Comparison study on the urban transportation fuel consumption and GHG emission using real-world vs. MOBILE6 and MOVES estimations for gasoline and hybrid electric vehicles

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ABSTRACT

This work presents a methodology to compare vehicle fuel consumption and GHG emissions from real-world in-use testing with EPA MOBILE 6 and MOVES (MOtor Vehicle Emission Simulator) estimations. For this study, fuel consumption data in real-world driving conditions from a sample of 74 instrumented vehicles is used, 21 of which are HEVs. Fuel consumption from the vehicles during the testing were recorded, analyzed, and compared to estimated emissions using the current EPA emissions estimation model, MOtor Vehicle Emission Simulator (MOVES) and MOBILE6. The authors observed discrepancies between the measured data and these estimates, especially when associated with cold-start emissions. More detailed analysis results, along with the detailed test methodologies, are provided in this paper. Among other results, the beneficial fuel efficiency merits of hybrid vehicles are demonstrated in particular in low speeds in urban (city) driving conditions. There is discrepancies between MOVES and MOBILE6, and real-world estimations in lower speeds. At speeds lower than 20km/hr the fuel consumption curves of the two former methods are slightly higher than the latter. However the former mentioned methods don't consider cold-start emissions. The average GHG emission obtained from MOVES and MOBILE6 are slightly higher than estimations based on real-world fuel consumption curves.

INTRODUCTION

Transportation makes up a great share of the total greenhouse gas emissions (GHG) around the world and reducing emissions from this sector has been a global challenge. Therefore factors affecting fuel consumption (and eventually GHG emissions) are the focus of many studies done from this perspective. Different factors affect fuel consumption rate of motor vehicles such as: vehicle type (make, model and year), operating speed, cold-start, ambient temperature, weather condition, type of road (local and highway) or surface, level of hybridization and etc (Fontaras et al. (*1*)).

Studies that have explored factors affecting fuel consumption are well stablished. These studies have looked at data collected in real world conditions as well as in laboratory controlled conditions. As for laboratory controlled methods, we can refer to EPA’s MOBILE and MOVES. MOBILE vehicle emission factor model, which is a software tool for predicting gram per mile emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO2), particulate matter (PM) and air toxics from cars, trucks, and motorcycles under various conditions. MOBILE has been replaced by MOVES as EPA’s official model for estimating emissions from cars, trucks and motorcycles[1]. EPA's Office of Transportation and Air Quality (OTAQ) has developed the MOtor Vehicle Emission Simulator (MOVES). This new emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. MOVES currently estimates emissions from cars, trucks & motorcycles[2].
In the literature rural and urban driving conditions have also been analyzed, not to mention the impact of eco-driving training (Rutty et al. (*2*); Wang et al. (*3*); Andrieu et al. (*4*)). Most studies focus on driving and vehicle characteristics such as, average speed, vehicle weight and vehicle-specific power (VSP) (Ahn et al., (*5*); Wu and Liu, (*6*); Ben-Chaim et al., (*7*); Mierlo et al., (*8*)). The studies in the literature tend to look at different types of vehicles (domestic gasoline and HEVs) in real world driving cycles and simulation driving cycles.
The impacts of a vehicle trip can only be quantified accurately by doing on-road measurements using a portable fuel consumption monitoring system (PFCMS) or a portable emission monitoring system (PEMS) to collect vehicle dynamics, engine data, road topography and tailpipe gas concentration of pollutants during operation. However, it is not feasible to measure every vehicle technology performing selected driving cycles, therefore numerical tools are commonly used to simulate vehicle operation. The literature has observed discrepancies between the measured data and what is modeled by MOVES and MOBILE6 (*9*). Therefore further research in this differences are necessary and are the focus of this study.

Despite the important contribution of this literature, very few studies have looked at real-wold observations where a large population of drivers and vehicles operating in different environments and weather conditions, in particular the low temperatures during the winter time were studied. Few studies have been done in cold North American cities that look at how the efficiency of vehicles can be affected by very low temperatures (under -20 °C during the winter months of February and March). In particular in Canadian cities such as, Montreal and Quebec City, the temperatures can drop as low as -35°C. Cold-start is another important factor affecting fuel consumption which has not been studied for it merits.

[1] . http://www.epa.gov/otaq/mobile.htm
[2] . http://www.epa.gov/otaq/models/moves/index.htm

In this regards, this paper aims at identifying the differences between real-world driving Vs. laboratory estimations (MOVES and MOBILE6) on GHG emission from the transportation sector with particular focus on the winter season, low temperatures and cold-starts controlling for the effect of other factors such as, operating speed and type of road (highway or local). In this study, segment-level data is used from instrumented vehicles as real-world observations.
This paper will continue on with a discussion of the background literature followed by a section on the data and methodology used in the study. The empirical results of the statistical models will then be demonstrated (OR presented) and concluding statements will be made.

BACKGROUND

This section includes a summary of the literature over the past decades on fuel consumption and the contributing parameters. Given the importance of speed on fuel consumption, the most basic fuel consumption model considers just this factor, most commonly average speed (*10*). Another simple model was developed to estimate fuel consumption based on vehicle-specific power (VSP), which is a function of slope, speed and acceleration (*3*). Based on this model, fuel consumption is minimized at speeds between 50 and 70 km/h, with acceleration having a strong influence on fuel economy (*3*). The strong effect of acceleration and deceleration is also demonstrated in the study by Tong et al. (*11*). Other studies have looked at other factors including gear-changing and proportion of time spent idling.
In most cases, separate analyses are conducted for highway and urban driving (Evans (*10*); Reynolds and Kandlikar (*12*); Redsell et al., (*13*)) because of the contrasting features of driving conditions in these two environments. In particular, in freeway driving, speed is relatively constant without the effects of stop signals (*10*). On the other side, urban or city driving is characterized by frequent changes in speed (stop and going situations) as a result of traffic control measures and driver interactions with neighboring vehicles (*10*).

