Estimating volumes of air through various engines in an urban setting

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Submitted to CMOS Bulletin SCMO (www.cmos.ca) April 21, 2006

Abstract

Volumes of air used by various engines are estimated then compared against daily air requirements of 9,700 litres for an average human. Typical truck, SUV and compact car engines during one hour of operation require about the same volume of air that 111, 40 and 29 people need for breathing during one day respectively. An airplane taking-off and landing requires the volume of air that about 8,000 people need for one day.

Using estimates of numbers of engines representative of a summer day on Montreal island, total air consumption volumes are calculated. The large number of combustion engines makes them the consumers of the largest volumes of air. All engines operating during one day consume about 3.1E+12 litres of air or about 175 times the daily air requirements for breathing by Montréal's 1.8+ million people.

Air volume data may help create personal air consumption footprint calculators or vehicle tachometer displays that tell the driver how much air is used when driving. Governments could develop pollutant management plans that include coupling local exhaust volume production with forecast volumes of fresh air necessary for diluting exhaust in order to clarify which polluting activities should be curtailed on poor air quality days.

Clean air exchange mechanisms similar to CO_2 trading could be established locally and globally to internalize into the marketplace the costs of air pollution from engines.

Introduction

Many air quality models parameterize net weights or volumes of pollutants dispersed into the environment. Here it is the volume of air passing through various engines which is estimated and packaged in familiar terms for the public.

First a reference volume of air is defined as the volume one average human needs for breathing during 24 hours. This volume of approximately 9,700 litres/human called here one human-day (hum-day) is derived using an inhaled volume of 0.5 litre per breath x 13.5 breaths/minute x 60 minutes/hour x 24 hours/day (Lough, 1983). 40 hum-days of air is the volume 40 people need for breathing for one day.

Similarly, 1 population-day (pop-day) of air is the volume obtained by multiplying 1 hum-day by the number of people in a population. In this study, the population of the island of Montréal in 2001 is used making 1 pop-day equal to 1,812,723 people x 9,700 L/person = 1.76E+10 litres. 100 pop-days of air is 100 times the volume of air required for breathing during one day by Montréal’s population.

These reference volumes of air will be used later to help present air volume information in terms the public can more easily relate and as a result may assist in better engaging the public in air pollution prevention activities.

Estimating combustion engine air consumption volumes

Volumes of air passing through combustion engines are estimated using the engine cylinder's displacement in litres (L) x engine rpm x number of minutes of operation.

A 2-stroke engine with displacement of 50 cc (0.050 L) operating for 30 minutes at 5000 rpm is estimated to consume 0.05 L x 5000 rpm x 30 minutes = 67,500 litres.

4-stroke combustion engine calculations require the rpm be divided by two since air is exhausted from the cylinders every second revolution (Association canadienne des automobilistes, 1983). A 4-stroke engine with one litre displacement operating for 60 minutes at 2500 rpm is estimated to consume 1 L x 2500**/2** rpm x 60 minutes/hour = 75,000 litres of air.

These volumes of air "consumed" by engines also serve as estimates of initial volumes of undiluted engine exhaust.

Cylinder volumes, or displacements, of various combustion engines are listed in column 1 of table 1 for a variety of engines. 2-stroke engine sizes were obtained by noting those available in local hardware stores. 4-stroke displacements were obtained from the many vehicle related advertisements and articles in Montreal's The Gazette newspaper (The Gazette, 2004, 2005).

Table 1

Air volume consumption information for combustion engines

Engine Type	(1) Cylinder Displacement Litres	(2) rpm	(3) Operating Time (min)	(4) Air volumes Consumed (L)	(5) hum-days of air per hour
2-stroke					
Lawn mower	.05	5000	30	7500	1.4
Hedger	.02	5000	30	3000	0.6
Chainsaw	.04	5000	30	6000	1.2
Jet ski	1.1	4000	30	130000	27
4-stroke					
LOCAL					
Smart car	0.8	3000	60	72000	7
Compact car	3.1	3000	60	280000	29
SUV	4.3	3000	60	390000	40
School bus	6.6	3000	60	600000	61
Truck	12.0	3000	60	1100000	111
Truck Constr	12.0	3000	60	1100000	111
HIGHWAY					
Compact car	3.1	2500	60	230000	24
SUV	4.3	2500	60	320000	33
Truck	12.0	2500	60	900000	93

4-stroke engines were considered either local or highway vehicles and assigned rpm values of 3000 and 2500 respectively. Local vehicles remained in the city while highway vehicles traveled through the city on a main highway.

