrary number of parallel processors.
- *write_regdist_files()* creates randomized registration distribution MOBILE input files for 14 vehicle classes and 25 model years for each of 13 regions, using data from CVS.
- *write_mileage_files()* creates randomized mileage accumulation MOBILE input files for 28 vehicle classes for each of 13 regions, using data from CVS.
- *write_speedvmt_files()* creates randomized speed distribution MOBILE input files for each of 13 regions, using data from Delcan (2003).
- *write_input_file()* creates a single MOBILE input file per Monte Carlo run that includes PM_{10} and $PM_{2.5}$ scenarios for 13 regions and 12 months (312 total scenarios).
- *rgs()* generates a randomized gasoline sulphur content.
- *mobile_to_cvs()* maps MOBILE vehicle classes to CVS vehicle classes.
- *monte_carlo_filename()* generates a filename of the form

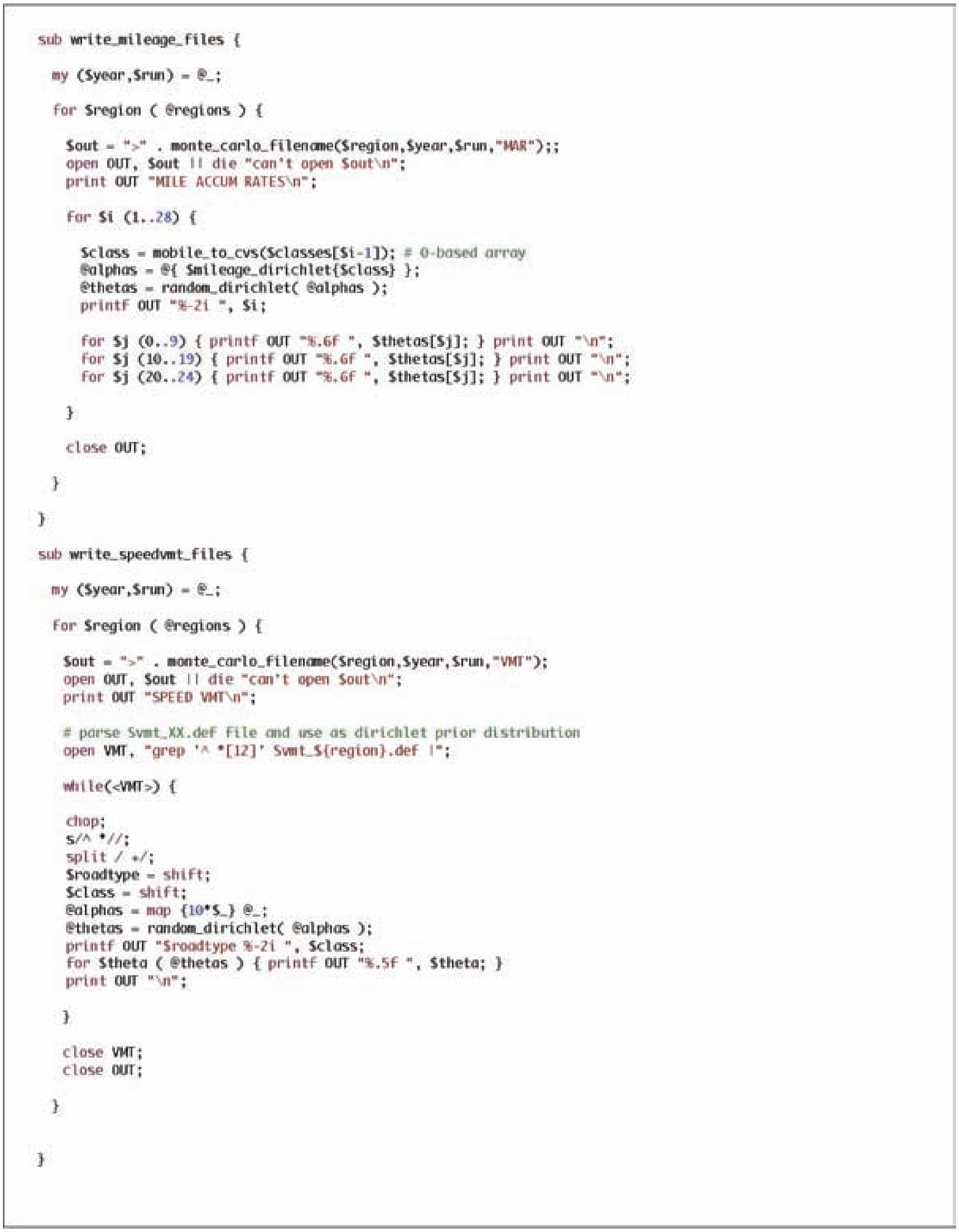
  <region>_<year>_<run number>.<extension>
- *run_mobile()* runs the MOBILE model executable[4] as a subprocess.
- *random_dirichlet()* generates a randomized Dirichlet vector.

---

[4] Version 6.2C (27-05-2005), slightly modified to compile with GNV Fortran on Mac OS X and Linux.

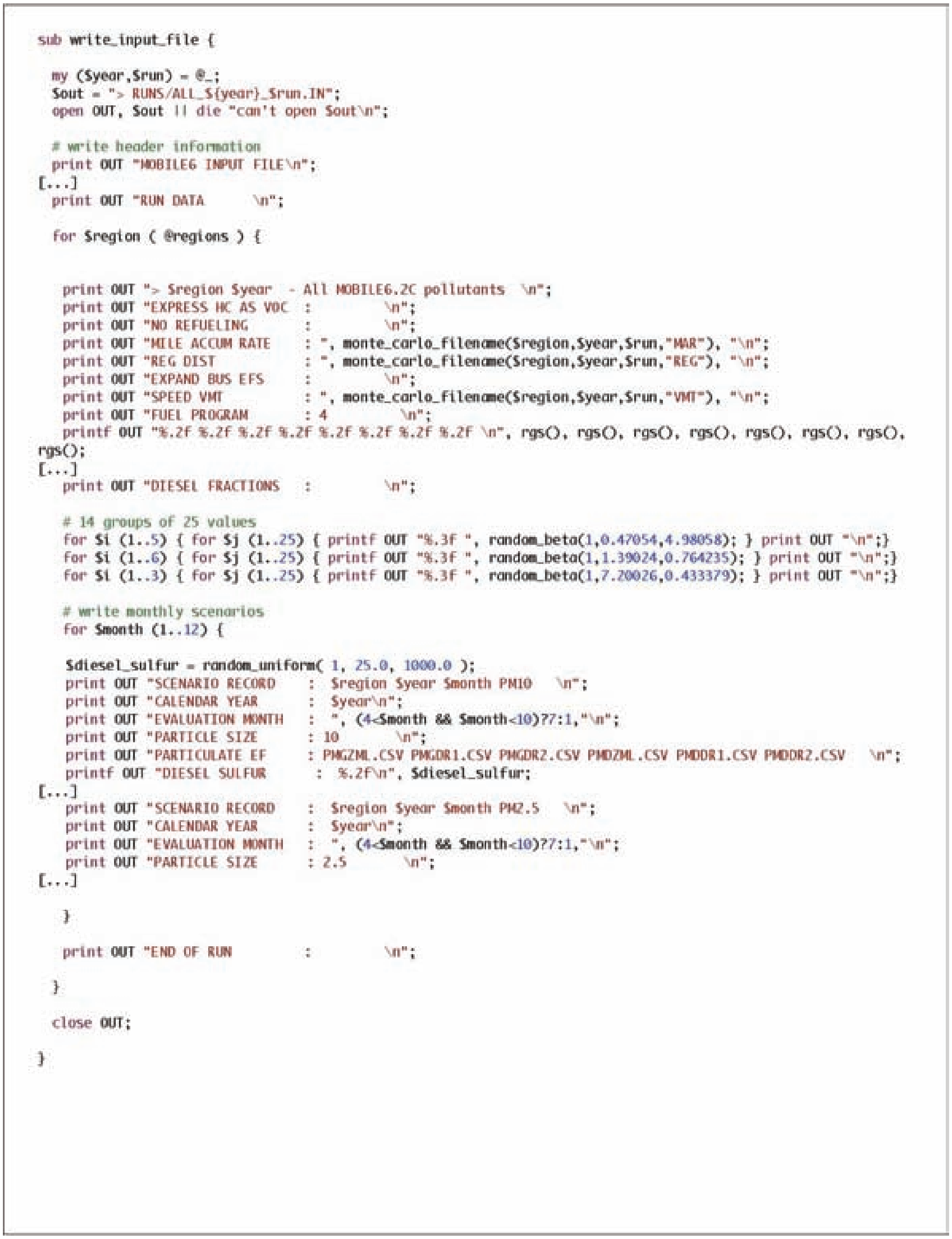
```perl
#!/usr/bin/perl

use threads;
use Math::Random qw(random_uniform random_beta);
use RegDist;
sub printarray;

monte_carlo_mobile_canada();
exit();

sub monte_carlo_mobile_canada {

  initialize_data();

  # keep running until ctrl-c
  while() {

    write_regdist_files( $year, $run );
    write_regdist_files( $year, $run+1 );
    write_mileage_files( $year, $run );
    write_mileage_files( $year, $run+1 );
    write_speedvmt_files( $year, $run );
    write_speedvmt_files( $year, $run+1 );
    write_input_file( $year, $run );
    write_input_file( $year, $run+1 );

    # start two threads and wait until they're done
    my $thread1 = threads->create('run_mobile', $year, $run );
    my $thread2 = threads->create('run_mobile', $year, $run+1 );
    $thread1->join();
    $thread2->join();

    $run+=2;

  }

}

sub write_regdist_files {

  my ($year,$run) = @_;

  for $region ( @regions ) {

    $out = "> " . monte_carlo_filename($region,$year,$run,"REG");
    open OUT, $out || die "can't open $out\n";
    print OUT "REG DIST\n";

    # 14 groups of 25 values
    for $i (1..14) {

      $class = $i<6 ? "L" : $i<12 ? "M" : "H";
      @alphas = @{ $regdist{uc $region}{$class} };
      @thetas = random_dirichlet( @alphas );
      printf OUT "%-2i ", $i;

      for $j (0..9) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";
      for $j (10..19) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";
      for $j (20..24) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";

    }

    close OUT;

  }

}
```