In the literature few studies have looked at the differences between real-world driving fuel consumption and GHG emissions and laboratory estimations such as MOVES and MOBILE6 (*9, 14, 15, 16 & 17*).

Lee et al. (*9)* developed a methodology to perform mandatory dynamometer vehicular emissions tests on real roads, performed on-road emissions tests, and compared the test results to the estimates using the current EPA emissions estimation model. Emissions from the vehicle during the testing were measured, analyzed, and compared to estimated emissions using the current EPA emissions estimation model, MOVES. The authors observed discrepancies between the measured data and the MOVES estimates, especially when associated with cold-start emissions. Frey et al. (*14*) demonstrate methods for developing modal emission rates from on-board data and laboratory second-by-second data for a 'pilot' dataset of light duty gasoline vehicles (LDGV). They discuss methods for characterization of variability and uncertainty for the conceptual models, and validation of the conceptual models versus independent data. Based upon the results of the conceptual model development, they make recommendations regarding future development of MOVES. Wang et al. (*15*) explore the influence of driving patterns on fuel consumption using a portable emissions measurement system on ten passenger cars in China. They show that vehicle fuel consumption per unit distance is optimum at speeds between 50 and 70 km/h, fuel consumption increasing significantly with acceleration. Nam et al. (*17*) use Portable Emission

Measurement Systems (PEMS) to instrument a vehicle with a PEMS developed by Ford and measure emissions during real-world driving. In an effort to improve mobile source emissions inventory estimates, the EPA proposes to utilize PEMS to characterize in-use emissions. Nam et al. (*17*) integrate a microscopic traffic model (VISSIM) with the load based Comprehensive Modal Emissions Model (CMEM). The emissions model was calibrated with data acquired for the instrumented vehicle using conventional dynamometer instrumentation. The magnitude of the emissions was found to be relatively low for both normal and aggressive driving, but was higher in the latter case. They conclude that comparing to second-by-second simulation models such as MOVES, their model takes into account aggressive driving which naturally causes higher emissions.
These studies typically have carried out analyses by looking at instantaneous speeds and other driving parameters collected with a data logger (*5& 11*). Large differences have been found between on-road collected data and label specifications by manufacturers (*18*).
Studies, justifiably, concentrate on vehicle parameters, driving conditions and, to a lesser extent, driver information to identify factors that influence fuel consumption. For this reason, strategies to improve fuel efficiency deal with changes in technology or driver behavior such as, adopting alternative green technologies and creating an eco-driving program.

Despite the important contribution of this literature, very few studies have looked at real-wold observations where a *large* population of drivers and vehicles operating in different environments and weather conditions, in particular the low temperatures during the winter time were studied. The size of the fleet under study in this paper is one of its advantages over the literature. Also driving in different weather conditions (cold ambient temperature) and environments, especially cold environments, gives this research strength over studies done before.

METHODOLOGY

Different steps were executed to accomplish this study, including:

Data preparation:

Real world driving vehicle data collection (eco-driving study): This study makes use of a rich database collected from studying driving behavior factors, specifically, eco-driving training as well as factors affecting fuel consumption of passenger vehicles in real driving conditions. For this purpose, a large sample of vehicles was instrumented with the participation of the drivers from different cities in the Province of Quebec, Canada. This project was financed by the Quebec Ministry of Natural Resources (MNR). The data was collected by a third party service provider (FPInnovations (*19*)), using on board recording devices from the ISAAC Instruments company. These devices provide access to engine operation data using an OBD-II connector (on-board diagnostics used to request data from the vehicle), enabling the recording of several parameters simultaneously at a rate of 5 samples per second (see **fig.1**).

Origin-Destination surveys (O-Ds): As described in more detail in the following section, this research involves calculating household-level, transportation-related GHG emissions. Household-level, transportation-related GHG emissions are estimated from the "bottom-up", starting with the most disaggregate data possible. The backbone of these calculations is data from three different origin-destination surveys from the years 1998, 2003 and 2008 for the region of Greater Montreal in Canada. The Montreal OD survey is one of the longest running and most detailed in the world. Every five years the survey interviews around 5% of the households in the region (approx. 65,000 households). It is also worth mentioning that this is not a panel dataset – households are selected randomly in each survey. The survey collects information about the households (household structure, number of vehicles, income, etc.), individuals (age, gender, employment status, etc.) as well as detailed information about their travel behavior on the day before the interview. In particular, for each trip by each member of the every household interviewed, the following information is collected: origin and destination locations, transportation mode(s), purpose, transit lines used, time of departure, car occupancy, etc. The socio-demographic information provided by these surveys is also used in the statistical models estimated to explain these emissions. The OD survey was provided by the regional public transportation planner, the Agence métropolitaine de transport (AMT).

EPA MOVES and MOBILE6 estimations: MOBILE 6 estimations were obtained from a study done by the Ministère des Transports du Québec (MTQ) (*20*). MTQ has adapted the U.S. model for MOBILE6 to get the base rate for emissions of air pollutants from Quebec's road vehicles. As for the MOVES estimations, data from the Montreal network has been simulated in MOVES to obtain the required fuel consumption curves and speed correction factors. The curves are then used as inputs in the GHG estimation procedure explained below. These curves are demonstrated in the results section.