The goal to calculate a volume of air passing through engines to become undiluted exhaust, assumes consumed air is not re-used by any other engine. It is also assumed that consumed air becomes tainted with combustion fumes and would be unfit for humans to breathe. For this calculation however, exhaust volumes are not diluted further with ambient air. Diluting exhaust with additional fresh air would likely increase significantly the volumes of air impacted by engines than volumes proposed here.

Airflow through an airplane engine is also estimated.

The Airbus A320 airplane was considered representative of the majority of planes flying in and out of Pierre Elliot Trudeau International Airport in Montréal where there are about 250 daily take-offs and landings (Isaac, 2005).

Operating characteristics of the Airbus A320 CFM56-5A1 turbo fan engines were provided by http://www.flybernhard.de and from personal communication with an airline pilot. Estimates of airflow were obtained from NASA’s engine simulator website http://www.grc.nasa.gov/WWW/K-12/airplane/ngnsim.html using configuration information in table 2 and verified with the site’s owner (Benson, Thomas, email communication, 2005).

Table 2

Configuration and air volume consumption data for Airbus A320 airplane

Process	Throttle (%)	Speed km/h	Core Airflow kg/s	Rate (L)/s	Minutes	Air Volume consumed (L)	hum-days for 2 engines
During Take-Off							
Terminal	40	0	.009	7	30	1.5E+07	1546
Taxiing	55	10	22.53	18000	5	5.3E+06	546
Runway	90	285	34.2	27000	1	1.6E+06	165
During Landing							
Landing	60	217	34	26000	15	3.2E+06	330
Taxiing	55	10	22.53	18000	5	5.3E+06	546
Terminal	40	0	.009	7	15	7.6+E06	784

					Total:	3.8E+07 (L)	

Large volumes of air are used by the plane’s engines during idling of engines while waiting at the terminal and taxiing to and from the runway.

Comparing air consumption volumes for various engines

Table 3 presents the summary of engine air consumptions.

Column (2) lists air consumption volumes for individual engines (except for 2 engines in the case of the Airbus) during the associated operating period in column (3).

Table 3

Summary air consumption volume estimates for various engines

(1) Category	(2) Consumption Of air (L)	(3) Units	(4) Number hum-day (2)/9700	(5) Total number in city	(6) Total daily consumption (L)/category	(7) Number pop-days per day
1 Person	**9.7E+03**	**(L)/day**	**1.0**	**1812723**	**1.76E+10**	**1.0**
2-stroke						
1 Mower	7.5E+03	(L)/0.5 hr	.77	443947	3.3E+09	0.2
1 Hedger	3.0E+03	(L)/0.5 hr	.31	443947	1.3E+09	0.1
1 Chainsaw	6.0E+03	(L)/0.5 hr	.62	88789	5.3E+08	.03
1 Jet ski	1.3E+05	(L)/0.5 hr	13.6	1421	1.9E+08	.01
4-stroke						
Local						
Efficient	7.2E+04	(L)/hour	7	1776	1.3E+08	0.01
Compact	2.8E+05	(L)/hour	**29**	1065473	3.0E+11	17
SUV	3.9E+05	(L)/hour	**40**	710315	2.8E+11	16
School bus	6.0E+05	(L)/hour	**61**	500	1.8E+09	0.1
Truck	1.1E+06	(L)/hour	**111**	266368	2.3E+12	131
Truck Constr	1.1E+06	(L)/hour	**111**	10000	8.6E+10	5
Highway						
Compact	2.3E+05	(L)/.75 hr	24	100000	1.7E+10	1
SUV	3.2E+05	(L)/.75 hr	**33**	90000	2.2E+10	1.2
Truck	9.0E+05	(L)/.75 hr	**93**	70000	4.7E+10	2.7
Airplane A320						
Take-off	4.4E+07	(L)	**4600**	250	1.1E+10	.63
Landing	3.2E+07	(L)	**3400**	250	8.0E+09	.45
				Total:	**3.1E+12 L**	**175**

Column (4) presents volumes of column (2) as multiples of hum-days of air.

