CIRRELT

Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

Untangling the Impacts of Various Factors on Emission Levels of Light Duty Gasoline Vehicles

Pegah Nouri
Catherine Morency

October 2015

CIRRELT-2015-53

Bureaux de Montréal :
Université de Montréal
Pavillon André-Aisenstadt
C.P. 6128, succursale Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince
2325, de la Terrasse, bureau 2642
Québec (Québec)
Canada G1V 0A6
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

Untangling the Impacts of Various Factors on Emission Levels of Light Duty Gasoline Vehicles

Pegah Nouri[1,*], Catherine Morency[1,2]

[1] Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, P.O. Box 6079, Station Centre-ville, Montréal, Canada H3C 3A7

[2] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

Abstract. In the last decade, climate change has become one of the major environmental issues. The reduction of greenhouse gas emission as the main contributor in climate change is now more and more critical. Therefore, precise and reliable emission estimation models are necessary to help evaluate the impacts of future projects, strategies, and policies. This increasing pressure has made the emission models more sophisticated than ever. At the same time, it is essential to understand how different variables affect emission and basically how emission models (such as MOVES) work. This study discusses and compares the contribution of each emission factor based on the available theoretical models for a light duty spark ignition gasoline engine. Since the models used in this paper are among the most precise and cited emission estimators which are based on redundant data, we focused on comparison of the factors rather than revalidation. In the first step of the analysis, the impact of each variable is calculated for a 1-kilometer trip. This is followed by an analysis for typical work-home trip. The major results of this study indicate that for a specific vehicle, the temperature has the highest contribution in vehicle's emission. The cold start excess emission can double the total emission in very cold temperature (-40°C), all things being equal. Increasing the vehicle's frontal area or road pavement can also become more significant than driving behavior (smooth vs. aggressive).

Keywords: CO2 emission, fuel consumption, emission factors.

Acknowledgements. The authors wish to acknowledge the contribution and financial support of the four partners of the Mobilite research Chair: City of Montreal, Quebec Ministry of transportation, Montreal metropolitan agency and the Montreal transit authority.

---

* Corresponding author: pegah.nouri@polymtl.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec
Bibliothèque et Archives Canada, 2015

INTRODUCTION

Roadway activities in North America are the primary source of GHGs, and are responsible for about 30% of greenhouse gases which half of it is produced by private vehicles [1, 2]. The vehicle emissions are divided in three categories: tailpipe emissions, evaporative emissions, and lifetime emissions [2]. The tailpipe emissions refer to the gases which are emitted while the engine is operating. The major gases from tailpipe emissions are hydrocarbons, nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) which are all considered as GHGs. In this paper we are focusing on the tailpipe CO_2 emission from gasoline light duty vehicles.

There are extensive studies on vehicles' emissions or fuel consumption; however, most of these studies are focused on one variable or a group of variables that affect emissions; therefore, it is hard to compare the magnitude of influence of each variable. In this study we try to integrate the main results of studies conducted on each of these variables and compare their influence on CO_2 emission, which can provide a good understanding of their impact.

The main contribution of this research is to explore the redundant studies on emission estimation and provide a simple approach to compare various emission factors. The result will offer a clear image of sensitivity of vehicle's emission to each of these factors.

This paper is organised as follows. First section covers some of the main studies on emission estimation and emission factors. In the second section, based on the models provided in the literature, the impact of each emission factor will be analyzed in two steps: for 1-kilometer trip with constant speed, and for a real world, regular home-work commuting trip. At the end, some application of the results will be explained.

BACKGROUND

The amount and composition of the vehicles' exhaust emissions depends on various factors. These factors are generally identified in five main categories:

1) Vehicle emission control level such as vehicle type and fuel type [2, 3];
2) Utilization parameter such as accumulated mileage; and inspection and maintenance [2];
3) Operating modes like speed, acceleration/deceleration, fraction of cold/hot starts, air conditioning, and road grade [2];
4) Ambient parameters such as temperature and humidity [2, 4];
5) Transportation system such as pavement texture [5].

Fuel type

The fuel type can change the exhaust greenhouse gas emission rate regardless of the vehicle and road characteristics based on its chemical components. As well said "*what goes in the vehicle will come out*" [6], therefore the content of the fuel directly influences the composition of the gases coming out of the exhaust.

Gasoline is the most common fuel used in North America and diesel takes the second position. Diesel engines have more efficient thermodynamics comparing to gasoline vehicles. Normally, the power of the diesel engines is 1.5 to 3 times more important than gasoline engines [7]. Specifically in North America, an average C-class gasoline vehicle produces about 43% more CO_2 in comparison with the same diesel vehicle [8]. Numbers are provided in Table 1.