Figure 30: *monte carlo mobile.pl* perl script



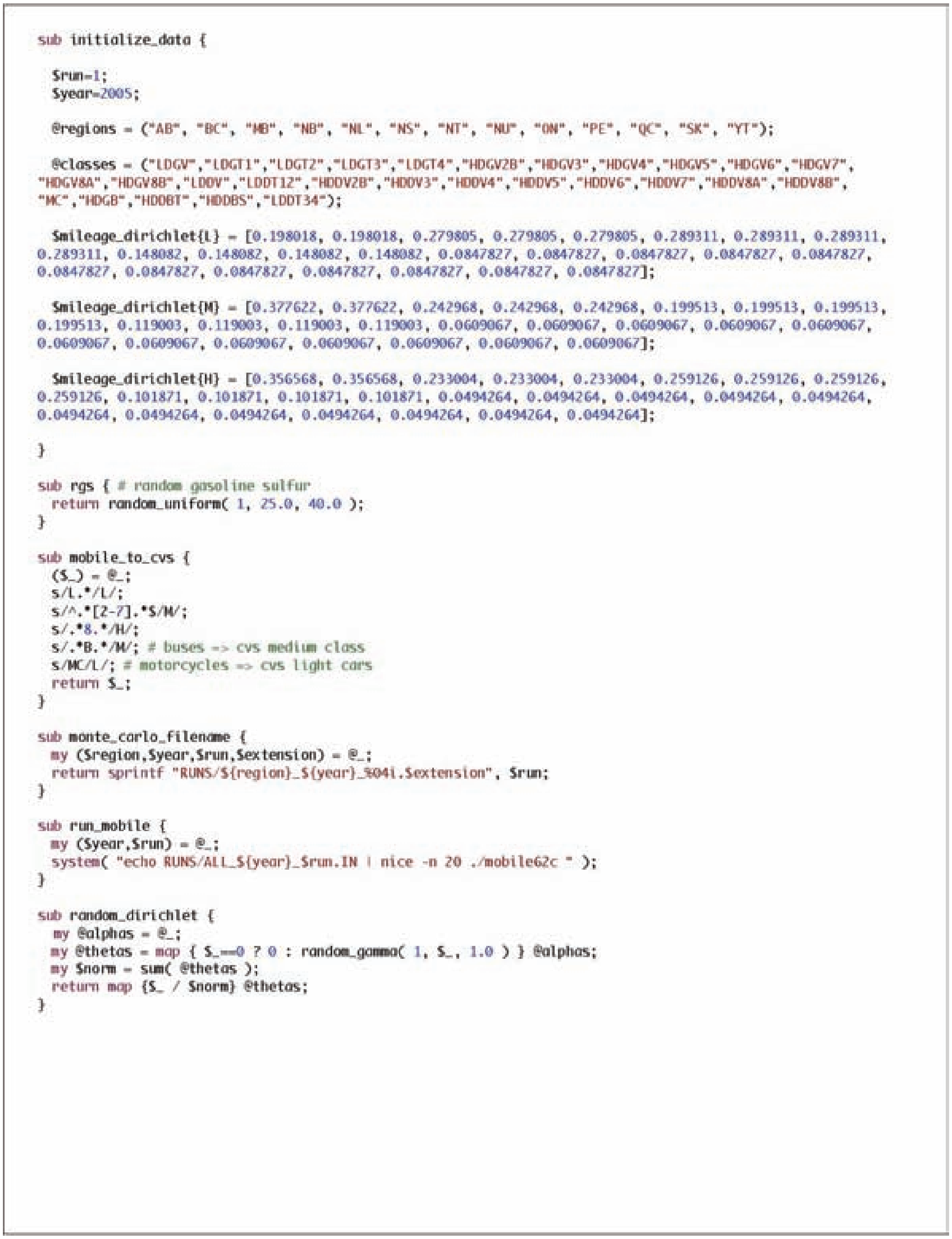
```
sub write_mileage_files {

  my ($year,$run) = @_;

  for $region ( @regions ) {

    $out = ">" . monte_carlo_filename($region,$year,$run,"MAR");;
    open OUT, $out || die "can't open $out\n";
    print OUT "MILE ACCUM RATES\n";

    for $i (1..28) {

      $class = mobile_to_cvs($classes[$i-1]); # 0-based array
      @alphas = @{ $mileage_dirichlet{$class} };
      @thetas = random_dirichlet( @alphas );
      printf OUT "%-2i ", $i;

      for $j (0..9) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";
      for $j (10..19) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";
      for $j (20..24) { printf OUT "%.6f ", $thetas[$j]; } print OUT "\n";

    }

    close OUT;

  }

}

sub write_speedvmt_files {

  my ($year,$run) = @_;

  for $region ( @regions ) {

    $out = ">" . monte_carlo_filename($region,$year,$run,"VMT");
    open OUT, $out || die "can't open $out\n";
    print OUT "SPEED VMT\n";

    # parse Svmt_XX.def File and use as dirichlet prior distribution
    open VMT, "grep '^ *[12]' Svmt_${region}.def |";

    while(<VMT>) {

     chop;
     s/^ *//;
     split / +/;
     $roadtype = shift;
     $class = shift;
     @alphas = map {10*$_} @_;
     @thetas = random_dirichlet( @alphas );
     printf OUT "$roadtype %-2i ", $class;
     for $theta ( @thetas ) { printf OUT "%.5f ", $theta; }
     print OUT "\n";

    }

    close VMT;
    close OUT;

  }


}
```

Figure 30: ***monte carlo mobile.pl*** **perl script (cont.)**



```
sub write_input_file {

  my ($year,$run) = @_;
  $out = "> RUNS/ALL_${year}_$run.IN";
  open OUT, $out || die "can't open $out\n";

  # write header information
  print OUT "MOBILE6 INPUT FILE\n";
[...]
  print OUT "RUN DATA      \n";

  for $region ( @regions ) {


    print OUT "> $region $year  - All MOBILE6.2C pollutants  \n";
    print OUT "EXPRESS HC AS VOC  :         \n";
    print OUT "NO REFUELING       :         \n";
    print OUT "MILE ACCUM RATE    : ", monte_carlo_filename($region,$year,$run,"MAR"), "\n";
    print OUT "REG DIST           : ", monte_carlo_filename($region,$year,$run,"REG"), "\n";
    print OUT "EXPAND BUS EFS     :         \n";
    print OUT "SPEED VMT          : ", monte_carlo_filename($region,$year,$run,"VMT"), "\n";
    print OUT "FUEL PROGRAM       : 4         \n";
    printf OUT "%.2f %.2f %.2f %.2f %.2f %.2f %.2f %.2f \n", rgs(), rgs(), rgs(), rgs(), rgs(), rgs(), rgs(),
rgs();
[...]
    print OUT "DIESEL FRACTIONS   :         \n";

    # 14 groups of 25 values
    for $i (1..5) { for $j (1..25) { printf OUT "%.3f ", random_beta(1,0.47054,4.98058); } print OUT "\n";}
    for $i (1..6) { for $j (1..25) { printf OUT "%.3f ", random_beta(1,1.39024,0.764235); } print OUT "\n";}
    for $i (1..3) { for $j (1..25) { printf OUT "%.3f ", random_beta(1,7.20026,0.433379); } print OUT "\n";}

    # write monthly scenarios
    for $month (1..12) {

     $diesel_sulfur = random_uniform( 1, 25.0, 1000.0 );
     print OUT "SCENARIO RECORD    :  $region $year $month PM10   \n";
     print OUT "CALENDAR YEAR      :  $year\n";
     print OUT "EVALUATION MONTH   :  ", (4<$month && $month<10)?7:1,"\n";
     print OUT "PARTICLE SIZE      : 10       \n";
     print OUT "PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV   \n";
     printf OUT "DIESEL SULFUR      :  %.2f\n", $diesel_sulfur;
[...]
     print OUT "SCENARIO RECORD    :  $region $year $month PM2.5   \n";
     print OUT "CALENDAR YEAR      :  $year\n";
     print OUT "EVALUATION MONTH   :  ", (4<$month && $month<10)?7:1,"\n";
     print OUT "PARTICLE SIZE      : 2.5       \n";
[...]

    }

    print OUT "END OF RUN         :         \n";

  }

  close OUT;

}
```