Individual airplane engines consume the largest volumes of air requiring, per pair of engines, an estimated 8,000 hum-day of air from each combination of take-off and landing.

For combustion engines, a local truck consumes approximately 111 hum-days of air per hour of operation. A highway truck using a lower rpm value and shorter transit time consumes approximately 93 hum-day of air per truck. Local school buses, SUVs and compact cars used 61, 40 and 29 hum-day of air per hour respectively. Jet skis, lawn mowers, chainsaws and hedgers consumed 27, 1.5, 1.2, 0.6 hum-days of air per hour respectively.

Estimating total engine air consumption volumes for Montréal

Table 3 data can be used to model total air consumption volumes for an urban area. A preliminary scenario is presented here to demonstrate the concept. There is interest in obtaining higher quality data from various municipal databases to feed into this model.

Column (5) of table 3 presents preliminary estimates of the total number of each engine type for the island of Montréal. For most engine types, multiplying the number of engines in column (5) by the corresponding air consumption rates in column (2) provides estimates of total volumes of air consumed, per day, by engine category. In the case of local trucks and school buses, those engines were operated for 8 and 6 hours per day respectively. Total air consumption volumes per day are shown in column (6).

The sum of numbers in column (6) represents the total volume of air consumed by all engines during one day, i.e. 3.1E+12 litres. This total also estimates the volume of undiluted exhaust produced by all engines here for a one day period.

Trucks, compact cars, SUVs and airplanes are responsible for about 75%, 10%, 9% and 0.7% of the exhaust produced during a one day period respectively. Truck engines produce the largest volumes of exhaust air.

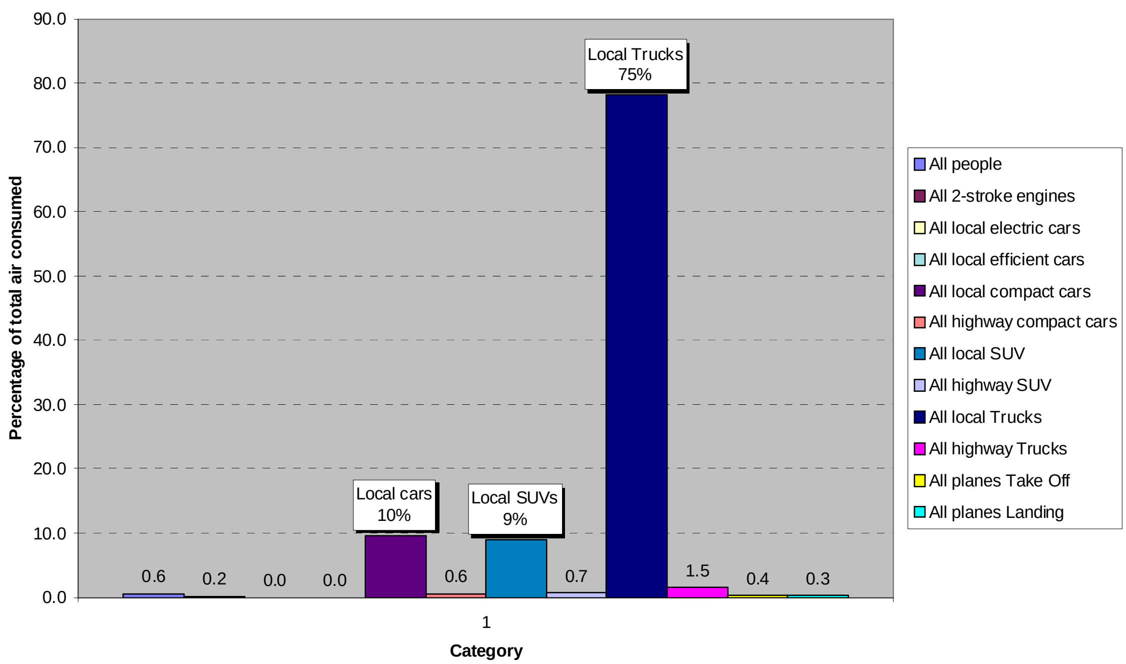

Figure 1: Percentage of total air volume consumed by engine category per day. Trucks consume the most air and a s a result produce most of the exhaust per day.