Trip-level GHG estimation:

For each trip in the three O-D surveys (1998, 2003 and 2008), two GHG emitting mode categories are distinguished; private motor vehicles, and public transit including transit buses and commuter trains. Some trips can involve more than one mode. The procedure for GHG emissions estimation is described as follows:

i. From a traffic assignment model developed and calibrated by the Quebec provincial ministry of transportation (MTQ) (*21*), congested times for each link of the road network were obtained along with their distances. Link travel times were obtained hourly for all periods of the day.
ii. Each trip was associated (according to its departure time) to a particular (time-of-day) network described in the previous step. The shortest path (based on congested times) was then calculated for each trip to obtain route, link distances and speeds for each link.
iii. For each trip and each emitting mode, ridership, fuel consumption rates and emission factors were calculated
iv. Overall GHG emissions for each trip were then calculated according to equations 1 and 2 below.

For trips involving motor vehicle as a unique or combined mode, the emissions are estimated using distance and average speed at the link level, vehicle fuel consumption rate (FCR) at the FSA-level and GHG emission factors. This procedure is detailed in Barla, et al. (*22*) and Barla, et al. (*23*).

Then, emissions for a given trip j departing in a particular hour *t* is estimated as:

$$GHG_{Ajt} = \sum_{i=1}^{N} [\, SP_{ijt} \times D_{Aij} \,] \times \frac{FC_{Aj} \times EF_A}{R_{Aj}} \tag{1}$$

Where:

A – automobile
i – Link (i=1,…, N links used by trip j)
j – Trip
t – Departure time (hour)

GHG_{Ajit} = GHGs for automobile trip j (in kg of CO_2) departing at time t.

Dij = Travel distance on segment (link in network) i in 100km.

SP_{ijt} = Speed correction factor for segment *i* of trip *j* departing at t. Since fuel consumption also depends upon speed, speed correction factors from the different sources under comparison in the study were used. These include i) Curves obtained from the eco-driving study mentioned in the data section; ii) curves developed by the MTQ which the factors were produced after a local calibration of MOBILE6 (for further details, see Babin et al. (*24*); iii) speed correction factors obtained from MOVES. For each source, link speed was matched with its corresponding speed correction factor and plugged in the GHG calculations.

FC_{Aj} = Average fuel consumption rate (FCR) in liters of gasoline/100km for the vehicle used in trip j. This was generated using the motor-vehicle fleet inventory of the automobile insurance corporation of Quebec (SAAQ). For further details see (Barla et al. (*25*). This inventory contains the make, year and model of each vehicle in the province as well as the fuel consumption rate per km. However, the address of the vehicle is provided at the FSA (3-digit postal code). Therefore, FCR at the FSA were generated. An FCR is then associated to each vehicle belonging to the same FSA.

EF_A = Emission factor for gasoline (2.289 kg of CO_2/ liter of gasoline). This is obtained from the national inventory report by Environment Canada.[3] Although this number is fixed for all gasoline vehicles for CO_2, for other GHG emissions such as CH_4 and N_2O, the emission factor depends on the type of vehicle (e.g. Light duty, heavy duty, Oxidation Catalyst, non-catalytic controlled and etc.). Since we didn't have knowledge of the type of vehicle owned by the household, we were unable to estimate the emission for other GHG emissions.

R_{Aj} = Number of passengers in trip j including the driver. This is determined from the O-D survey data. Car trips in the same household, departing at the same hour and with the same origin-destination are associated to the same motor-vehicle trip.

For uni-modal or multimodal trips involving public bus transit and/or commuter trains, GHGs are estimated in a similar fashion. In this case, however, average speeds at the trip-level are used since link-level speeds were not available, but this speed estimate considers congestion.

[3] National Inventory Report 1990-2009 (2011 submission), Environment Canada. (http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1)

For the bus portion, GHGs are calculated using the following equation:

$$GHG_{Bj} = \frac{FC(S)_{Bj} \times D_{Bj} \times EF_B}{R_{Bj}} \quad (2)$$

GHG_{Bj} = GHGs for bus portion of transit trip j (kg of CO_2)

$FC(S)_B$ = Average fuel consumption as a function of operating speeds *(S)* in liters of diesel/100km).
Fuel consumption rates for the typical fuel bus technology operating in real conditions were obtained from a recent field study done by the local transit agency, the Société de transport de Montréal (STM). The fuel consumption curve according to this study is given by $FC(S) = 255.33*(Bus\ speed)^{-0.4753}$

D_{Bj} = Distance traveled by bus in transit trip j (km). For each trip involving transit (bus, metro and commuter trains) in the Montréal region, distances are obtained using the public transit software, MADIGAS (Chapleau (*26*). Trips were simulated by the *Agence Métropolitaine de Transport* (AMT).

EF_B= Emission factor for diesel. Here, an emission factor of 2.663 kg CO_2/ liter of diesel is considered based on the recommendation of Environment Canada for Canadian city conditions[2].

R_{Bj}= Ridership for bus on trip j. In this case we use a mean value for each line used in the trip. This is obtained from the bus provider agencies for each bus line.

For commuter train lines using diesel or diesel-electric locomotives, average fuel consumption for passenger-km (FC/PK) were directly estimated by the local commuter train agency (Agence métropolitaine de transport - AMT). This was done by dividing the annual fuel consumption (liters of diesel) by their respective annual passenger kilometers traveled. Travel distance by rail (DR) is then estimated for each trip (km). By multiplying (DR) by the fuel consumption rate per passenger km (FC/PK), liters of fuel consumed for the train segment are estimated. To get the kg of CO_2 for each trip, the resulting liters of fuel for each trip is multiplied by the emission factor for CO_2 obtained from Environment Canada. This is equal to 2.663 kg of CO_2 for each liter of diesel fuel consumed by trains. The GHG emissions from the metro (subway system) are assumed to be zero since it runs on hydro-electricity.
To obtain the household inventory, GHGs are estimated for each uni-modal and multimodal trip in the O-D surveys. Trip level emissions are then aggregated at the individual and household level. We have to add here that the use of different speed correction (or fuel consumption) curves does not only effect the pure car trips, but also the multi-modal trips involving a car portion (e.g. park-and-rides, kiss-and-rides and etc.)