Figure 30: *monte carlo mobile.p*l perl script (cont.)



```
sub initialize_data {

  $run=1;
  $year=2005;

  @regions = ("AB", "BC", "MB", "NB", "NL", "NS", "NT", "NU", "ON", "PE", "QC", "SK", "YT");

  @classes = ("LDGV","LDGT1","LDGT2","LDGT3","LDGT4","HDGV2B","HDGV3","HDGV4","HDGV5","HDGV6","HDGV7",
"HDGV8A","HDGV8B","LDDV","LDDT12","HDDV2B","HDDV3","HDDV4","HDDV5","HDDV6","HDDV7","HDDV8A","HDDV8B",
"MC","HDGB","HDDBT","HDDBS","LDDT34");

  $mileage_dirichlet{L} = [0.198018, 0.198018, 0.279805, 0.279805, 0.279805, 0.289311, 0.289311, 0.289311,
0.289311, 0.148082, 0.148082, 0.148082, 0.148082, 0.0847827, 0.0847827, 0.0847827, 0.0847827, 0.0847827,
0.0847827, 0.0847827, 0.0847827, 0.0847827, 0.0847827, 0.0847827, 0.0847827];

  $mileage_dirichlet{M} = [0.377622, 0.377622, 0.242968, 0.242968, 0.242968, 0.199513, 0.199513, 0.199513,
0.199513, 0.119003, 0.119003, 0.119003, 0.119003, 0.0609067, 0.0609067, 0.0609067, 0.0609067, 0.0609067,
0.0609067, 0.0609067, 0.0609067, 0.0609067, 0.0609067, 0.0609067, 0.0609067];

  $mileage_dirichlet{H} = [0.356568, 0.356568, 0.233004, 0.233004, 0.233004, 0.259126, 0.259126, 0.259126,
0.259126, 0.101871, 0.101871, 0.101871, 0.101871, 0.0494264, 0.0494264, 0.0494264, 0.0494264, 0.0494264,
0.0494264, 0.0494264, 0.0494264, 0.0494264, 0.0494264, 0.0494264, 0.0494264];

}

sub rgs { # random gasoline sulfur
  return random_uniform( 1, 25.0, 40.0 );
}

sub mobile_to_cvs {
  ($_) = @_;
  s/L.*/L/;
  s/^.*[2-7].*$/M/;
  s/.*8.*/H/;
  s/.*B.*/M/; # buses => cvs medium class
  s/MC/L/; # motorcycles => cvs light cars
  return $_;
}

sub monte_carlo_filename {
  my ($region,$year,$run,$extension) = @_;
  return sprintf "RUNS/${region}_${year}_%04i.$extension", $run;
}

sub run_mobile {
  my ($year,$run) = @_;
  system( "echo RUNS/ALL_${year}_$run.IN | nice -n 20 ./mobile62c " );
}

sub random_dirichlet {
  my @alphas = @_;
  my @thetas = map { $_==0 ? 0 : random_gamma( 1, $_, 1.0 ) } @alphas;
  my $norm = sum( @thetas );
  return map {$_ / $norm} @thetas;
}
```

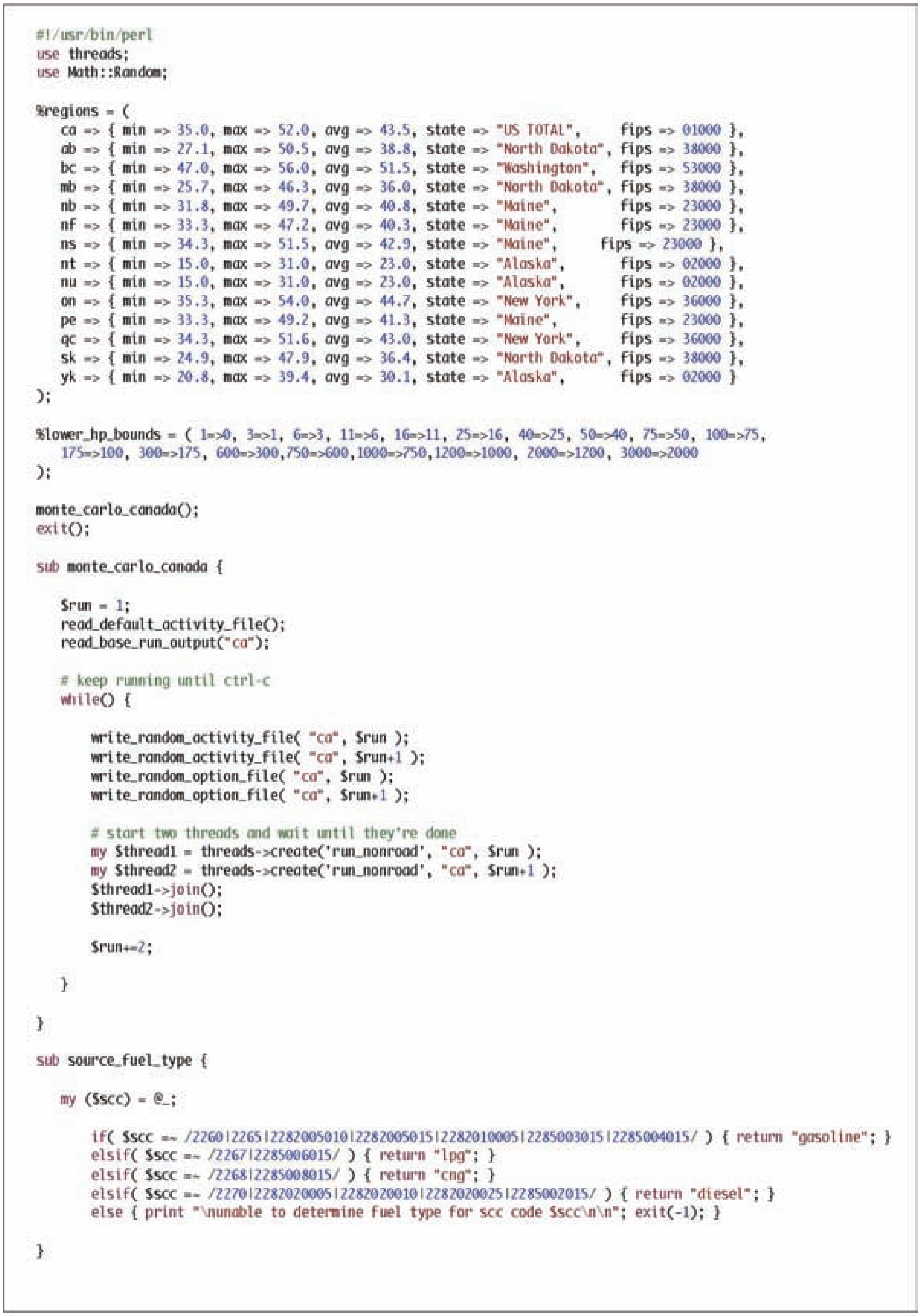
Figure 30: ***monte carlo mobile.pl*** **perl script (cont.)**

A.2.2 Monte Carlo NONROAD perl script

- *monte_carlo_nonroad_canada()* is the main loop of this script. It will keep running until the program is stopped manually using ctrl-c. Two independent runs of the model are executed in parallel threads to double performance on dual-processor machines. This code can easily be modified for an arbitrary number of parallel processors.
- *source_fuel_type()* maps NONROAD source classification codes (SCC) to fuel types gasoline, diesel, LPG and CNG.
- *read_default_activity_file()* reads the NONROAD default activity file.
- *read_base_run_output()* reads the output of base runs of NONROAD model.
- *write_random_activity_file()* creates a randomized NONROAD activity file by allocating total fuel consumed to different SCCs using a Dirichlet prior distribution obtained from base runs of NONROAD model.
- *run_nonroad()* runs the NONROAD model executable[5] as a subprocess.
- *write_random_option_file()* creates a NONROAD option file for each run that includes historical weather data from MSC and randomized sulphur content per fuel.
- *random_dirichlet()* generates a randomized Dirichlet vector.