Table 1: Average CO_2 emission rates for 2001 model year Gasoline and Diesel C-class Vehicles [8]

		Fuel consumption [L/100km]	CO_2 emission [g CO_2/km]
North America	Gasoline	9.3	220
	Diesel	5.8	154
Germany	Gasoline	9.0	213
	Diesel	5.9	156

The CO_2 emission of the gasoline and diesel are usually calculated based on the fuel consumption using Equation 1 and Equation 2 [8].

$$[CO_2]_d = 26.5 \times FC_d \quad \text{Equation 1}$$

$$[CO_2]_g = 23.6 \times FC_g \quad \text{Equation 2}$$

The subscript d and g denote diesel and gasoline, respectively; also FC is the fuel consumption rate in litre per 100 kilometers. However, as mentioned, in this study we are solely focusing on gasoline spark ignition engines.

Vehicle Type

The vehicle specification can have significant influence on the fuel consumption and therefore CO_2 emission. These specifications range from physical characteristics such as mass, shape, and size of the vehicle to combustion technology, size and torque of the engine. Any change in each of these characteristics can influence the vehicles' emissions considerably. For instance the 2013 Ford fusion with 1.6 L and 2.5 L engines (both 4 cylinders) consume 8.0/5.3 and 9.2/5.8 (L/100km; city/highway) respectively.

To emphasize how the type of car can affect emissions, we can compare two extreme 2012-vehicles. On one side, the most fuel-efficient 2012 gasoline vehicle in all classes in Canada is the Toyota Prius with 3.5 L/100km fuel consumption rate in the city. On the other side, the Bugatti Veyron consumes 26.1 L/100km which is about 7.5 times more than the Prius [9]. This explains the sensitivity of the fleet characteristics in determining the total fuel consumption and related CO_2 emission.

Vehicles with smaller engine size can reduce emissions significantly. There is a linear correlation between engine capacity and idle fuel consumption. Based on the data from tests on the roads, it has been found that the linear relation has a slop of 8.5 for spark ignition (SI) engines [10].

Accumulated Mileage

There are just a few studies on the influence of accumulated mileage on vehicles' emissions and they mostly focus on pollutants such as HC and CO. The impact of accumulated mileage is usually discussed along with the inspection/maintenance program. It is expected that, all being equal, the shorter the average lifetime of the vehicle, the lower the energy consumption and emissions. This means that older vehicles produce higher emissions because of the degradation of their emission control systems [11-14]. But at the same time, as vehicles get older they tend to be driven less [15]. Furthermore, it is very briefly mentioned that CO_2 emission (the focus of our study) is insensitive to vehicle mileage [12].

Inspection and maintenance

As mentioned previously, the study of inspection and maintenance (I/M) programs is also discussed in the analysis of accumulated mileage and life-cycle emissions [16]. In a study of vehicle maintenance, it is found that more than 60% of the vehicles had an average of 5% improvement in fuel economy after tuning. This was particularly evident on older vehicles that do not have closed loop engine management systems [10]. The tuning of vehicles can improve the fuel efficiency through decreasing the particular frictional resistance and therefore increasing the thermodynamic efficiency. The effect of thermodynamic efficiency is usually determined in calculating the power demand which will be discussed in the next section.

Speed, Acceleration and Deceleration

Speed and acceleration are the most discussed variables in vehicle emission analysis, because of the dynamic nature of speed profile and its significant influence on emissions. The precision of emission estimation models are usually based on their speed profile. The simplest method is the distance based average fuel consumption which provides a very simple approximation that is very limiting to understand impacts of potential strategies. In this method the fuel consumption is not sensitive to speed. The next method is based on the average speed on a link which is an improvement over the distance-based method, but is still limited. As for the previous one, this method is not very reliable since different speeds can give same average speed but different fuel consumptions. The most accurate model yet is the power-based instantaneous speed model.

One example of average speed model is Synchro [17]:

$$FC = X \times (0.284977 - 0.003738 \times v + 0.00002201 \times v^2) - D \times 2.774 + S \times 0.0000089756 \times v^2 \quad \text{Equation 3}$$

FC Fuel consumption in litre
X Distance in km
v Speed in km/h
D Total sign delay in hours
S Total stops in vehicle/h

As we can see, the main variables are the average speed on the link and the distance. This model provides the average fuel consumption for a common full-size sedan.

The most detailed model, the power-based model, was initially developed by Post, Kent [18]. This concept has been studied and improved by other researchers ever since [10, 19]. This model calculates the fuel consumption based on the power demand to run the vehicle. The power demand is calculated based on the energy required to overcome 5 types of forces: drive-train resistance (Z_d), tire rolling resistance (Z_r), aerodynamic resistance (Z_a), inertial and gravitational resistance (Z_e), and for the accessories (Z_m):

$$Z_t = Z_d + Z_r + Z_a + Z_e + Z_m \quad \text{Equation 4}$$

$$Z_d = 2.36 \times 10^{-7} v^2 M \quad \text{Equation 5}$$

$$Z_r = (3.72 \times 10^{-5} v + 3.09 \times 10^{-8} v^2) M \quad \text{Equation 6}$$

$$Z_a = 1.29 \times 10^{-5} C_d A v^3 \quad \text{Equation 7}$$

$$Z_e = 2.78 \times 10^{-4} (a + g \sin\theta) M v \quad \text{Equation 8}$$

v Speed (km/h)
a Acceleration (m/s^2)
M Vehicle mass (kg)
C_d The aerodynamic drag coefficient
A The vehicle frontal area (m^2)

$$FC = \alpha + \beta Z_t \quad \text{Equation 9}$$

α Idle fuel consumption rate (ml/min)
β Thermodynamic efficiency of power generation (proportional to engine capacity in spark ignition engines) (litres)