Comparing the different estimation methods:

In this step as explained briefly in the speed correction factor variable description, different curves for speed correction factor and fuel consumption are tried in the GHG estimation process to capture the effect of using different methods. Real-world observations from the eco-driving study are compared to MOBILE 6 and MOVES. The GHG for the different years of OD based on this difference are reported and compared in the results section.

DATA

Real world driving (eco-driving study)

A sample of 95 vehicles and drivers (workers) from four corporations in four cities in the Quebec Province participated in this study. The cities were Montreal, Quebec City, Trois-Rivières and Sherbrooke, which represent the typical urban areas in the provinces with different population sizes. Among them, Montreal is a major urban agglomeration with 3.8 million habitants in the metropolitan area (Stat. Can. (*27*)). This region is characterized by its high relative population density on the island portion of the city, with important congestion problems in the main arteries and bridges connecting suburban areas with central neighbourhoods and the central business district. Quebec City is the second largest city, with a population of 0.76 million inhabitants in the metropolitan region and is characterized by a large network of urban freeways and a car-oriented mobility. In this city the congestion problems are much less serious than in Montreal. The other two cities, Trois-Rivières and Sherbrooke, have a population of 0.15 and 0.20 inhabitants respectively and traffic congestion basically does not exist.

A data logger (**fig. 1**)was installed in each of the 95 vehicles, in order to record the driving parameters such as, instantaneous speed, fuel consumption, driving regime, and idling time. It is important to mention that out of the 95 instrumented vehicles, 21 were large vans or trucks that were left out of this analysis since hybrid minivans did not exit at the time of the study and also the proportion would have made the analysis biased. This meant that a total of 74 vehicles with 21 of them being HEVs were considered in the analysis.

Fig. 1: An example of the visible data logger installed on the fleets, ISAAC instruments[4]

The period of data collection started in July 2009 and finished in July 2010. This strategy was implemented with the aim of including the four different seasons and eliminating the driving adaption process. As part of the study, a subsample of drivers (74%) was trained with eco-driving techniques in order to evaluate the potential effects of an eco-driving program. The rest of the drivers were not trained and categorized as the control group.

4. Source: PROJET PILOTE DE FORMATION À L'ÉCOCONDUITE POUR VÉHICULES LÉGERS, http://www.ecomobile.gouv.qc.ca/images/pdf/CahierEcoconduite_2011-LowRes.pdf

For this analysis, data was aggregated at the "segment" level, where a segment was defined as the distance travelled below or above a speed threshold value of 70km/h. This threshold value was selected to differentiate between driving conditions in local (city) and highway roadways. This meant that 'city' segments were roadways with a maximum speed recorded below 70 km/h, whereas 'highway' segments were roadways in which the maximum speed recorded was greater than or equal to 70 km/h. Note that the posted speed limits were not used to determine whether a segment was a city or highway link.

Based on the instantaneous data (speed, fuel consumption, acceleration, etc.), a set of variables were generated such as, average fuel consumption rate (FCR) measured in liters per 100 kilometers FCR can be described by the relationship $FCR_{it} = FC_{it}/D_{it}$ where FC_{it} denotes fuel consumption in segment *t* and vehicle *i* and D is the length of segment *t* in 100km.

As mentioned before, this study involved four classes of vehicles (hybrids, hatchback, sedan, SUV). In the HEV and non-HEV group, the following make, model and year of vehicles were included (**Table 1**).

Table 1: characteristics of vehicles in HEV class and non-HEV class

HEV class				
Manufacturer	**Model**	**Year**	**Type**	**Number of vehicles**
Honda	Civic	2006 & 2009	Sedan	11
Toyota	Camry H	2008	Sedan	1
Toyota	Prius	2005-2009	Hatchback	8
Lexus	RX400H	2008	SUV	1
Non-HEV class				
Manufacturer	**Model**	**Year**	**Type**	**Number of vehicles**
Acura	TSX Premium	2009	Sedan	1
Chevrolet	Uplander	2008 & 2009	Mini-vans	9
Dodge	Nitro SXT 4RM	2007	SUV	1
Ford	Escape XLS	2006	SUV	1
Ford	Escape XLT 2RM	2008	SUV	1
Ford	Escape XLT I4	2009	SUV	3
Ford	Focus SE	2009	Sedan	5
Ford	Fusion SE	2009	Sedan	4
Honda	Civic DX	2008	Sedan	1
Honda	Civic DX G	2008	Sedan	1
Honda	Civic LX	2007	Hatchback	1
Hyundai	Elantra L	2008	Sedan	1
Mazda	3 Sport GS	2008	Hatchback	1
Mazda	3	2007	Sedan	1
Mazda	5 GS	2007	Mini-vans	1
Mazda	5 GT	2007	Mini-vans	1
Mercedes	C230 4Matic	2008	Sedan	1
Mitsubishi	Lancer SE	2009	Sedan	1
Nissan	Rogue TI	2008	SUV	1
Nissan	Versa SL	2009	Hatchback	2
Pontiac	G5	2008	Hatchback	1
Pontiac	Vibe	2009	Mini-vans	1
Saturn	Aura XE	2008	Sedan	1
Saturn	Ion	2005	Sedan	1
Subaru	Legacy 2.5GT	2007	Sedan	1
Toyota	Camry LE	2007	Sedan	1
Toyota	Corolla CE	2008 & 2009	Sedan	4
Toyota	Matrix	2009	Mini-vans	1
Toyota	Yaris	2009	Sedan	2
Volkswagen	Passat CC 2.0 TSI	2010	Sedan	1
Volvo	V50	2005	Mini-vans	1

RESULTS

This section starts with the results of the exploratory analysis for each of the methods being compared.