The number of pop-days of air for each engine category is shown in column (7) and was obtained by dividing values of column (6) by the number of litres in 1 pop-day.

All trucks combined use approximately 139 pop-days of air per day. SUVs and cars combined use about 35 pop-days of air per day. Airplane engines use about 1 pop-day of air per day. All 2-stroke engines use just over 0.3 pop-day of air per day.

Though airplane engines individually consume the most air per engine, trucks and passenger vehicles as a group use far more air than all airplane engines combined.

In total, all engines combined use about 175 pop-days of air per day, i.e. 175 times the volume of air required by Montreal’s population for a 1 day period.

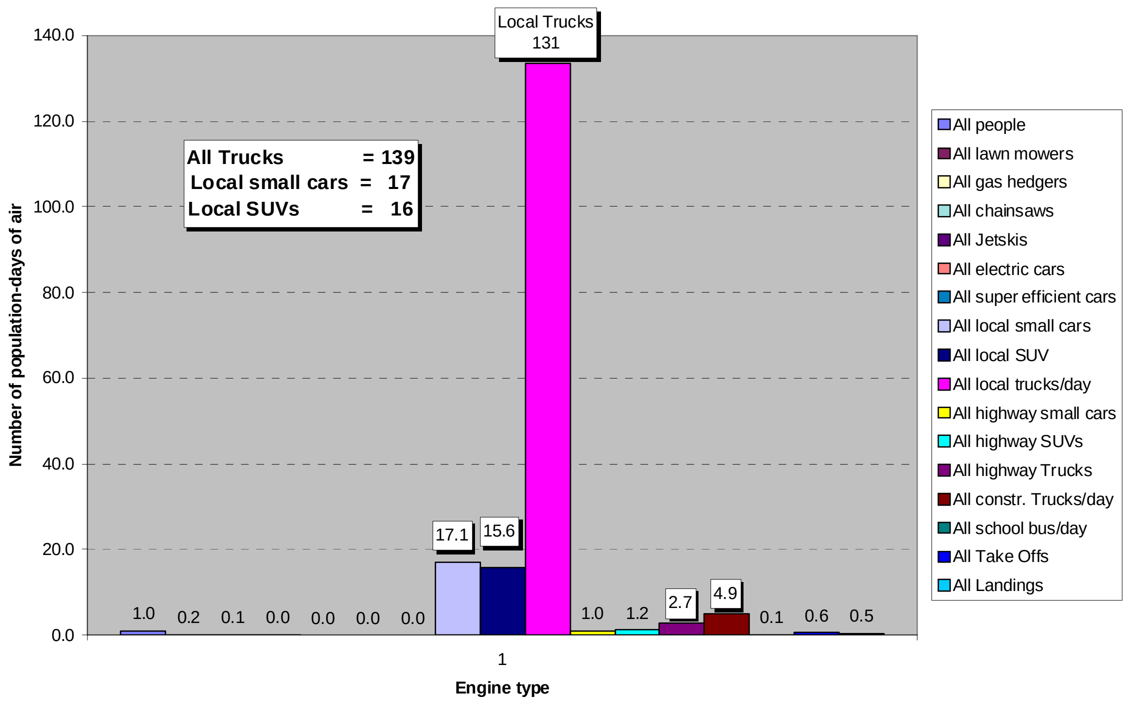

Figure 2: Air consumption volume per engine category expressed as number of population-days of air. All trucks combined produce about 139 pop-days worth of exhaust air.

Air volume consumption data helps highlight producers of large volumes of exhaust and may assist justifying restrictions on certain activities during smog alert days as a way to more effectively prevent air pollution and protect the public’s health.

Air consumption in stagnant air under a summertime ridge

How quickly would a volume of air get converted into exhaust by engines operating under a stagnant high pressure ridge typical of summertime conditions conducive to smog?