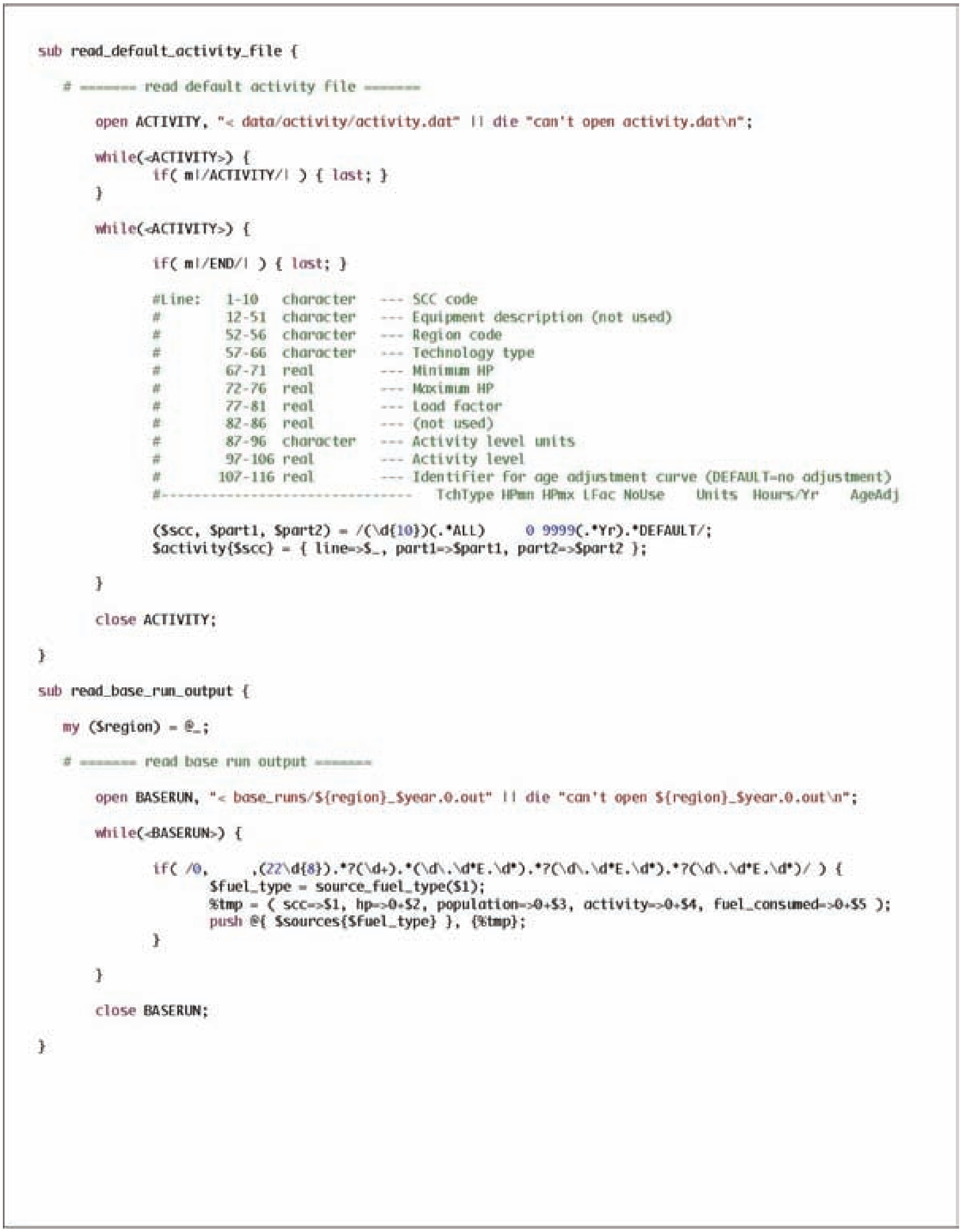
---

[5] EPA version, slightly modified to compile with GNV Fortran on Mac OS X and Linux.



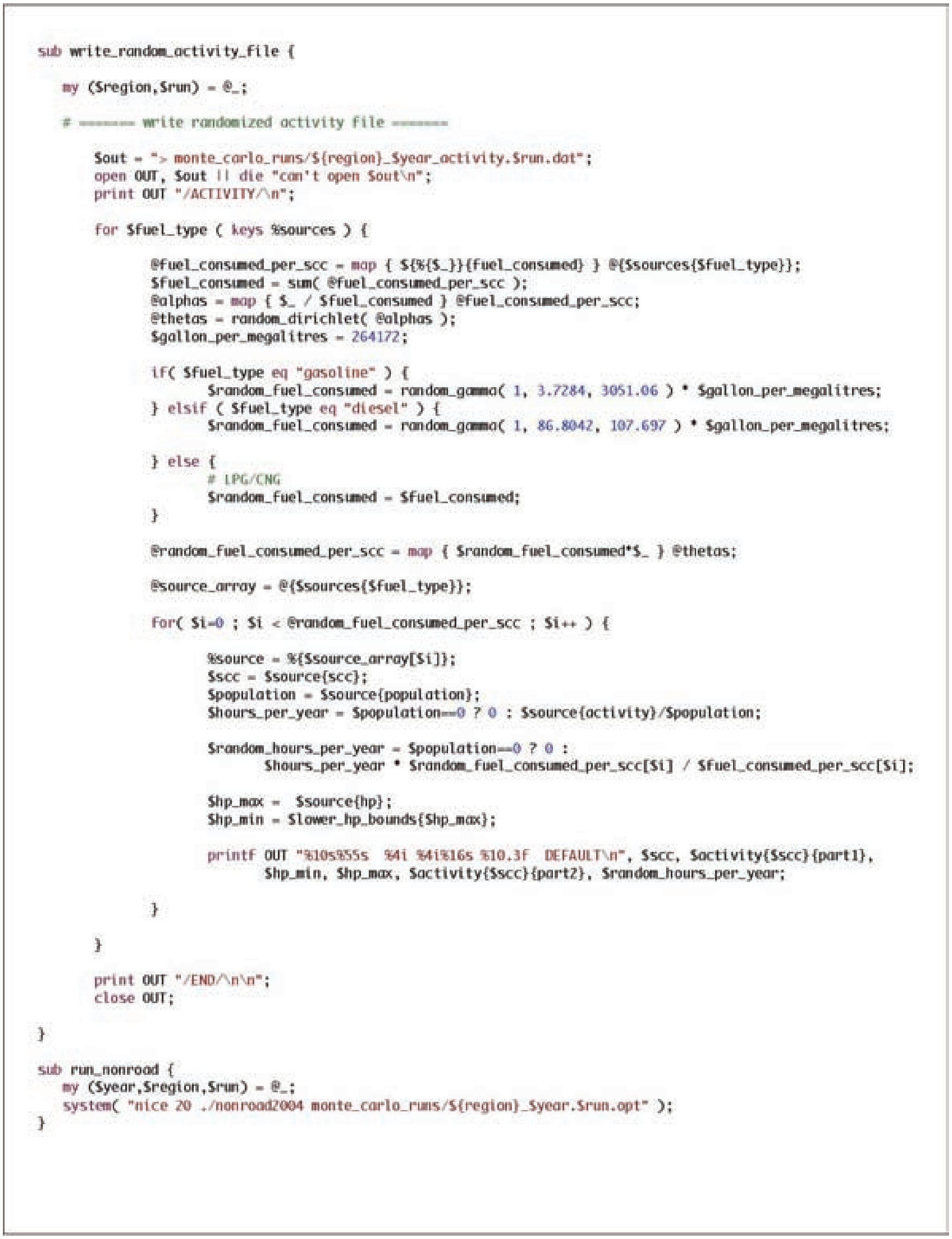
```perl
#!/usr/bin/perl
use threads;
use Math::Random;

%regions = (
   ca => { min => 35.0, max => 52.0, avg => 43.5, state => "US TOTAL",     fips => 01000 },
   ab => { min => 27.1, max => 50.5, avg => 38.8, state => "North Dakota", fips => 38000 },
   bc => { min => 47.0, max => 56.0, avg => 51.5, state => "Washington",   fips => 53000 },
   mb => { min => 25.7, max => 46.3, avg => 36.0, state => "North Dakota", fips => 38000 },
   nb => { min => 31.8, max => 49.7, avg => 40.8, state => "Maine",        fips => 23000 },
   nf => { min => 33.3, max => 47.2, avg => 40.3, state => "Maine",        fips => 23000 },
   ns => { min => 34.3, max => 51.5, avg => 42.9, state => "Maine",     fips => 23000 },
   nt => { min => 15.0, max => 31.0, avg => 23.0, state => "Alaska",       fips => 02000 },
   nu => { min => 15.0, max => 31.0, avg => 23.0, state => "Alaska",       fips => 02000 },
   on => { min => 35.3, max => 54.0, avg => 44.7, state => "New York",     fips => 36000 },
   pe => { min => 33.3, max => 49.2, avg => 41.3, state => "Maine",        fips => 23000 },
   qc => { min => 34.3, max => 51.6, avg => 43.0, state => "New York",     fips => 36000 },
   sk => { min => 24.9, max => 47.9, avg => 36.4, state => "North Dakota", fips => 38000 },
   yk => { min => 20.8, max => 39.4, avg => 30.1, state => "Alaska",       fips => 02000 }
);

%lower_hp_bounds = ( 1=>0, 3=>1, 6=>3, 11=>6, 16=>11, 25=>16, 40=>25, 50=>40, 75=>50, 100=>75,
   175=>100, 300=>175, 600=>300,750=>600,1000=>750,1200=>1000, 2000=>1200, 3000=>2000
);

monte_carlo_canada();
exit();

sub monte_carlo_canada {

   $run = 1;
   read_default_activity_file();
   read_base_run_output("ca");

   # keep running until ctrl-c
   while() {

       write_random_activity_file( "ca", $run );
       write_random_activity_file( "ca", $run+1 );
       write_random_option_file( "ca", $run );
       write_random_option_file( "ca", $run+1 );

       # start two threads and wait until they're done
       my $thread1 = threads->create('run_nonroad', "ca", $run );
       my $thread2 = threads->create('run_nonroad', "ca", $run+1 );
       $thread1->join();
       $thread2->join();

       $run+=2;

   }

}

sub source_fuel_type {

   my ($scc) = @_;

       if( $scc =~ /2260|2265|2282005010|2282005015|2282010005|2285003015|2285004015/ ) { return "gasoline"; }
       elsif( $scc =~ /2267|2285006015/ ) { return "lpg"; }
       elsif( $scc =~ /2268|2285008015/ ) { return "cng"; }
       elsif( $scc =~ /2270|2282020005|2282020010|2282020025|2285002015/ ) { return "diesel"; }
       else { print "\nunable to determine fuel type for scc code $scc\n\n"; exit(-1); }

}
```