Temperature

The most important environmental factor that affects emissions is temperature. The effect of temperature on emissions can be discussed in two status of the vehicle: hot running engine, and cold start. The temperature can also have an effect on emissions through the use of AC which will be discussed in a separate section. For the hot running status, temperature can have different effects for different gases. Choi, Beardsley [20] illustrate the impact of temperature on THC, CO, NO_X and total $PM_{2.5}$ levels; however, CO_2 is not discussed in the literature.

On the other hand the impact of temperature on fuel consumption during the cold start has been discussed widely in the literature [21-23]. The emission control systems' performance deteriorates below normative range temperatures [24]; since, in colder temperature and higher air density, more fuel is required ,more gases are also produced [25, 26].

A general formula for cold-start-related excess emissions of a trip is proposed by [27] based on ambient temperature, average speed, travelled distance and parking duration.

$$EE(T, V, \delta, t) = \omega_{20°C, 20km,h} \times f(T, V) \times \left\{\frac{1 - e^{a \times \delta}}{1 - e^{a}}\right\} \times g(t) \quad \text{Equation 10}$$

EE excess emissions for a trip in g
V speed (km/h)
T ambient temperature in °C
t parking time in hours
$\delta = \frac{d}{d_c(T,V)}$ dimensionless travelled distance
d travelled distance (km)

$d_c(T,V)$ cold distance (km)
$\omega_{20°C,20km,h}$ reference excess emission (at 20 °C and 20 km/h)

The functions $\omega_{20°C,\ 20km/h}$, f(T,V), a, dc(T,V) and g(t) are introduced in André and Joumard [27]. Generally it is mentioned in Weilenmann, Vasic [28] that lower emissions at higher temperatures may be due to the fact that warm air has lower density which makes engine throttle less to give the same power and thus running is more efficient.

Air Conditioning

The influence of air-conditioning on fuel consumption and CO_2 emission of the passenger cars is an important issue especially in the case of more recent automatic systems, since there are activated most of the time. The energy use is more than the energy used for rolling resistance, aerodynamic drag or driveline losses for a typical 27 mpg (8.7 l/100km) vehicle [29]. The fuel efficiency drops substantially when AC is on and the effect is higher with less fuel efficient gasoline vehicles [30]. This influence is more significant for hybrid vehicles. For example, the fuel consumption of an average gasoline vehicle drops by 35% whereas it drops by 1287% for an average hybrid vehicle [29].

The study of air conditioning has two aspects: first finding the comfort zone and the probability of turning on the air conditioning and second which is free from comfort analysis. In thermal comfort studies it is assumed that if a person is not satisfied with the thermal environment, she will turn on the AC. The determining factors for the model are air temperature, mean radiant temperature, humidity ratio, air velocity, activity, and clothing. Based on these factors the model will then determine the predicted mean vote (PMV) and predicted percent dissatisfied (PPD).

In the study of air-conditioning usage in an aggregated level, Johnson [29] has developed two indicators: the PMV indicator predicts the mean thermal sensation vote of a large population for a given heat balance on a typical body (Equation 11 and Equation 12) and PPD which is synonym with percent of the population that turn on the AC (Equation 12).

$$PMV = (0.303 \times \exp(-0.036 \times M) + 0.028) \times (M - E_{diff} - E_{rsw} - E_{Res} - C_{Res} - R - C) \quad \text{Equation 11}$$

$$PPD = 100 - 95 \times \exp(-0.03353 PMV^4 - 0.2179 PMV^2) \quad \text{Equation 12}$$

Vehicle air conditioning is the most significant fuel consumer after driving the vehicle [31]. In some countries this problem is worse. In India 19.4% of the fuel consumption is devoted to air conditioning [32]. US consume 7.1 billion gallons (27 billion liters) of gasoline for vehicle's air conditioning which equals 57.6 megaton CO_2. The total consumption varies significantly with the average regional climate. For instance, total annual excess emission caused by air conditioning in Florida is about four times more than in New York [31].