First a reference supply of stagnant air is defined as the volume within the boundary layer 1.0 km high over the 500 km^2 area of Montreal island giving a volume of 5.0E+14 litres.

If the city’s engines produce 3.1E+12 litres of undiluted exhaust per day and assuming engines use only clean air at input, it would take about 160 days for all engines to have converted the stagnant boundary layer air into undiluted engine exhaust.

It’s important to remember vehicle exhaust should be diluted prior to humans breathing it and for this reason the volume of fresh air used to dilute exhaust should be considered as air impacted or required by engines. Using a first order approximation of diluting each litre of exhaust into 1000 litres of fresh air suggests engines require [1.31E+12 litres exhaust + 1.31E15 litres of fresh air] per day. Thus when dilution is considered and fresh air considered necessary then engines effectively consume the reference volume of air in 5E+14/3.1E+15 = 0.16 days.

This back of the envelope calculation highlights the volumes of exhaust engines produce and how critically important a source of fresh air is to dilute the exhaust down to safer levels for breathing.

The concept demonstrates the importance of a source of fresh air in the process of exhaust management. Guidelines may be required to help communities pro-actively manage their exhaust producing activities when stagnant weather systems prevent enough fresh air from diluting the exhaust to safe enough levels for humans.

Information such as volume of readily available fresh air for dilution or the number of days to full local air consumption by engines may offer greater tools and incentives to governments for discouraging behaviours that pollute the local air supply especially in stagnant air scenarios.

Public education tools promoting air consumption awareness

Since education is often a preferred approach by governments to encourage environmentally sustainable practices, air volume consumption awareness may be an effective tool.

A web page could allow the calculation of one's air volume consumption "footprint". Users could provide information such as car engine size, driving times, small engines used at home, area of lawn, number of trees, etc. A net balance of air consumed can be calculated and displayed as shown in figures 3.1 and 3.2

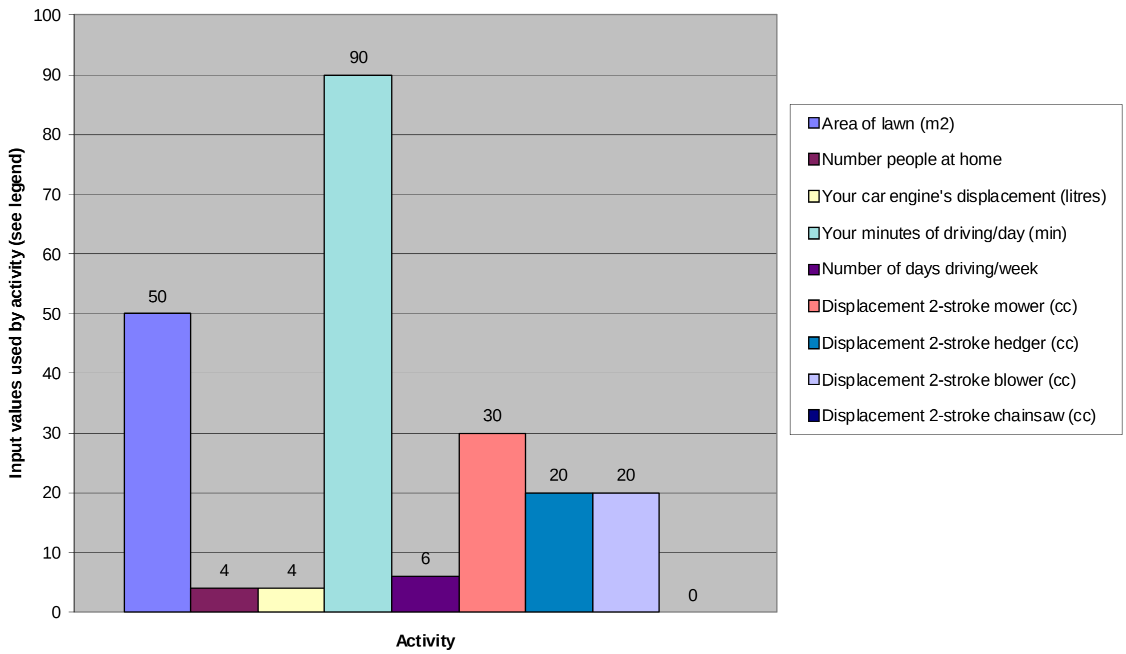

Figure 3.1: Sample input parameters for air volume consumption “footprint” calculations. Net air consumptions calculated using these parameters are shown in figure 3.2