Figure 31: ***monte carlo mobile.pl*** **perl script**



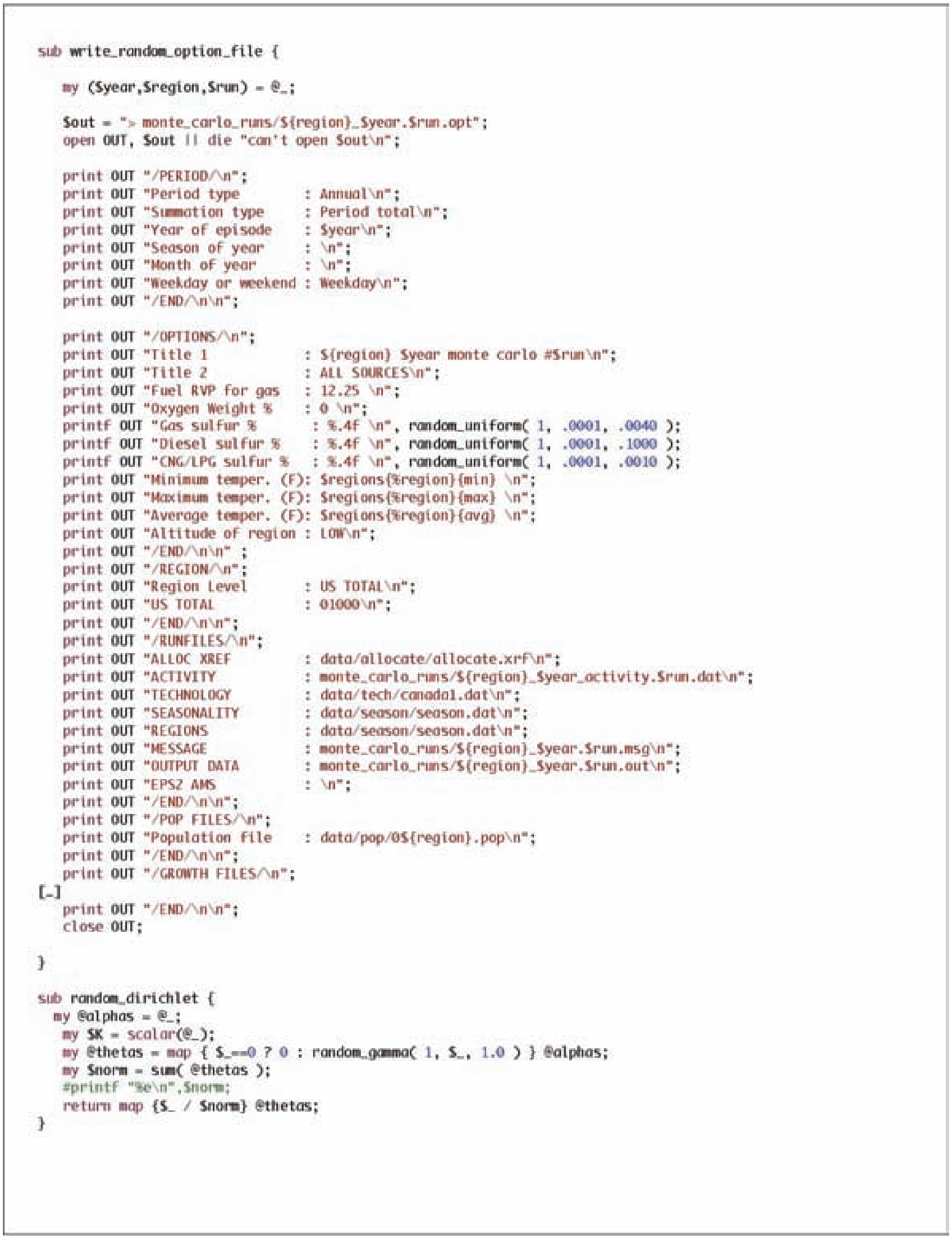
```
sub read_default_activity_file {

    # ======= read default activity file =======

        open ACTIVITY, "< data/activity/activity.dat" || die "can't open activity.dat\n";

        while(<ACTIVITY>) {
                if( m|/ACTIVITY/| ) { last; }
        }

        while(<ACTIVITY>) {

                if( m|/END/| ) { last; }

                #Line:   1-10   character   --- SCC code
                #        12-51  character   --- Equipment description (not used)
                #        52-56  character   --- Region code
                #        57-66  character   --- Technology type
                #        67-71  real        --- Minimum HP
                #        72-76  real        --- Maximum HP
                #        77-81  real        --- Load factor
                #        82-86  real        --- (not used)
                #        87-96  character   --- Activity level units
                #        97-106 real        --- Activity level
                #       107-116 real        --- Identifier for age adjustment curve (DEFAULT=no adjustment)
                #--------------------------------   TchType HPmn HPmx LFac NoUse    Units  Hours/Yr    AgeAdj

                ($scc, $part1, $part2) = /(\d{10})(.*ALL)     0 9999(.*Yr).*DEFAULT/;
                $activity{$scc} = { line=>$_, part1=>$part1, part2=>$part2 };

        }

        close ACTIVITY;

}

sub read_base_run_output {

    my ($region) = @_;

    # ======= read base run output =======

        open BASERUN, "< base_runs/${region}_$year.0.out" || die "can't open ${region}_$year.0.out\n";

        while(<BASERUN>) {

                if( /0,     ,(22\d{8}).*?(\d+).*(\d\.\d*E.\d*).*?(\d\.\d*E.\d*).*?(\d\.\d*E.\d*)/ ) {
                        $fuel_type = source_fuel_type($1);
                        %tmp = ( scc=>$1, hp=>0+$2, population=>0+$3, activity=>0+$4, fuel_consumed=>0+$5 );
                        push @{ $sources{$fuel_type} }, {%tmp};
                }

        }

        close BASERUN;

}
```

Figure 31: ***monte carlo mobile.pl*** **perl script (cont.)**



```
sub write_random_activity_file {

   my ($region,$run) = @_;

   # ======= write randomized activity file =======

       $out = "> monte_carlo_runs/${region}_$year_activity.$run.dat";
       open OUT, $out || die "can't open $out\n";
       print OUT "/ACTIVITY/\n";

       for $fuel_type ( keys %sources ) {

              @fuel_consumed_per_scc = map { ${%{$_}}{fuel_consumed} } @{$sources{$fuel_type}};
              $fuel_consumed = sum( @fuel_consumed_per_scc );
              @alphas = map { $_ / $fuel_consumed } @fuel_consumed_per_scc;
              @thetas = random_dirichlet( @alphas );
              $gallon_per_megalitres = 264172;

              if( $fuel_type eq "gasoline" ) {
                     $random_fuel_consumed = random_gamma( 1, 3.7284, 3051.06 ) * $gallon_per_megalitres;
              } elsif ( $fuel_type eq "diesel" ) {
                     $random_fuel_consumed = random_gamma( 1, 86.8042, 107.697 ) * $gallon_per_megalitres;

              } else {
                     # LPG/CNG
                     $random_fuel_consumed = $fuel_consumed;
              }

              @random_fuel_consumed_per_scc = map { $random_fuel_consumed*$_ } @thetas;

              @source_array = @{$sources{$fuel_type}};

              for( $i=0 ; $i < @random_fuel_consumed_per_scc ; $i++ ) {

                     %source = %{$source_array[$i]};
                     $scc = $source{scc};
                     $population = $source{population};
                     $hours_per_year = $population==0 ? 0 : $source{activity}/$population;

                     $random_hours_per_year = $population==0 ? 0 :
                            $hours_per_year * $random_fuel_consumed_per_scc[$i] / $fuel_consumed_per_scc[$i];

                     $hp_max =  $source{hp};
                     $hp_min = $lower_hp_bounds{$hp_max};

                     printf OUT "%10s%55s  %4i %4i%16s %10.3f  DEFAULT\n", $scc, $activity{$scc}{part1},
                            $hp_min, $hp_max, $activity{$scc}{part2}, $random_hours_per_year;

              }

       }

       print OUT "/END/\n\n";
       close OUT;

}

sub run_nonroad {
   my ($year,$region,$run) = @_;
   system( "nice 20 ./nonroad2004 monte_carlo_runs/${region}_$year.$run.opt" );
}
```

Figure 31: *monte carlo mobile.pl* perl script (cont.)



```perl
sub write_random_option_file {

   my ($year,$region,$run) = @_;

   $out = "> monte_carlo_runs/${region}_$year.$run.opt";
   open OUT, $out || die "can't open $out\n";

   print OUT "/PERIOD/\n";
   print OUT "Period type          : Annual\n";
   print OUT "Summation type       : Period total\n";
   print OUT "Year of episode      : $year\n";
   print OUT "Season of year       : \n";
   print OUT "Month of year        : \n";
   print OUT "Weekday or weekend : Weekday\n";
   print OUT "/END/\n\n";

   print OUT "/OPTIONS/\n";
   print OUT "Title 1              : ${region} $year monte carlo #$run\n";
   print OUT "Title 2              : ALL SOURCES\n";
   print OUT "Fuel RVP for gas     : 12.25 \n";
   print OUT "Oxygen Weight %      : 0 \n";
   printf OUT "Gas sulfur %         : %.4f \n", random_uniform( 1, .0001, .0040 );
   printf OUT "Diesel sulfur %      : %.4f \n", random_uniform( 1, .0001, .1000 );
   printf OUT "CNG/LPG sulfur %     : %.4f \n", random_uniform( 1, .0001, .0010 );
   print OUT "Minimum temper. (F): $regions{%region}{min} \n";
   print OUT "Maximum temper. (F): $regions{%region}{max} \n";
   print OUT "Average temper. (F): $regions{%region}{avg} \n";
   print OUT "Altitude of region : LOW\n";
   print OUT "/END/\n\n" ;
   print OUT "/REGION/\n";
   print OUT "Region Level         : US TOTAL\n";
   print OUT "US TOTAL             : 01000\n";
   print OUT "/END/\n\n";
   print OUT "/RUNFILES/\n";
   print OUT "ALLOC XREF           : data/allocate/allocate.xrf\n";
   print OUT "ACTIVITY             : monte_carlo_runs/${region}_$year_activity.$run.dat\n";
   print OUT "TECHNOLOGY           : data/tech/canada1.dat\n";
   print OUT "SEASONALITY          : data/season/season.dat\n";
   print OUT "REGIONS              : data/season/season.dat\n";
   print OUT "MESSAGE              : monte_carlo_runs/${region}_$year.$run.msg\n";
   print OUT "OUTPUT DATA          : monte_carlo_runs/${region}_$year.$run.out\n";
   print OUT "EPS2 AMS             : \n";
   print OUT "/END/\n\n";
   print OUT "/POP FILES/\n";
   print OUT "Population file      : data/pop/0${region}.pop\n";
   print OUT "/END/\n\n";
   print OUT "/GROWTH FILES/\n";
[…]
   print OUT "/END/\n\n";
   close OUT;

}

sub random_dirichlet {
  my @alphas = @_;
   my $K = scalar(@_);
   my @thetas = map { $_==0 ? 0 : random_gamma( 1, $_, 1.0 ) } @alphas;
   my $norm = sum( @thetas );
   #printf "%e\n",$norm;
   return map {$_ / $norm} @thetas;
}
```