Real world driving (eco-driving study)

A summary statistics is presented in **Table 2** of the real-world performance of both HEVs and non-HEVs. Clearly from here, the important differences in fuel economy between HEV and Non-HEV can be seen, which on average goes from 9.18 to 16.85 lit/100 km. Note that the FCR of Non-HEVs was greatly influenced by the important subgroup of SUVs. When looking only at sedan vehicles, fuel efficiency of regular gasoline vehicles is 8.46 and 12.84 lit/100 km for sedan HEV.

Table 2: Summary Statistics of Tested Variables

Variable	Description	Mean		Std. Dev.	
		HEV	Non-HEV	HEV	Non-HEV
FCR	Fuel consumption rate (lit/100km)	9.18	16.85	8.13	12.79
idlepart	Fraction of time spent idling	0.06	0.11	0.14	0.18
avgspeed	Average speed on link (km/hr)	50.72	48.95	27.96	26.73
coldstart	Cold start (0=warm start,1=cold start)	0.19	0.18	0.39	0.36
linktype	Link type (0=city; 1=highway)	0.41	0.39	0.49	0.49
Training	(0: pre-training; 1: post-training)	0.76	0.70	0.43	0.46
hatchback	Vehicle is hatchback (0=no;1=yes)	0.37	0.03	0.48	0.16
sedan	Vehicle is sedan (0=no;1=yes)	0.57	0.39	0.50	0.49
suv	Vehicle is SUV (0=no;1=yes)	0.06	0.10	0.24	0.29
temp	Ambient temperature (C)	8.53	10.27	11.14	11.70
summer	June to August (0=no; 1=yes)	0.20	0.28	0.40	0.45
winter	December to March (0=no; 1=yes)	0.41	0.37	0.49	0.48
peak	Peak (0=the rest; 1=6-9am, 3-6pm)	0.53	0.44	0.50	0.50

With respect to hatchback vehicles, the conventional gasoline hatchback's fuel economy is 13.42 lit/100 km, whereas it is only 8.26 lit/100 km for the HEV hatchback. Overall, the difference between the fuel economy of HEV and non-HEV of the same vehicle class is quite significant, but the difference is less important when looking at the SUV class (13.50 and 14.84 for HEV and non-HEV SUV, respectively).

To explore the association of FCR with key factors such as, speed, a set of box plots were built for each vehicle category. **Figure 2** shows the fuel consumption box plots for non-HEV and HEV sedans. As expected, the effect of average speed is greatly associated with FCR that decrease in a non-linear way as speed increases. In the non-HEVs plot, a smoother curve can be observed, whereas for the HEVs, the curve has a bump between speeds of 40 to 60 km/hr. This could be explained by the fact that HEVs start using their gasoline engine at speeds around this range which results in more fuel consumption. Also the average FCR (black horizontal line in **figure 2**) is lower for the HEV sedans compared to Non-HEV.

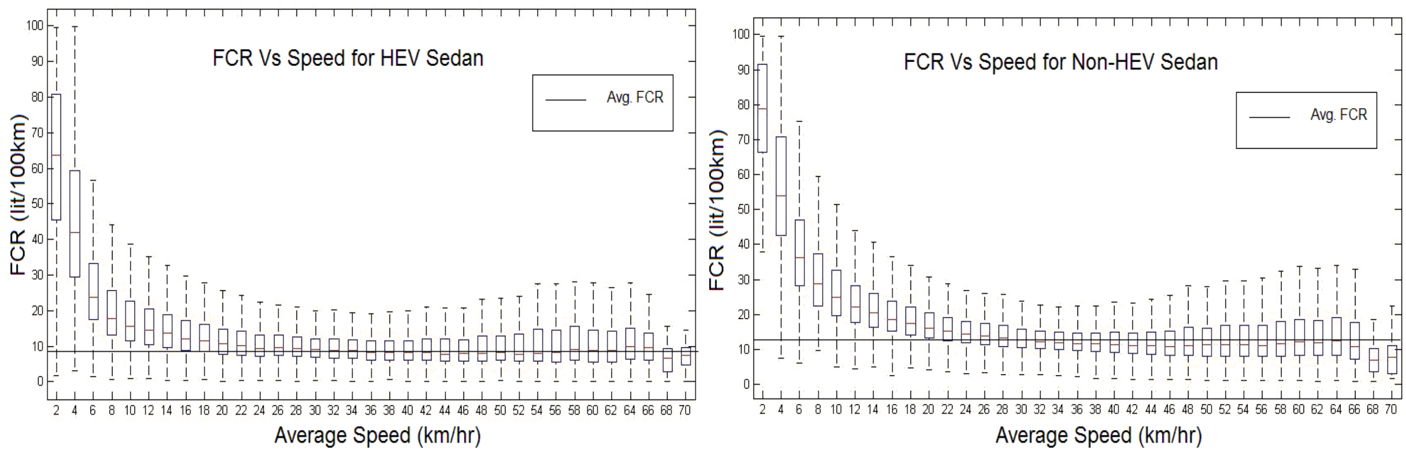

Fig. 2: Fuel consumption vs. speed box plot for non-HEVs and HEV sedans

Comparison fuel consumption curves (real-world different vehicle classes)

To explore the differences between technologies (HEV vs. non-HEV), FCR curves were generated to capture the effect of speed on this variable. Different non-linear relationships were attempted, from which a 2-parameter exponential growth curve ($FCR = b_1 \times b_2^{avgspeed}$) was found to be the best curve among other possible functions (based on R^2). Various curves were then built depending on the type of technology and road (highway vs. city). These curves along with their formulas are presented in **Fig 3**. From this figure we can see that the HEVs curve is below non-HEV curves which shows the better fuel economy of HEV.