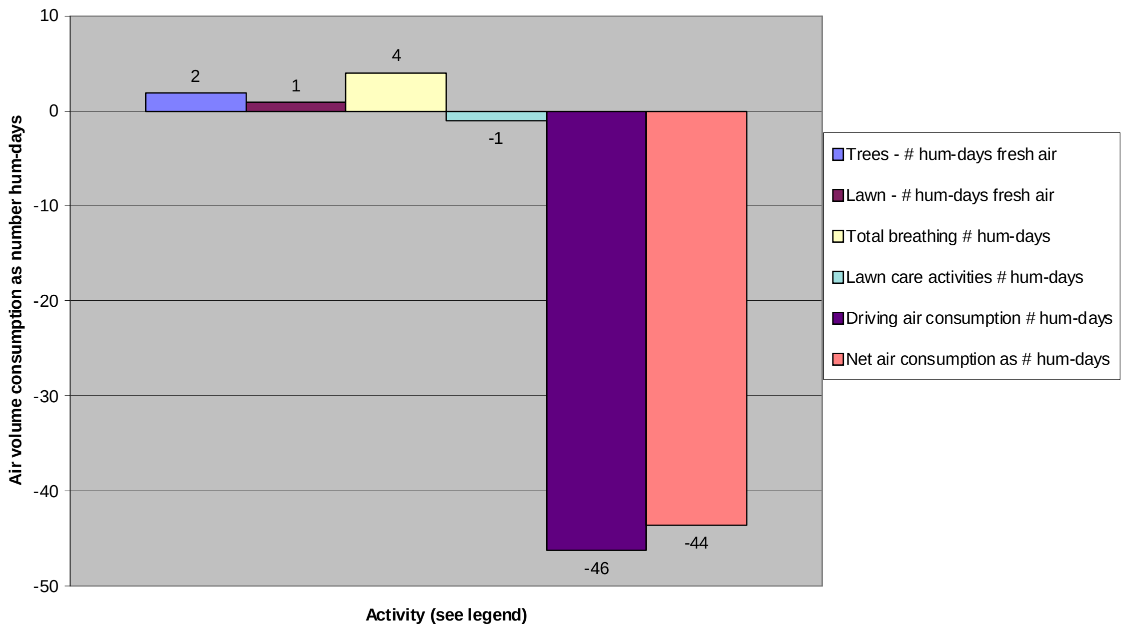

Figure 3.2: Sample estimates of air production & consumption volumes as number of hum-days per activity per day based on input parameters of figure 3.1. Positive (negative) values indicate volumes of fresh (tainted) air produced.

Air consumption footprint calculations could assist in rationalizing and personalizing the need to practice less polluting behaviour. It is important to realize especially on poor air quality days, that for each hour of not driving one’s car, the air that could be used by more than 30 people to breathe during one day will not be converted into engine exhaust.

Air consumption footprint calculations could be undertaken for city or regional areas using their own local vehicle databases. Knowing how many litres of air per day are locally consumed and tainted allows communities to more clearly set pollution reduction objectives and develop a locally owned and operated air quality management plans. This plan could include an exhaust avoidance approach which prevents certain engines creating exhaust on those days when there is not enough fresh air to dilute the exhaust to safe levels for breathing.

Air volume consumption information could also be added to vehicle dashboard tachometers to remind drivers of the number of hum-days of air consumed and exhaust produced while driving. A sample tachometer is shown in figure 4.

Figure 4: A tachometer displaying the number of human-days of air consumed by a 3.5 L engine as a function of rpm. Driving at 2000 rpm for one hour uses 22 hum-days of air through the engine and converts that air into exhaust.

Local trading systems to internalize costs of air pollution

Progressive taxation tools are becoming more common to encourage resource conservation and pollution prevention.

Some municipalities are charging citizens for disposing of garbage volumes produced above a certain limit like 2 bags per week. Water meters are used to encourage water conservation in a user-pay system.