At the disaggregated level, the AC's fuel consumption is very sensitive to temperature, solar irradiation and speed. The maximum average extra CO_2 is the result of urban driving at 37˚C and with the sun shining: it amounts to 82.7 g/km (26%) [28]. The difference between A/C on and off clearly increases with temperature and solar irradiation. The extra CO_2 emission is highest in urban (81 g/km at 37˚C sun) and lowest in highway driving (17 g/km at 37˚C), because of the slow urban speed and therefore the long time it takes to cover the same distance. Also, the load of the compressor on the engine varies significantly with thermal load of the A/C. However, even though extra fuel per kilometer decreased from urban to highway driving, the estimated power consumed by A/C system increases sharply [28]. Equation 13 models the excess emission based on the use of A/C based on different driving environment. The constants of the model are also provided in the Table 2.

$$if\ T > 5°C, then\ (if\ c > aT + b, then\ emission = c, ifnot\ emission = aT + b), ifnot\ emission = 0 \quad \text{Equation 13}$$

Table 2 : Parameters for proposed CO_2 and fuel consumption (FC) model

CO_2		shade			sun		
parameter	**unit**	**urban**	**rural**	**highway**	**urban**	**rural**	**highway**
a	g/(km/^{o}C)	2.4422	0.8522	0.6842	2.6889	0.9863	0.7778
b	g/km	-18.7718	-9.9298	-10.9286	-17.1977	-11.2158	-12.1216
c	g/km	18.4666	6.2840	3.6224	23.7000	5.0084	2.1753
FC		**shade**			**sun**		
parameter	**unit**	**urban**	**rural**	**highway**	**urban**	**rural**	**highway**
a	g/(km/^{o}C)	0.7804	0.2847	0.2793	0.8488	0.3231	0.2790
b	g/km	-6.0888	-3.5017	-5.0211	-5.0211	-3.7406	-43917
c	g/km	5.7801	2.0163	1.1428	1.1428	1.5853	0.6512

Pavement Condition

The pavement condition and texture can influence fuel consumption in two ways. First, the pavement texture (roughness) can increase/decrease the friction force which influences the power demand and therefore the fuel consumption. Also, the pavement condition can affect driving behaviour such as inevitable hard deceleration and after that acceleration. The latter is not discussed in the literature.

In one study, Ardekani and Sumitsawan [33] compare two types of pavements: Asphalt Concrete (AC) versus Portland Cement Concrete (PCC). It was observed that under urban driving speeds of 48 km/h, the fuel consumption per unit distance is lower on concrete pavements compared to asphalt pavements. These findings were based on test runs on two sets of typical PCC and AC street sections in Arlington, Texas, with each pair of study sites having similar gradient all the time and roughness index values for the same pavement type.

Table 3: Average fuel consumption rates for PCC versus AC sections under dry pavement conditions

	Average fuel consumption (10^{-3} gals/mile)
PCC. Dry. Constant speed	40.7
Ac. Dry. Constant speed	42.7
PCC. Dry. Acceleration	236.4
Ac. Dry. Acceleration	236.9

Also, the study of the Canadian national research council confirms the result of the previous study. In this report, three types of pavements were compared: asphalt, concrete and composite (asphalt top-coat over concrete) in two seasons. In this research it is indicated that in winter testing, the passenger car consumed 0.3 l/km more (2.9%) on asphalt than on concrete. Also, the car consumed 2.3% less fuel (0.2 L/km) on composite pavement compared to concrete [34]. On the other hand, in summer testing, the passenger cars consumed 0.1 L/100 km (1.5%) more on composite roads when compared to concrete and 0.05 L/100km (0.3%) less on asphalt roads comparing to concrete [34]. These differences are mainly caused by changing tire and road surface condition.

In the next section, these equations will be illustrated through figures to understand how exactly they contribute to emission. They will also be applied to a typical trip to see how realistic they are. At the end I will compare the sensitivity of each variable to see which factor is more sensitive to change and how important is the magnitude of its effect.

RESULTS AND DISCUSSIONS

In the previous section the emission factors and the theoretical models have been discussed. As mentioned, many variables can affect the fuel consumption and CO_2 emission. In this section, each variable is analyzed to understand to what extent it can influence the emission. A 2008-model Nissan Versa specifications has been used in this analysis therefore the engine capacity has been set constant all the time.

Vehicle weight and aerodynamic characteristic are two specifications that can be modified by the users. For instance, carrying large loads inside the vehicles increases the total vehicle weight. Also, the aerodynamic characteristics of a vehicle can be modified by adding some features outside the vehicle like bike racks, kayak or luggage. Any of these alterations can increase the fuel consumption and consequently, increase CO_2 emission. Every extra 100 kg weight can increase the CO_2 emission by 0.135, 0.168, or 0.202 grams per kilometer for speeds of 20, 60, and 100 km/h respectively [10].

Also, the CO_2 emission increased by 5, 45, and 124 g/km; for 20, 60 and 100 km/h of speeds, by doubling the drag area of our model vehicle. Therefore, if we compare these two results, it is definitely recommended to have all the possible excess weight inside the vehicles instead of putting it on an additional luggage rack on the roof.