Figure 31: ***monte carlo mobile.pl*** **perl script (cont.)**

A.2.3 NO_x correction factors

As early as Krause (1971), it was recognized that engine NO_x emissions are significantly affected by the thermodynamic conditions of the intake air. Specifically, the intake air temperature and humidity have the dominant effects (Gingrich et al., 2003). Because of these sensitivities, it is reasonable to assume that regional variations in temperature and humidity can significantly impact engine-out emission levels.

Basically, “the story is that NO_x emissions are strongly influenced by ambient air humidity levels. On a hot, sweaty day in Houston, actual NO_x emissions are lower than on a standard day, and we need to bump the measured value up. Conversely, on a hot dry day in Los Angeles (in the desert), the NO_x emissions are higher than the standard day, so we need to adjust down. Water vapor in the air displaces available oxygen. On a humid day, less oxygen υ lower peak temperatures υ lower engine out NO_x emissions. Reverse the story for a dry day.” (Fritz, 2008, email communication).

The effect of humidity and temperature has been included in light-duty on-road vehicle emissions estimates in MOBILE6, which includes the effect of air conditioning loads on the engine and the exhaust emission effects described. However, the effect of temperature and humidity has not been included in the MOBILE6 for heavy-duty vehicles and NONROAD emission models even though the emission data used in the development of emission factors has been adjusted for temperature and humidity (Lindhjem et al., 2004).

For a given value of relative humidity, barometric pressure and temperature will result in different values of absolute humidity. Relationships between these variables are referred to as psychrometry, and the graphical representation of these relationships is called a psychrometric chart (Figure 32).

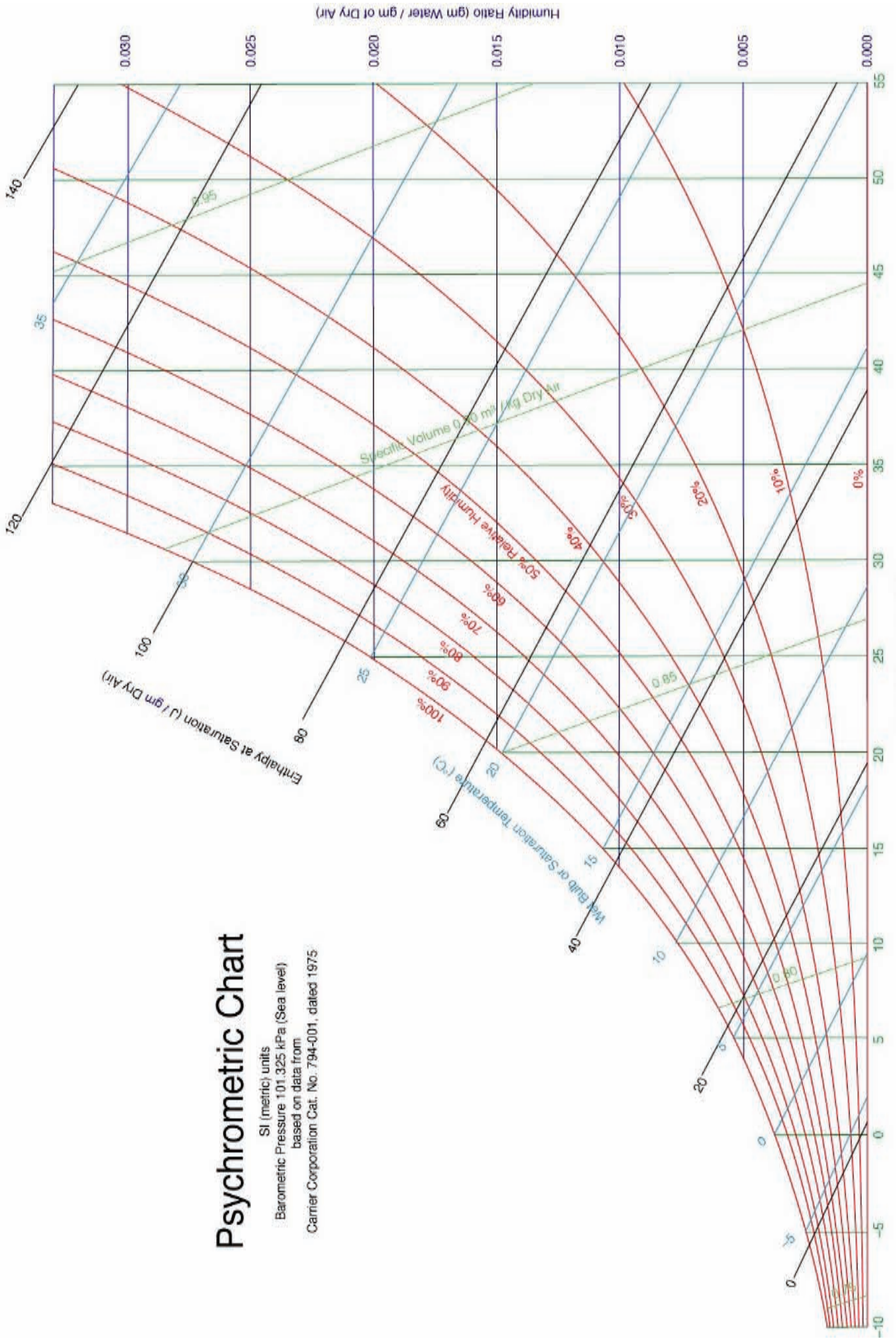


Figure 32: Psychrometric chart

A.3 MOBILE technical details

A.3.1 MOBILE-CVS probabilistic framework

First, we map the CVS vehicle classes to the MOBILE vehicle classes:

$$\{L, M, H\} = \Big\{< 4.5 \text{ tonnes},\ 4.5-15 \text{ tonnes},\ > 15 \text{ tonnes}\Big\} \tag{6}$$

$$L = \Big\{LDV, LDT1, LDT2, LDT3, LGT4\Big\} \tag{7}$$

$$LG = \Big\{LDGV, LDGT1, LDGT2, LDGT3, LDGT4\Big\} \tag{8}$$

$$LD = \Big\{LDDV, LDDT12, LDDT34\Big\} \tag{9}$$

$$M = \Big\{HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7\Big\} \tag{10}$$

$$MG = \Big\{HDGV2b, HDGV3, HDGV4, HDGV5, HDGV6, HDGV7\Big\} \tag{11}$$

$$MD = \Big\{HDDV2b, HDDV3, HDDV4, HDDV5, HDDV6, HDDV7\Big\} \tag{12}$$

$$H = \Big\{HDV8a, HDV8b\Big\} \tag{13}$$

From CSV table 2-1 (Table 20), we get

$$\sum \mathcal{M}(AB, \{LG \cup LD\}, 0) = C(AB, L, 0) = 133386 \tag{14}$$

$$\sum \mathcal{M}(AB, \{LG \cup LD\}, -1) = C(AB, L, -1) = 185464 \tag{15}$$

$$\vdots$$

$$\sum \mathcal{M}(AB, \{LG \cup LD\}, -18) = C(AB, L, -18) = 44221 \tag{16}$$

$$\sum \mathcal{M}(AB, \{LG \cup LD\}, \{-19, \ldots, -25\}) = C(AB, L, -19) = 197194 \tag{17}$$

$$\sum \mathcal{M}(BC, \{LG \cup LD\}, 0) = C(BC, L, 0) = 107727 \tag{18}$$

$$\vdots$$

$$\sum \mathcal{M}(YT, \{LG \cup LD\}, \{-19, \ldots, -25\}) = C(YT, L, -19) = 3703 \tag{19}$$