There are precedents in the Canadian Environmental Protection Act allowing for companies to track volumes of exhaust pollutants so they can manage exhaust volumes over a period of time to attain clean air targets for their fleet of vehicles (Canada Gazette, 2003)

Air volume consumption information could be used as a basis for internalizing the cost of air pollution into our economic system. Should one's activities impact on more than an allocated volume of air, users could pay a pre-determined "polluting" fee, or trade, barter or buy volumes of available clean air from others whose activities and lifestyles do not consume as much air.

User fees that more clearly account for the air used in combustion could be incorporated into the price of liquid fuels. For example a vehicle with a 3.5 L engine operating at 2500 rpm, with a gas mileage of 10 L/100km and taking one hour to travel 100 km would convert (3.5 L x 2500 rpm / 2 x 60 minutes) 262,500 litres of fresh air into exhaust. Dividing by 10, this translates into 26,250 litres of air converted into exhaust per litre of gasoline consumed.

The price of gasoline could also be made to vary in a manner that is inversely proportional to the forecast availability of fresh air, i.e. gas prices could increase (decrease) when the fresh air necessary for diluting exhaust decreases (increases). Wind mileage information like that presented in figure 5 could be used to help price fuels in a manner that reflects the atmosphere’s ability to effectively dilute the pollution.