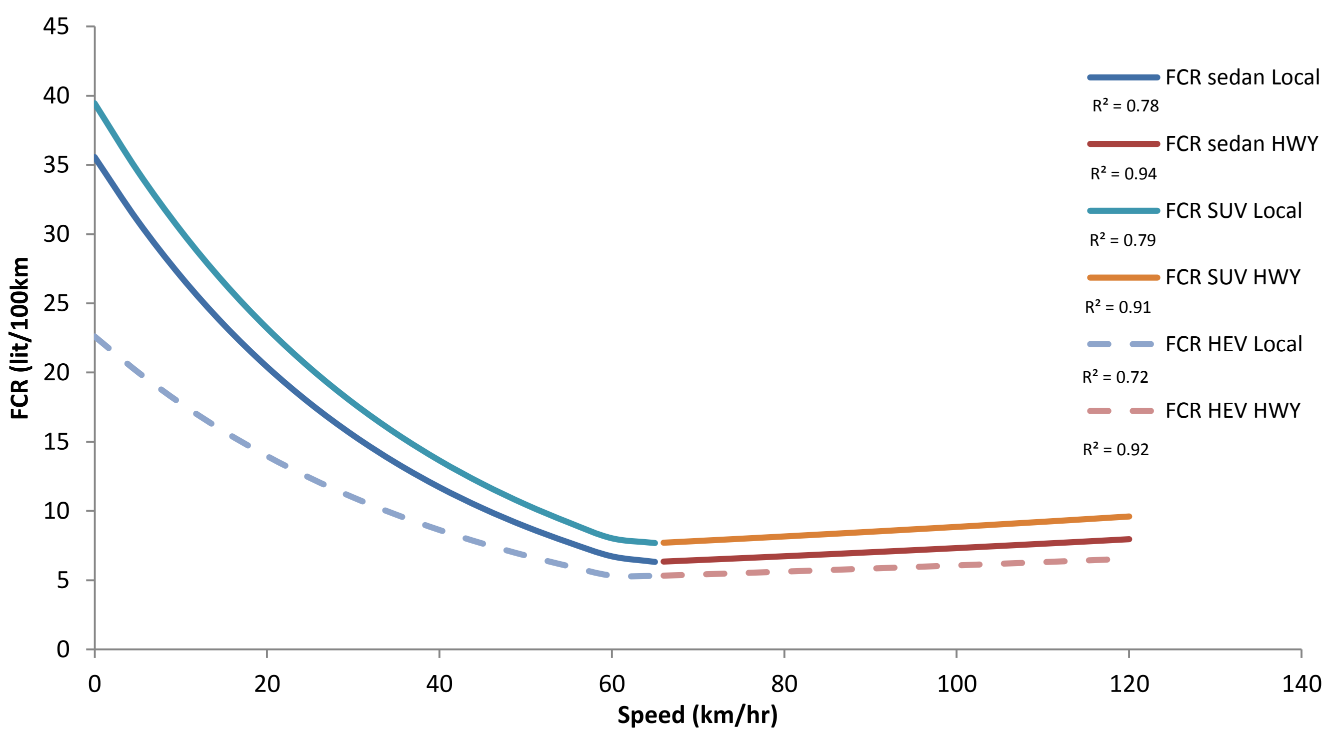

Fig. 3: Effect of speed and road type on FCR for different vehicle types (eco-driving study)

The highest FCR belong to SUV with its curve on top. It is also evident that the performance of HEVs with respect to regular vehicles is more important in local streets than highways. This is explained by the fact that the electro-motor is used at lower speeds to replace or help the combustion engine while at higher highway speeds the fuel consumption of a HEV is equivalent to a similar non-HEV sedan vehicle (*1*).

Comparison curves between the different methods

As the paper's title mentions, the main objective of this paper is to compare fuel consumption and eventually GHG emissions using three different methods proposed in the literature and previous research. In order to achieve this goal, fuel consumption curves for the different approaches were plotted. **Fig 4** presents these results. These curves are modeled using the raw data obtained from each method. Next, different non-linear relationships were attempted, from which a 2-parameter exponential growth curve ($FCR = b_1 \times b_2^{avgspeed}$) was found to be the best curve among other possible functions (based on R^2).