The next factors are speed and acceleration which are co-dependent. A slight change in each of them can change the CO_2 emission significantly. Therefore, it is more comprehensive to have a continuous result (Figure 1). As we can see, the optimum speed with respect to CO_2 emission for this vehicle is around 40 km/h. Also, being in congestion can increase emissions as well as driving on high speeds. Moreover, the road grade as a factor in determining the power demand can affect emission. Each 5 degree road grade can increase CO_2 emission by about 50 g/km.

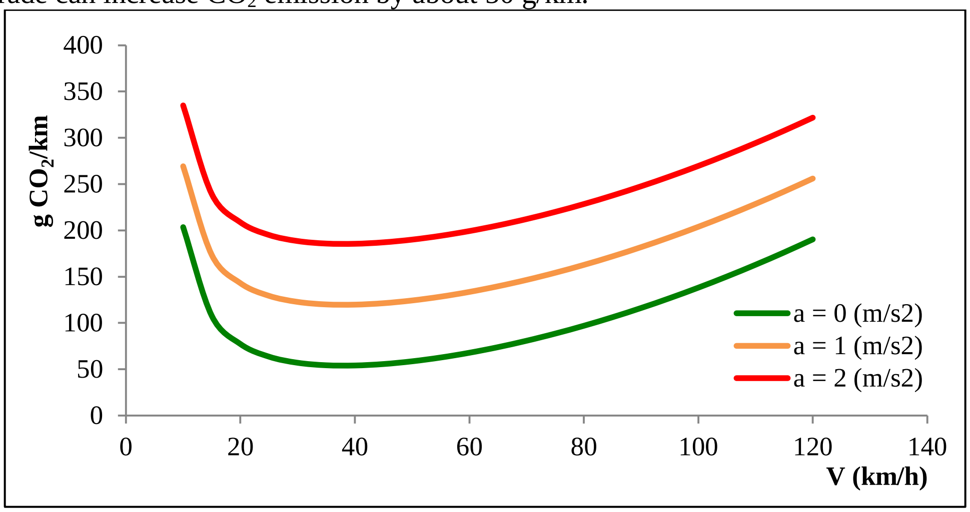

Figure 1: The impact of speed and acceleration of fuel consumption

After power demand, the major influential variable is ambient temperature. As discussed in the background, the temperature can affect emission in two states of vehicle: first, cold start and then, hot running. As we can see in Figure 2 running on a cold engine can increase the excess emission as much as 375 g/km. On the Other hand, it takes longer to warm-up the engine as it gets colder. In -40 °C it takes about 11 km to warm up whereas, in 20 °C this would take only 2.5 km. Figure 2 is just providing the excess emission for the first kilometer; therefore, the time it takes to warm-up is not included in the calculations.

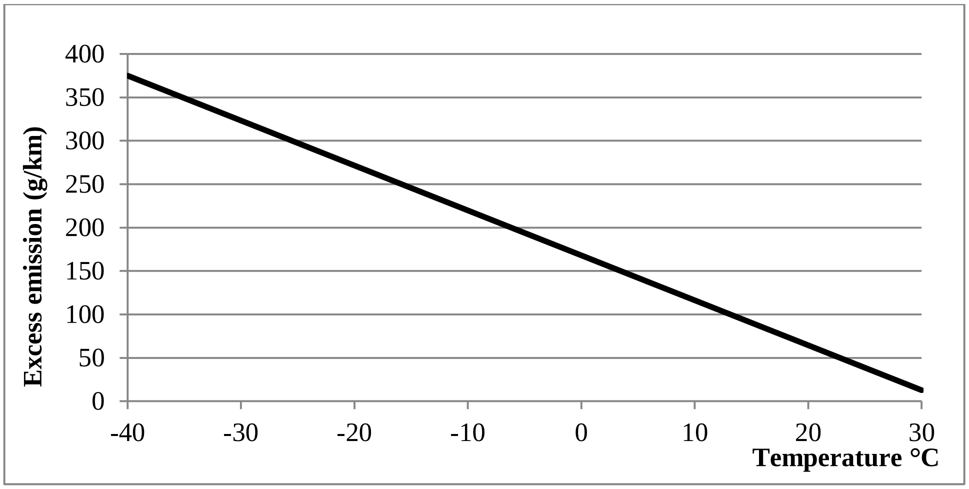

Figure 2: Cold start excess CO_2 emission in different ambient temperatures [27]

Furthermore, the rise in temperature induces using of A/C (and engine coolant system). In Figure 3 we can see how A/C can increase CO_2 emission and how different environment can have influence on it. In urban areas, the excess emission is significantly higher whereas in highways we can see relatively less emission. For example increase in temperature from 20 to 30° Celcius can increase emission about 25 g/km in urban areas and this number reduces to 8 g/km for highway travel.