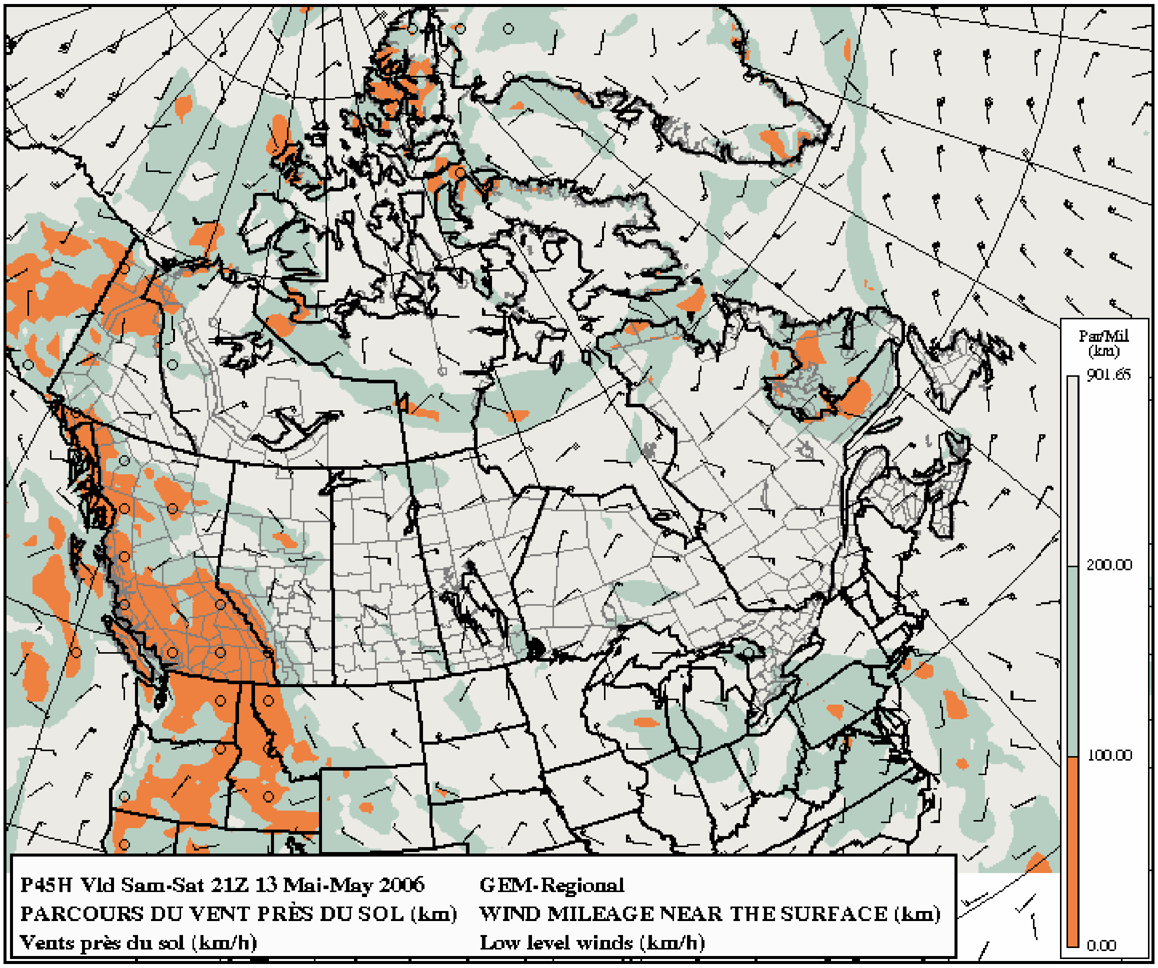

Figure 5: A sample wind mileage forecast map showing an approximation of the distance a parcel of air would travel during the day if moved by the wind. Air quality suffers in areas with low wind mileage values should these areas become polluted. Mileage maps are available on www.weatheroffice.ec.gc.ca via the Air Quality Forecasts page.

Then concept of clean air trading could also be applied internationally. Developed countries with their large numbers of operating engines could pay countries with few or no engines as a way to purchase from developing countries the right to pollute the air we all share globally. This provides incentives for polluting countries to reduce their polluting sources and rewards developing countries for practicing sustainable development not based on combustion engines. This market-economy approach could assist in reducing the exchange of trans-border pollutants. Market mechanisms such as these are already being used to help reduce production of CO_2 globally.

Conclusion

A ventilation-based accounting of the volumes of exhaust air passing through or consumed by urban engines is presented.

Volumes of fresh air converted into engine exhaust are provided using engine cylinder displacement (L) x rpm[/2] x minutes of operation. The method provides data that could be used for public awareness and economic tools to help internalize, into the marketplace, the cost of air pollution from combustion engines.

For combustion engines, a truck consumes the most air requiring 111 hum-days per hour. Local school buses, SUVs and compact cars consumed 61, 40 and 29 hum-days of air per hour respectively. Smaller engines like jet skis, lawn mowers, chainsaws and hedgers consumed 27, 1.6, 1.2, 0.6 hum-day of air per hour respectively.

Using estimates numbers of engines on Montreal island, engines consume approximately 3.10E+12 litres of air per day which represents about 175 times the volume of air required for breathing by the 1.8+ million people during a 24 hour period.

Under a stagnant ridge of high pressure it is estimated it all engines would convert the clean air in the 1 km boundary layer into undiluted exhaust in about 160 days. If however, each litre of exhaust is diluted with 1000 additional litres of fresh air, the air in the boundary layer effectively becomes consumed in less than 1 day as a result.

Air consumption information allows for new types of air quality related education tools. A web interface could help users calculate air consumption footprints. Tachometers in vehicles could remind drivers of how many hum-days of air are being converted into exhaust while they drive. “What if” scenarios can help individuals and governments evaluate the impact on air consumption of proposed lifestyle changes.

Local clean air trading systems based on the concept of air volume consumption could allow those requiring larger volumes of air to pay for the air they need. Such user-pay systems could be established locally and globally.

Future work includes expanding the list of consumers of air, adding volumetric contributions from post-engine processes such as smog and roadway generated particulates, determining proper exhaust dilution factors and packaging information so as to allow a variety of users to run their own air volume scenarios.

An easy to use and user friendly mechanism that quantifies how we use the air in our daily lives could help internalize exhaust management into our economic system. Action on this front is necessary in order to prevent the “tragedy of the commons” as applied to the essential resource that is our shared atmosphere.

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Acknowledgements

The author, while not an expert in air quality chemistry, became interested in air volume consumption during his daily walks to and from work. A preliminary poster on air consumption volumes was presented at the Canadian Meteorological and Oceanographic Society (CMOS) conference in Vancouver of June 2005. That poster data was further consolidated into this publication. Comments from various CMC colleagues, in particular Richard Hogue, and from the editor of the CMOS Bulletin SCMO were very helpful at improving the publication. The author thanks his family for assisting in the development of these concepts.