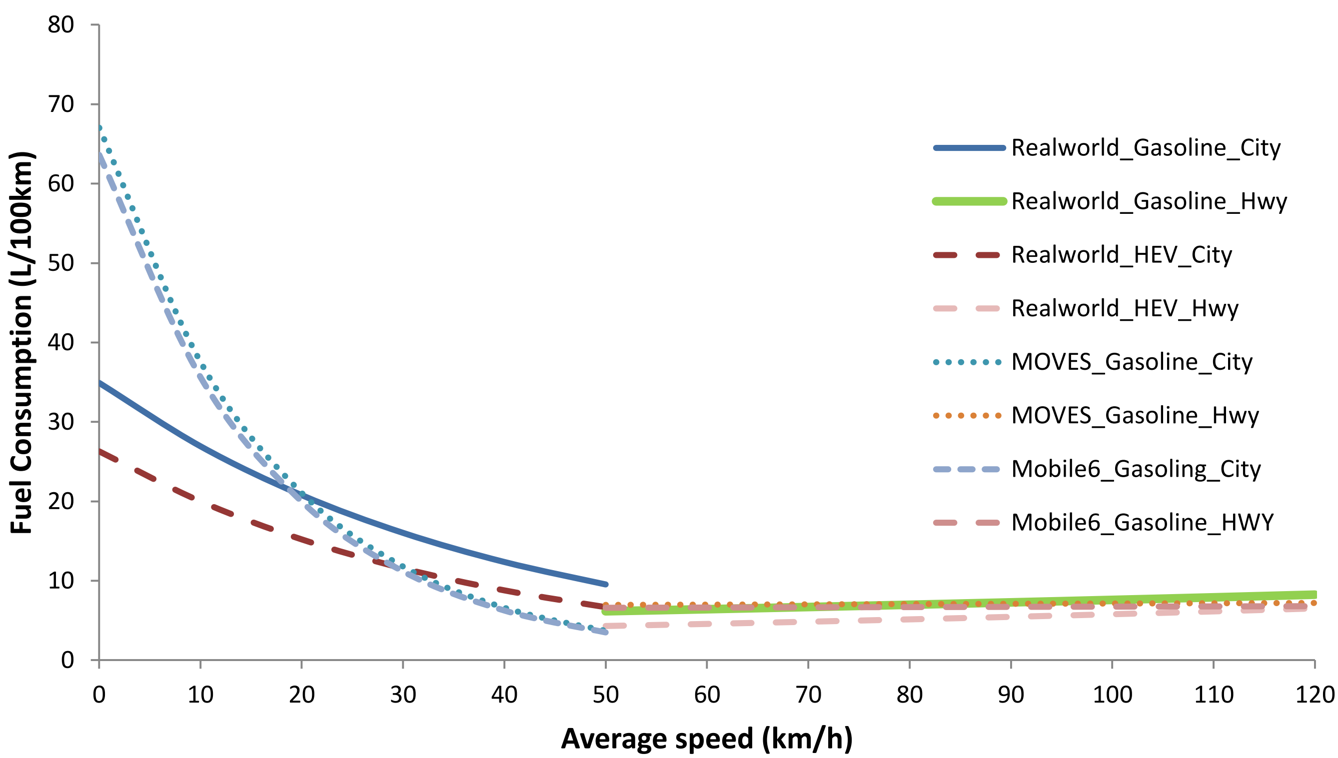

Fig. 4: Effect of road type and estimation methods on FCR

As one can observe from **fig. 4**, for each method a set of two curves have been plotted which are for highway and city driving. There reason being that one equation for both highway and city driving would not have a high enough R-square so a separation was needed. The other important observation is that the MOVES and MOBILE 6 city curves behave very differently for speeds less than 20km/hr comparing to the real-world observations. They predict higher fuel consumption comparing to real-world curves for this speed range.