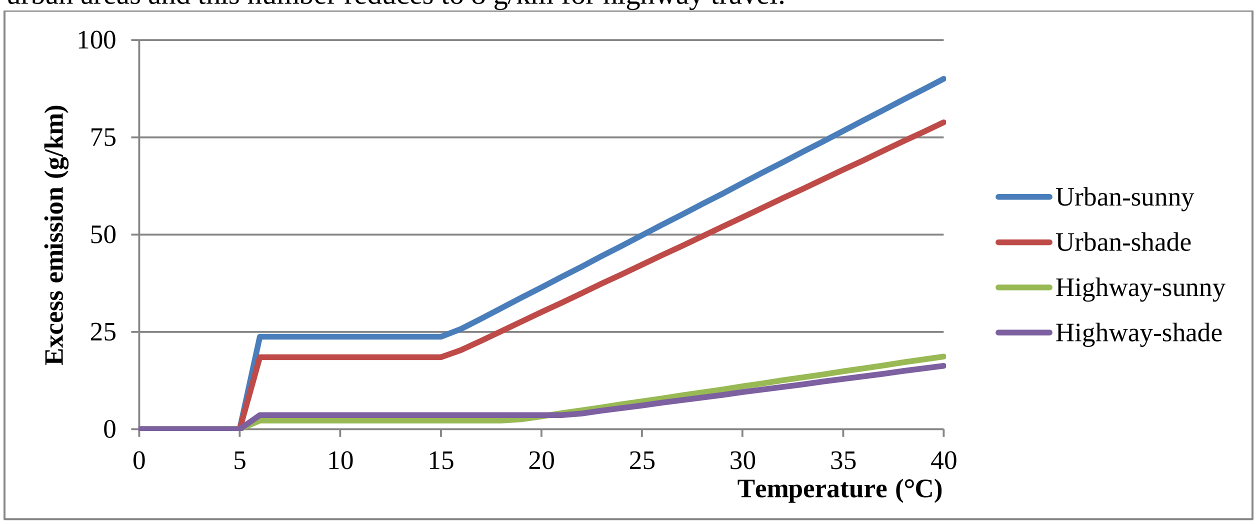

Figure 3: The excess CO_2 emission due to use of A/C in different ambient temperature and environment [28]

Furthermore, if we change the asphalt for composite, the vehicles can increase their emission by 3.6 g/km in summer and reduce by 12 g/km. Depending on the regions and their environment we can then decide which type of road can help reduce the total vehicle emissions.

To understand how some of these factors can add up in the everyday driving condition, a schematic representation of a few of these factors has been illustrated in Figure 4.

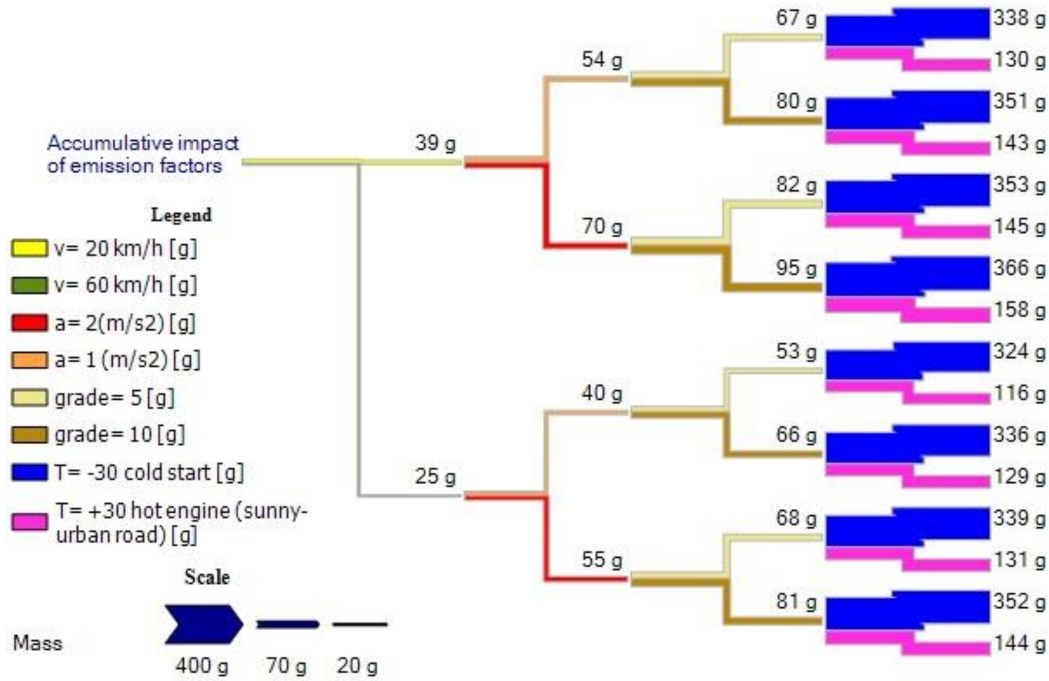

Figure 4: Schematic representation of cumulative impacts of emission factors

Up to this part we can understand how each of these variables can affect emission and we are now able to compare them. However, these analyses will become more and more realistic if we apply them to a typical urban trip.