Table 20: CVS Table 2-1

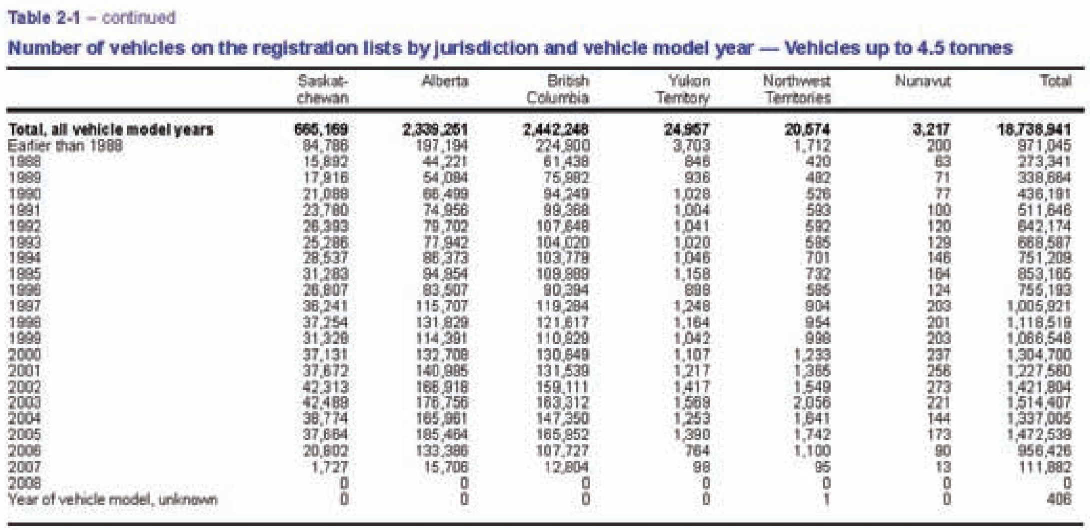


Table 2-1 – continued

Number of vehicles on the registration lists by jurisdiction and vehicle model year — Vehicles up to 4.5 tonnes

	Saskat-chewan	Alberta	British Columbia	Yukon Territory	Northwest Territories	Nunavut	Total
Total, all vehicle model years	**665,169**	**2,339,251**	**2,442,248**	**24,957**	**20,574**	**3,217**	**18,738,941**
Earlier than 1988	84,786	197,194	224,900	3,703	1,712	200	971,045
1988	15,892	44,221	61,438	846	420	63	273,341
1989	17,916	54,084	75,982	936	482	71	338,684
1990	21,088	66,499	94,249	1,028	526	77	436,191
1991	23,780	74,956	99,368	1,004	593	100	511,646
1992	26,393	79,702	107,648	1,041	592	120	642,174
1993	25,286	77,942	104,020	1,020	585	129	668,587
1994	28,537	86,373	103,779	1,046	701	146	751,209
1995	31,283	94,854	109,989	1,158	732	164	853,165
1996	26,807	83,507	90,394	898	585	124	755,193
1997	36,241	115,707	119,284	1,248	904	203	1,005,921
1998	37,254	131,829	121,617	1,164	954	201	1,118,519
1999	31,328	114,391	110,929	1,042	998	203	1,086,548
2000	37,131	132,708	130,849	1,107	1,233	237	1,304,700
2001	37,672	140,985	131,539	1,217	1,365	256	1,227,560
2002	42,313	166,918	159,111	1,417	1,549	273	1,421,804
2003	42,489	176,756	163,312	1,569	2,056	221	1,514,407
2004	38,774	165,961	147,350	1,253	1,641	144	1,337,005
2005	37,664	185,464	165,852	1,390	1,742	173	1,472,539
2006	20,802	133,386	107,727	764	1,100	90	956,426
2007	1,727	15,706	12,804	98	95	13	111,882
2008	0	0	0	0	0	0	0
Year of vehicle model, unknown	0	0	0	0	1	0	406

Table 21: CVS Table 2-2

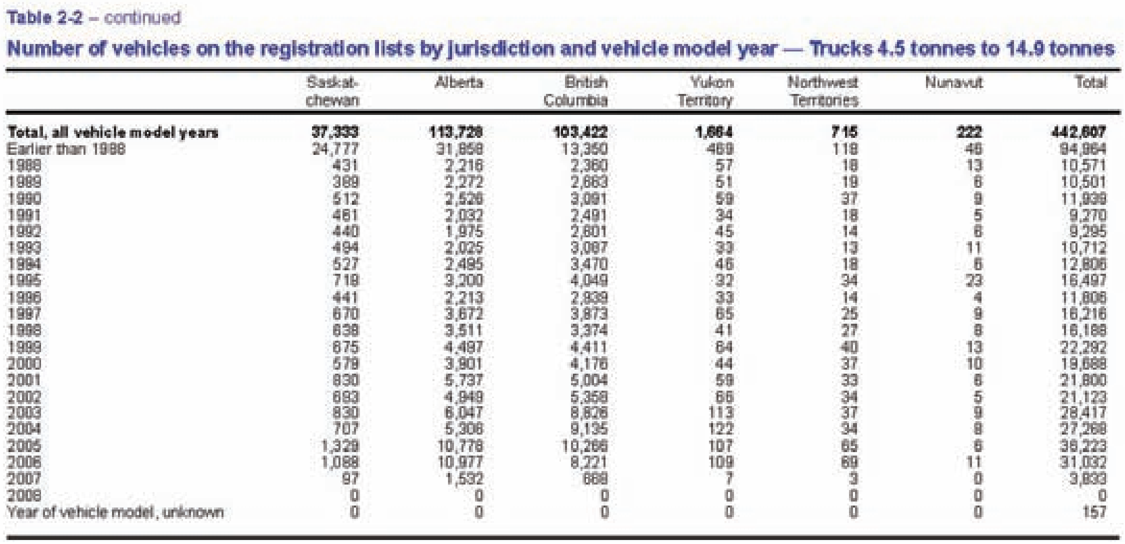


Table 2-2 – continued

Number of vehicles on the registration lists by jurisdiction and vehicle model year — Trucks 4.5 tonnes to 14.9 tonnes

	Saskat-chewan	Alberta	British Columbia	Yukon Territory	Northwest Territories	Nunavut	Total
Total, all vehicle model years	**37,333**	**113,728**	**103,422**	**1,664**	**715**	**222**	**442,607**
Earlier than 1988	24,777	31,858	13,350	469	118	46	94,964
1988	431	2,216	2,360	57	18	13	10,571
1989	389	2,272	2,663	51	19	6	10,501
1990	512	2,528	3,091	59	37	9	11,939
1991	461	2,032	2,491	34	18	5	9,270
1992	440	1,975	2,801	45	14	6	9,295
1993	494	2,025	3,087	33	13	11	10,712
1994	527	2,495	3,470	46	18	6	12,806
1995	718	3,200	4,049	32	34	23	16,497
1996	441	2,213	2,839	33	14	4	11,806
1997	670	3,672	3,873	65	25	9	16,216
1998	638	3,511	3,374	41	27	8	16,188
1999	675	4,497	4,411	64	40	13	22,292
2000	579	3,901	4,176	44	37	10	19,688
2001	830	5,737	5,004	59	33	6	21,800
2002	693	4,949	5,358	66	34	5	21,123
2003	830	6,047	8,826	113	37	9	28,417
2004	707	5,306	9,135	122	34	8	27,268
2005	1,329	10,778	10,266	107	65	6	38,223
2006	1,088	10,977	8,221	109	69	11	31,032
2007	97	1,532	668	7	3	0	3,833
2008	0	0	0	0	0	0	0
Year of vehicle model, unknown	0	0	0	0	0	0	157

Table 22: CVS Table 2-3

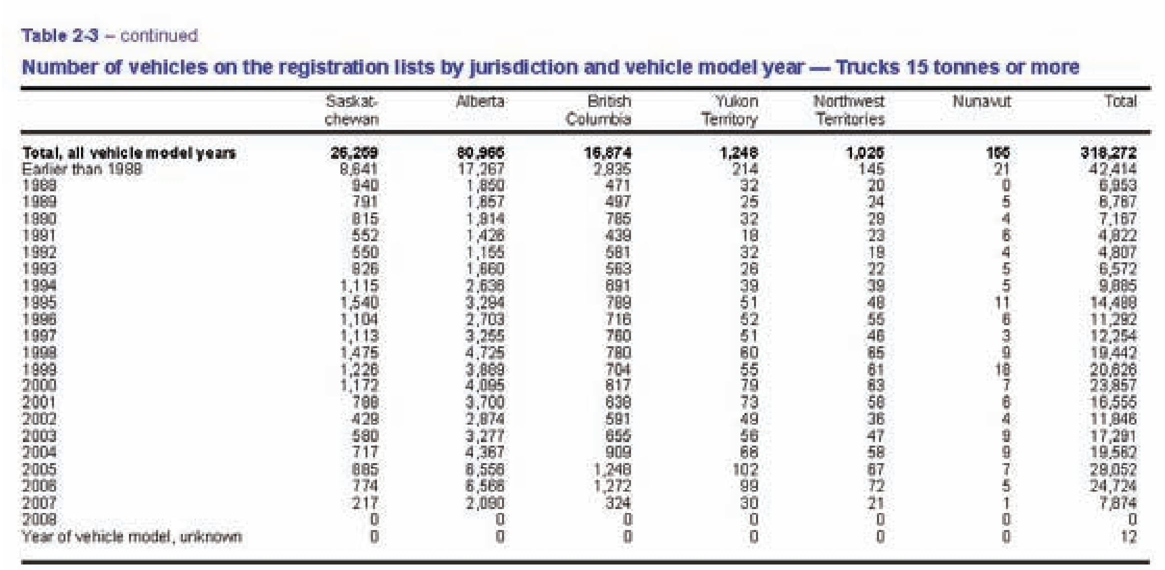


Table 2-3 – continued

Number of vehicles on the registration lists by jurisdiction and vehicle model year — Trucks 15 tonnes or more