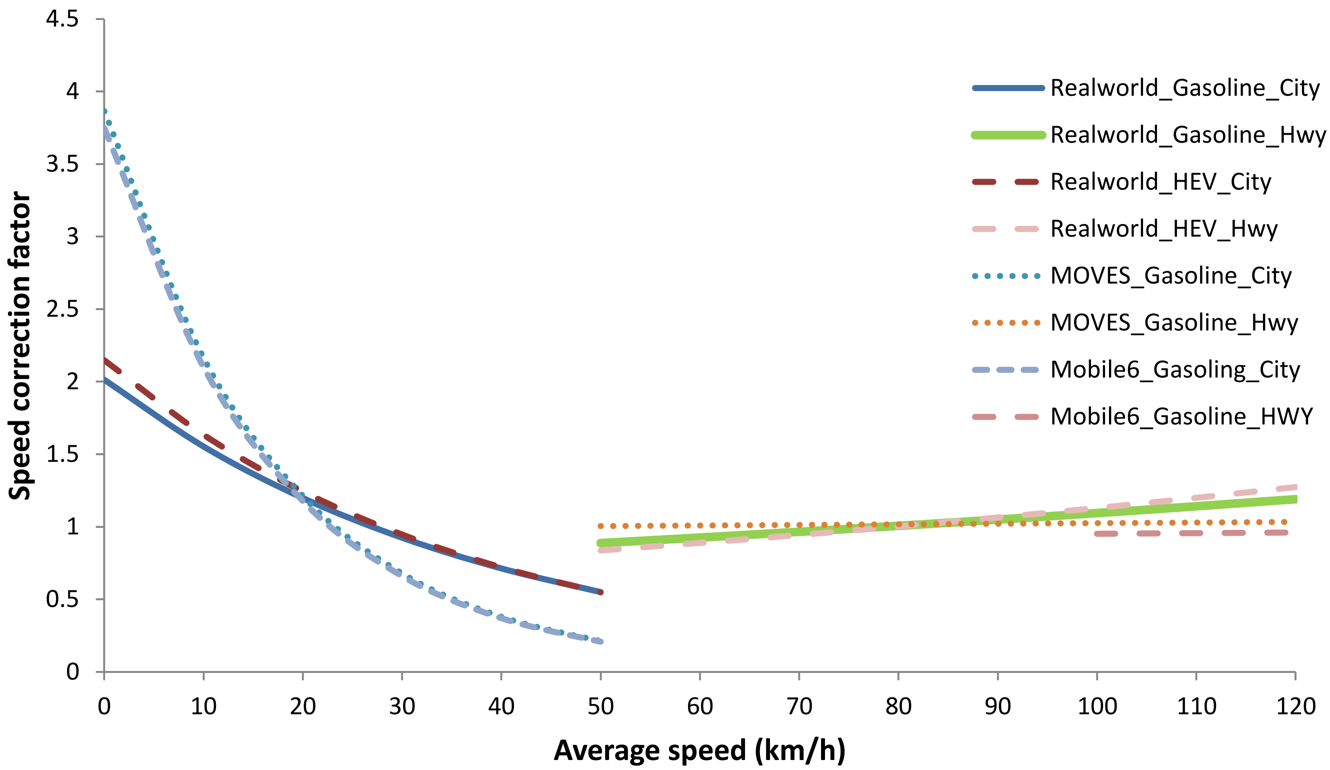

Fig. 5: Effect of road type and estimation methods on speed correction factor

In order to be able to use the curves obtained from the methods under comparison in the GHG emission calculation procedure, these fuel consumption curves are standardized to obtain speed correction factors. This is presented in **Fig. 5**. A similar pattern to what was observed in **fig. 4** is eminent here with the curves from MOVES and MOBILE6 having higher factors for speeds under 10km/hr. The highway curves on the other hand are very similar with a lot of overlaps. The high speed correction factors for MOBILE6 and MOVES could cause the GHG emission to go up for trips which are during peak hours (congested trips with lower speeds). On the other hand as has been stated in the literature, the MOVES and MOBILE6 curves do not capture the cold-start emission to the full extent which results in lower cold-start emissions. These curves are used as part of the GHG estimation procedure at the link segment level. For the real world observations, since both HEV and gasoline vehicle speed correction curves are very similar and overlap for most of the graph, an average curve has been used in the analysis. The output for the different methods are reported in **table 3**.

Table3: 2008, 2003 and 1998 transportation GHG at the household level (eco-driving, MOBILE6 and MOVES)

OD	Variable	Mean	Std. Dev.	Min	Max
1998	Total GHG (Eco-driving curves) (kg)	10.54	11.25	0	234.55
	Car GHG (Eco-driving curves) (kg)	10.09	11.15	0	234.55
	Total GHG (MOVES curves) (kg)	11.22	11.94	0	244.42
	Car GHG (MOVES curves) (kg)	11.72	12.03	0	244.42
	Total GHG (MOBILE6 curves) (kg)	11.17	11.89	0	243.33
	Car GHG (MOBILE6 curves) (kg)	11.67	11.98	0	243.33
2003	Total GHG (Eco-driving curves) (kg)	9.60	12.23	0	249.23
	Car GHG (Eco-driving curves) (kg)	9.30	12.07	0	227.68
	Total GHG (MOVES curves) (kg)	10.93	13.30	0	236.09
	Car GHG (MOVES curves) (kg)	11.29	13.47	0	257.75
	Total GHG (MOBILE6 curves) (kg)	10.87	13.23	0	234.79
	Car GHG (MOBILE6 curves) (kg)	11.23	13.40	0	256.34
2008	Total GHG (Eco-driving curves) (kg)	8.24	31.39	0	1714.00
	Car GHG (Eco-driving curves) (kg)	7.87	31.34	0	1714.00
	Total GHG (MOVES curves) (kg)	9.04	22.36	0	1597.61
	Car GHG (MOVES curves) (kg)	8.62	22.30	0	1597.61
	Total GHG (MOBILE6 curves) (kg)	9.00	22.26	0	1590.54
	Car GHG (MOBILE6 curves) (kg)	8.58	22.20	0	1590.54

In **table 3**, the term "total GHG" implies the sum of car and transit GHG at the household level. The overall total transportation GHG trend over the years (for each method) shows a decrease average. We believe this is due to the better fuel economy of the cars over the years and increased mode share of transit. This has been stated in previous research by some of the authors (*28*). Another more important output of **table 3** is the comparison in average total GHG values based on different fuel consumption curves used in the estimation procedure. On average we can see that MOVES and MOBILE 6 estimates are slightly higher than real-world eco-driving estimates. To be more precise, we can observe a 14% and 13% higher average GHG from MOVES and MOBILE 6, respectively, comparing to real-world. This is a slightly big difference which should be taken into account.

CONCLUSION

The impacts of a vehicle trip can only be quantified accurately by doing on-road measurements using a PFCMS or a PEMS to collect vehicle dynamics, engine data, road topography and tailpipe gas concentration of pollutants during operation. However, it is not feasible to measure every vehicle technology performing selected driving cycles, therefore numerical tools are commonly used to simulate vehicle operation. The literature has observed discrepancies between the measured data and what is modeled by MOVES and MOBILE6 (*9*). The goal of this study was to evaluate the effect of using different car fuel consumption curves on overall fuel consumption and GHG emissions of the city of

Montreal over a 10 year period. We also observed discrepancies between the measured data and these estimates, especially when associated with cold-start emissions and low speed (speed lower than 20km/hr). Among other results, the beneficial fuel efficiency merits of hybrid vehicles are demonstrated in particular in low speeds in urban (city) driving conditions. There is discrepancies between MOVES and MOBILE6, and real-world estimations in lower speeds. At speeds lower than 20km/hr the fuel consumption curves of the two former methods are slightly higher than the latter. However the former mentioned methods don't consider cold-start emissions. The average GHG emission obtained from MOVES and MOBILE6 are slightly higher than estimations based on real-world fuel consumption curves.
The overall total transportation GHG trend over the years (for each method) shows a decrease average. We believe this is due to the better fuel economy of the cars over the years and increased mode share of transit. This has been stated in previous research by some of the authors (*28*). Another more important output of **table 3** is the comparison in average total GHG values based on different fuel consumption curves used in the estimation procedure. On average we can see that MOVES and MOBILE 6 estimates are slightly higher than real-world eco-driving estimates. To be more precise, we can observe a 14% and 13% higher average GHG from MOVES and MOBILE 6, respectively, comparing to real-world. This is a slightly big difference which should be taken into account by researchers and EPA when launching the new version of MOVES.

As more work continues on the matter, more disaggregate fuel consumption measures will be used to validate the results. Data and analysis will be regenerated to measure the sensitivity of the results with respect to the level of data aggregation.

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