For this purpose, a data logger was plugged into a volunteer's vehicle and the driver was asked to drive as usual. One average morning trip from home to workplace was then chosen. The selected trip takes about 30 minutes and is 14.5 km long. It includes highways as well as arterials and residential streets. The maximum speed along the trip is 62 km/h. The vehicle is a 2008 Nissan Versa with 1.8 L engine capacity.

Table 4 describes how each of the emission factors contributes to the CO_2 emission in a more tangible manner. The analysis is based on one trip that has been recorded with an OBD data logger. The information that was retrieved from the trip is the instantaneous speed, GPS location (to determine that the vehicle is on the highway or not). The instantaneous fuel consumption is also being recorded by the data logger; however, it has not been used in the analysis. Therefore, the total emission for the trip in Table 4 is the calculated emission based on no excess weight or cargo and hot engine. Also, the figures regarding the pavement are a comparison with asphalt.

Based on these analyses the average importance of influence in descending order is:

1- Temperature (both cold start and AC)
2- Change in aerodynamic characteristics of the vehicle
3- Speed and acceleration
4- Pavement
5- Vehicle load

Table 4: Comparison of the emission factors for the experiment's trip

	CO_2 emission (g)
Total emission for the trip (no excess emission)	1159.02
Excess emission	
Weight increase	
100 kg	16.15
200 kg	32.31
Drag area	
CdA=14	322.50
CdA=21	646.38
Speed/Acceleration	
No stop and free flow traffic	-310.56
Aggressive with frequent stop*	77.62
Temperature	
-40	1174.64
-20	823.39
0	450.13
20	355.64
30	532.51
Pavement	
Composite in summer	50.61
Composite in winter	-168.72

* To produce aggressive driving with frequent stops the section of the trip that could represent the aggressive behavior was repeated over the entire trip.

Also, we should not forget that all these analyses were based on a single vehicle and different vehicles can significantly change the total emission.

CONCLUSION

Vehicle emission estimation is widely discussed in the literature and most of the variables have been modeled based on extensive data that has been collected over years. The emission models have become more and more complex in response to increasing analytical needs. However, this sophistication has caused difficulties in defining separate variables and their contribution. Most of the recent emission estimation models are referred to as a black box which makes it more difficult to understand their process of estimation.

This study tries to untangle the emission factors and explain how different variables can influence emission. The results explain which factors are more influential; this can help improve planning for emission reduction by opening new horizons with respect to strategies to reduce emission. Based on the analysis of our model vehicle, the first three contributing factors are cold start excess emission, drag area, and speed/acceleration; followed by use of air conditioning, pavement and extra load. Hence, strategies to reduce the occurrence of cold starts (such as heated parking for instance) may become worth examining in our particular context. The aim of this study was to simplify the decision making by providing a comprehensive overview of the influence of the various factors and their relative importance. Having access to more clearly defined models can definitely improve the process of decision making as well as further development and improvement of the models.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contribution and financial support of the four partners of the Mobilite research Chair: City of Montreal, Quebec Ministry of transportation, Montreal metropolitan agency and the Montreal transit authority.