	Saskat-chewan	Alberta	British Columbia	Yukon Territory	Northwest Territories	Nunavut	Total
Total, all vehicle model years	**26,259**	**80,966**	**16,874**	**1,248**	**1,026**	**106**	**318,272**
Earlier than 1988	8,641	17,267	2,835	214	145	21	42,414
1988	940	1,850	471	32	20	0	6,953
1989	791	1,857	497	25	24	5	6,767
1990	815	1,914	785	32	29	4	7,167
1991	552	1,426	439	18	23	6	4,822
1992	550	1,155	581	32	19	4	4,807
1993	826	1,860	563	26	22	5	6,572
1994	1,115	2,638	891	39	39	5	9,885
1995	1,540	3,294	789	51	48	11	14,489
1996	1,104	2,703	716	52	55	6	11,292
1997	1,113	3,255	760	51	46	3	12,254
1998	1,475	4,725	780	60	65	9	19,442
1999	1,226	3,869	704	55	61	18	20,626
2000	1,172	4,095	817	79	63	7	23,857
2001	798	3,700	638	73	58	6	16,555
2002	429	2,874	591	49	36	4	11,846
2003	580	3,277	655	56	47	9	17,291
2004	717	4,367	909	66	58	9	19,562
2005	885	8,558	1,248	102	67	7	28,052
2006	774	6,568	1,272	99	72	5	24,724
2007	217	2,090	324	30	21	1	7,874
2008	0	0	0	0	0	0	0
Year of vehicle model, unknown	0	0	0	0	0	0	12

and, similarly, from CVS table 2-2 (Table 21), we get

$$\sum \mathcal{M}(AB, \{MG \cup MD\}, 0) = C(AB,M,0) = 10977 \tag{20}$$

$$\vdots$$

$$\sum \mathcal{M}(AB, \{MG \cup MD\}, \{-19,\ldots,-25\}) = C(YT,M,-19) = 469 \tag{21}$$

and, finally, from CVS table 2-3 (Table 22), we get

$$\sum \mathcal{M}(AB, \{HG \cup HD\}, 0) = C(AB,L,0) = 10977 \tag{22}$$

$$\vdots$$

$$\sum \mathcal{M}(AB, \{HG \cup HD\}, \{-19,\ldots,-25\}) = C(YT,L,-19) = 214 \tag{23}$$

A.3.2 Monte Carlo VKT

We also need estimates for the vehicle-miles-travelled (VMT). Looking at CVS tables 4-1 to 4-4 (see tables 8–10 of this report), we can derive similar equations for VMT as we did above for registrations. There are, however, a few important differences. Whereas before we had sums of random variables equal to a known quantity (TYPE

III in Table 19), we now have sums of random variables equal to another random variable (TYPE IV in Table 19). Also, a conversion factor of 0.621371 miles per kilometre is needed since CVS numbers are reported in kilometres, while MOBILE takes vehicle-miles-travelled as input.

First, we map kilometres travelled by CVS vehicle class to sums by corresponding MOBILE vehicle classes:

$$\mathcal{C}_{LG} = \mathcal{M}_{LDGV} + \mathcal{M}_{LDGT1} + \mathcal{M}_{LDGT2} + \mathcal{M}_{LDGT3} + \mathcal{M}_{LDGT4} \tag{24}$$

$$\mathcal{C}_{LD} = \mathcal{M}_{LDDV} + \mathcal{M}_{LDDT12} + \mathcal{M}_{LDDT34} \tag{25}$$

where

$$\begin{aligned} \mathcal{C}_{L} &= \mathcal{C}_{LG} + \mathcal{C}_{LD} \qquad (26) \\ &= \mathcal{M}_{LDGV} + \mathcal{M}_{LDGT1} + \mathcal{M}_{LDGT2} + \mathcal{M}_{LDGT3} + \mathcal{M}_{LDGT4} \qquad (27) \\ &\quad + \mathcal{M}_{LDDV} + \mathcal{M}_{LDDT12} + \mathcal{M}_{LDDT34} \qquad (28) \end{aligned}$$

From CVS table 4-1 (Table 8), we get

$$\sum \mathcal{M}(AB, \{LG \cup LD\}, \{0, -25\}) = 0.621371\ C(AB, L) \sim \mathrm{N}(38375.4, 3799.16) \tag{29}$$

$$\sum \mathcal{M}(AB, \{MG \cup MD\}, \{0, -25\}) = 0.621371\ C(AB, M) \sim \mathrm{N}(2145.0, 319.605) \tag{30}$$

$$\sum \mathcal{M}(AB, \{HG \cup HD\}, \{0, -25\}) = 0.621371\ C(AB, H) \sim \mathrm{N}(4975.5, 492.575) \tag{31}$$

$$\sum \mathcal{M}(BC, \{LG \cup LD\}, \{0, -25\}) = 0.621371\ C(BC, L) \sim \mathrm{N}(29730.3, 2943.3) \tag{32}$$

$$\vdots$$

$$\sum \mathcal{M}(YT, \{HG \cup HD\}, \{0, -25\}) = 0.621371 C(YT, H) \sim \mathrm{N}(109.7, 16.3453) \tag{33}$$

and, similarly, from CVS table 4-2 (Table 9), we get

$$\sum \mathcal{M}(\{AB, ..., YT\}, \{LG, LD\}, \{0, -1, -2\}) = 0.621\ C(\{AB, ..., YT\}, L, <3) \sim \mathrm{N}(58785, 5819) \tag{34}$$

$$\sum \mathcal{M}(\{AB, ..., YT\}, \{LG, LD\}, \{-3, -4, -5\}) = 0.621\ C(\{AB, ..., YT\}, L, 3-5) \sim \mathrm{N}(83066, 4070) \tag{35}$$

$$\vdots$$

$$\sum \mathcal{M}(\{AB, ..., YT\}, \{HG, HD\}, \{-15, ..., -25\}) = 0.621\ C(\{AB, ..., YT\}, H, >14) \sim \mathrm{N}(1079, 214) \tag{36}$$

For CVS light-duty vehicles up to 4.5 tonnes,

$$\begin{array}{cr}
\mathcal{M}^{AB}_{LDV} + \mathcal{M}^{AB}_{LDT1} + \mathcal{M}^{AB}_{LDT2} + \mathcal{M}^{AB}_{LDT3} + \mathcal{M}^{AB}_{LDT4} = C^{AB}_{L} & (37) \\
\mathcal{M}^{BC}_{LDV} + \mathcal{M}^{BC}_{LDT1} + \mathcal{M}^{BC}_{LDT2} + \mathcal{M}^{BC}_{LDT3} + \mathcal{M}^{BC}_{LDT4} = C^{BC}_{L} & (38) \\
\vdots & \\
\mathcal{M}^{YT}_{LDV} + \mathcal{M}^{YT}_{LDT1} + \mathcal{M}^{YT}_{LDT2} + \mathcal{M}^{YT}_{LDT3} + \mathcal{M}^{YT}_{LDT4} = C^{YT}_{L} & (39) \\
\cline{1-1}
\mathcal{M}_{LDV} + \mathcal{M}_{LDT1} + \mathcal{M}_{LDT2} + \mathcal{M}_{LDT3} + \mathcal{M}_{LDT4} = C_{L} & (40)
\end{array}$$

For CVS medium-duty vehicles (4.5–15 tonnes),

$$\begin{array}{cr}
\mathcal{M}^{AB}_{HDV2b} + \mathcal{M}^{AB}_{HDV3} + \mathcal{M}^{AB}_{HDV4} + \mathcal{M}^{AB}_{HDV5} + \mathcal{M}^{AB}_{HDV6} + \mathcal{M}^{AB}_{HDV7} = C^{AB}_{M} & (41) \\
\mathcal{M}^{BC}_{HDV2b} + \mathcal{M}^{BC}_{HDV3} + \mathcal{M}^{BC}_{HDV4} + \mathcal{M}^{BC}_{HDV5} + \mathcal{M}^{BC}_{HDV6} + \mathcal{M}^{BC}_{HDV7} = C^{BC}_{M} & (42) \\
\vdots & \\
\mathcal{M}^{YT}_{HDV2b} + \mathcal{M}^{YT}_{HDV3} + \mathcal{M}^{YT}_{HDV4} + \mathcal{M}^{YT}_{HDV5} + \mathcal{M}^{YT}_{HDV6} + \mathcal{M}^{YT}_{HDV7} = C^{YT}_{M} & (43) \\
\cline{1-1}
\mathcal{M}_{HDV2b} + \mathcal{M}_{HDV3} + \mathcal{M}_{HDV4} + \mathcal{M}_{HDV5} + \mathcal{M}_{HDV6} + \mathcal{M}_{HDV7} = C_{M} & (44)
\end{array}$$

For CVS heavy-duty vehicles (>15 tonnes),

$$\begin{array}{cr}
\mathcal{M}^{AB}_{HDV8a} + \mathcal{M}^{AB}_{HDV8b} = C^{AB}_{H} & (45) \\
\mathcal{M}^{BC}_{HDV8a} + \mathcal{M}^{BC}_{HDV8b} = C^{BC}_{H} & (46) \\
\vdots & \\
\mathcal{M}^{YT}_{HDV8a} + \mathcal{M}^{YT}_{HDV8b} = C^{YT}_{H} & (47) \\
\cline{1-1}
\mathcal{M}_{HDV8a} + \mathcal{M}_{HDV8b} = C_{H} & (48)
\end{array}$$

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