REFERENCES

1. Barla, P., et al., *Disaggregated Empirical Analysis of Determinants of Urban Travel Greenhouse Gas Emissions.* Transportation Research Record: Journal of the Transportation Research Board, 2010. **2156**: p. 160-169.
2. Murshed, D. *Estimating Greenhouse Gases from Roadway Transportation-Methodology Overview*. 2010. Kunming, China: ASCE.
3. Corvalan, R.M. and C.M. Urrutia, *Emission Factors for Gasoline Light-Duty Vehicles: Experimental Program in Santiago, Chile.* Journal of the Air & Waste Management Association, 2000. **50**(12): p. 2102-2111.
4. Wang, H., et al., *A bottom-up methodology to estimate vehicle emissions for the Beijing urban area.* Science of The Total Environment, 2009. **407**(6): p. 1947-1953.
5. Bachman, W., et al., *Modeling Regional Mobile Source Emissions in a Geographic Information System Framework.* Transportation Research Part C: Emerging Technologies, 2000. **8**(1-6): p. 205-229.
6. GmbH, *Gasoline engine management : [systems and components]*. 3rd ed., completely rev. and extended ed. 2006, Plochingen; Chichester, West Sussex, England: Robert Bosch GmbH.
7. Atkins, R.D., *An Introduction to Engine Testing and Development*. 2009: SAE International.
8. Sullivan, J.L., et al., *CO_2 Emission Benefit of Diesel (versus Gasoline) Powered Vehicles.* Environmental Science & Technology, 2004. **38**(12): p. 3217-3223.
9. *Fuel Consumption Ratings*. 2012 2011-09-06 [cited 2012 Feburary-22]; Available from: http://oee.nrcan.gc.ca/transportation/tools/fuel-consumption-guide/fuel-consumption-guide.cfm.
10. Leung, D.Y.C. and D.J. Williams, *Modelling of Motor Vehicle Fuel Consumption and Emissions Using a Power-Based Model.* Environmental Monitoring and Assessment, 2000. **65**(1): p. 21-29.
11. Lawson, D.R., *"Passing the Test" – Human Behavior and California's Smog Check Program.* Air & Waste, 1993. **43**(12): p. 1567-1575.
12. Ntziachristos, L. and Z. Samaras, *Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters.* Atmospheric Environment, 2000. **34**(27): p. 4611-4619.
13. Samaras, Z., et al., *Alternative short tests for inspection and maintenance of in-use cars with respect to their emissions performance.* International Journal of Vehicle Design, 1998. **20**(1): p. 292-303.
14. Zachariadis, T., L. Ntziachristos, and Z. Samaras, *The effect of age and technological change on motor vehicle emissions.* Transportation Research Part D: Transport and Environment, 2001. **6**(3): p. 221-227.
15. Van Wee, B., H.C. Moll, and J. Dirks, *Environmental impact of scrapping old cars.* Transportation Research Part D: Transport and Environment, 2000. **5**(2): p. 137-143.
16. Washburn, S., J. Seet, and F. Mannering, *Statistical modeling of vehicle emissions from inspection/maintenance testing data: an exploratory analysis.* Transportation Research Part D: Transport and Environment, 2001. **6**(1): p. 21-36.
17. Cobian, R., et al., *Vehicle Emissions and Level of Service Standards: Exploratory Analysis of the Effects of Traffic Flow on Vehicle Greenhouse Gas Emissions.* Ite Journal-Institute of Transportation Engineers, 2009. **79**(4): p. 30-+.
18. Post, K., et al., *Fuel consumption and emission modelling by power demand and a comparison with other models.* Transportation Research Part A: General, 1984. **18**(3): p. 191-213.
19. Biggs, D.C. and R. Akcelik, *An energy-related model of instantaneous fuel consumption.* Traffic Engineering and Control, 1986. **27**(6): p. 320-325.
20. Choi, D., et al., *MOVES Sensitivity Analysis:The Impacts of Temperature and Humidity on Emissions*, 2011.
21. Sentoff, K.M., M.K. Robinson, and B.A. Holmén, *Second-by-Second Characterization of Cold-Start Gas-Phase and Air Toxic Emissions from a Light-Duty Vehicle*, in *89th Annual Meeting of Transportation Research Board*2010: Washington D.C.

22. Andrews, G.E., et al., *Influence of ambient temperature on cold-start emissions for a Euro 1 SI car using in-vehicle emissions measurement in an urban traffic jam test cycle.* General Emissions 2005, 2005: p. 133-154.
23. Weilenmann, M., J.-Y. Favez, and R. Alvarez, *Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories.* Atmospheric Environment, 2009. **43**(15): p. 2419-2429.
24. Laurikko, J., *On exhaust emissions from petrol-fuelled passenger cars at low ambient temperatures*, 1998, Helsinki University of Technology: Espoo.
25. Bielaczyc, P. and J. Merkisz, *Exhaust Emission from Passenger Cars During Engine Cold Start and Warm-Up.* SAE Technical Paper 970740, 1997.
26. Bielaczyc, P. and J. Merkisz, *Cold Start Emissions Investigation at Different Ambient Temperature Conditions.* SAE Technical Paper 980401, 1998.
27. André, J. and R. Joumard, *Modelling of cold start excess emissions for passenger cars*, 2005, Institut National de Recherche sur les Transports et leur Securite (INRETS).
28. Weilenmann, M.F., et al., *Influence of Mobile Air-Conditioning on Vehicle Emissions and Fuel Consumption: A Model Approach for Modern Gasoline Cars Used in Europe.* Environmental Science & Technology, 2005. **39**(24): p. 9601-9610.
29. Johnson, V., *Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach.* SAE Technical Paper 2002-01-1957, 2002.
30. Welstand, J.S., et al., *Evaluation of the effects of air conditioning operation and associated environmental conditions on vehicle emissions and fuel economy.* SAE transactions, 2003. **112**(4): p. 1993-2006.
31. Weilenmann, M.F., R. Alvarez, and M. Keller, *Fuel Consumption and CO_2 Pollutant Emissions of Mobile Air Conditioning at Fleet Level - New Data and Model Comparison.* Environmental Science & Technology, 2010. **44**(13): p. 5277-5282.
32. Chaney, L., et al. *Fuel savings and emission reductions from next-generation mobile air conditioning technology in India*. in *VTMS 8 - Vehicle Thermal Management Systems Conference and Exhibition, May 20, 2007 - May 24, 2007*. 2007. Nottingham, United kingdom: Chandos Publishing.
33. Ardekani, S.A. and P. Sumitsawan, *Effect of pavement type on fuel consumption and emissions in city driving*, 2010, The Ready Mixed Concrete Research & Education Foundation. p. 71.
34. Taylor, G. and J. Patten, *Effects of Pavement Structure on Vehicle Fuel Consumption - Phase III*, 2006, Transportation Association of Canada. p. 98.