Fuel Economy and Emissions from Light-Duty Vehicles using Ethanol-Gasoline Blends and a Hybrid Vehicle under Conditions of a Mexican City

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ABSTRACT

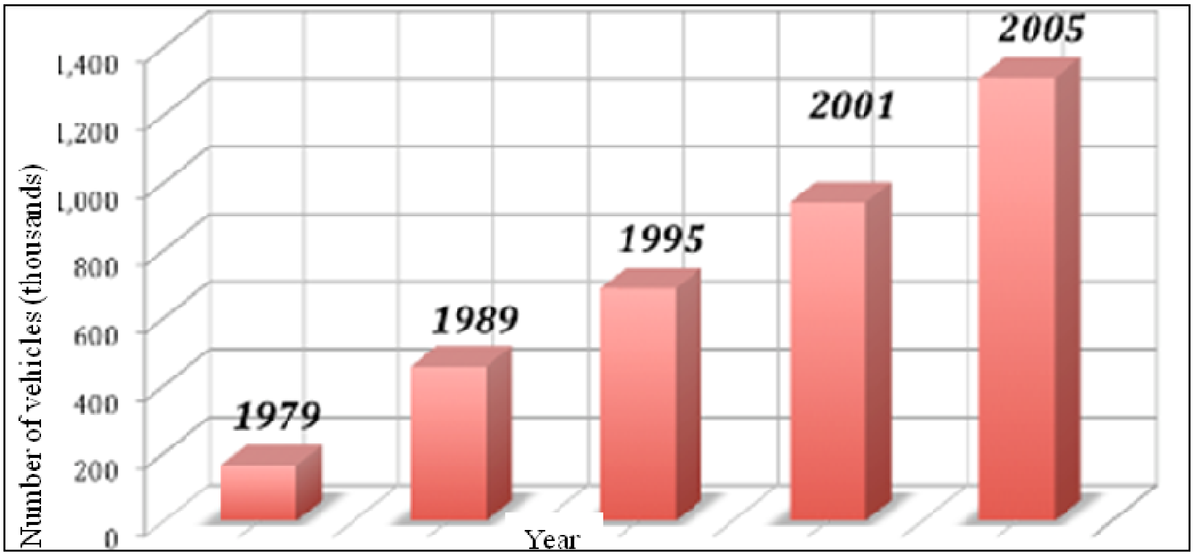
Assessing emissions from light-duty vehicles in Mexico is important because of their elevated contribution to the total amount of emissions from anthropogenic sources. The recent introduction of hybrid vehicles to the country and the programs that are set to start introducing gasoline oxygenated with ethanol represent an opportunity to reduce mobile source emissions. In this work, we present a study conducted to estimate fuel consumption of a hybrid light-duty vehicle and conventional light-duty vehicles using 5% and 15% v/v ethanol-gasoline blends. In addition, CO_2, CO, NO_x and total hydrocarbons (THC) emissions from cold-start, hot-start, controlled-circuit and real-world driving tests were also conducted. Results were compared to vehicles equipped with conventional internal combustion engines using regular gasoline blends. The results showed that the hybrid vehicle tested had a fuel economy (16.5 km/L) higher than that of the internal combustion vehicles (11.1 km/L) when driven in Monterrey, Mexico. The fuel economy dropped from 0.4% to 4.5% when the conventional vehicles used a 5% ethanol blend, while the reduction ranged from 3.0% to 9.9% when a 15% blend was used. With respect to emissions, the hybrid vehicle presented lower emissions than those of an internal combustion vehicle; the reductions were in the order of 43% for CO_2, 71% for CO, 80% for THC, and >90% for NOx. On the other hand, when ethanol-gasoline fuel blends were used, CO_2 and NOx emissions tended to decrease with respect to using the conventional blends, CO tended to increase, while THC a more erratic behavior.

INTRODUCTION

Atmospheric pollution has been one of the major environmental issues in the past years because of the increasing concentrations of primary pollutants emitted to the air, such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), sulfur dioxide (SO_2) and suspended particulate matter, and because of the reactivity of some of these species which produces secondary pollutants such as ozone (O_3), aldehydes, nitric acid, secondary organic aerosols, among others.[1] The presence of contaminants in the atmosphere has been found to cause adverse effects in human health. For example, inhalation of high levels of CO can produce poisoning, as it replaces oxygen in the blood's hemoglobin,[2] and high concentrations of SO_2 may cause severe lung damage and bronchial tube inflation.[3]

Emissions produced by mobile sources are of increasing interest in Mexico because they generate an important percentage of primary pollutants emitted to the atmosphere, especially in urban areas.[2] For example, in the Monterrey Metropolitan Area (MMA), mobile sources produced 99% of the CO, 64% of the NOx, and 8.1% of the SO_2 emitted in 1999.[4] Additionally, 92% of the total CO_2 emitted during 2002 was generated by the transportation sector.[5] This level of pollutant production may worsen with the increasing amount of vehicles in Mexican cities. For example, the MMA has a large vehicular fleet which has been increasing in size during the past years, as presented in Figure 1.

Figure 1. Vehicular fleet growth in Monterrey, Mexico from 1979 to 2005.



Source: Nuevo Leon State Council for Transportation and Highway Administration (*Consejo Estatal de Transporte y Vialidad del Estado de Nuevo León*), 2005.

Due to the size of the vehicular fleets and global pollution levels emitted from these sources, new engine technologies and alternative fuels have been studied in recent years searching for low emissions and higher fuel economy. For example, hybrid vehicles were introduced in the country in 2006 and there is a federal government program to start introducing gasoline-ethanol fuel blends in the major metropolitan areas. Hybrid vehicles have been studied since they were released to the market about 15 years ago. Different investigations have shown they have a higher fuel economy than conventional vehicles powered solely by internal combustion engines.[6,7] Thus, the total emissions produced by hybrid vehicles are, in principle, less. Other studies have found that ethanol-gasoline fuel blends provide lower emissions of hydrocarbons (HC) and CO compared with regular gasoline blends,[8,9] even though fuel economy is impacted negatively due to the decreased energy these ethanol blends possess (measured as lower heating value).[10]

Pollutant emissions from vehicles have been widely studied using dynamometer tests and more recently real driving cycles.[11,12] This last technique has been of interest because it generates information under different transit conditions without the controlled performance of a laboratory dynamometer test. Different driving cycles have been developed, being the FTP (Federal Test Procedures) one of the most used.[13] This study focused on the assessment of the environmental performance of a hybrid vehicle and conventional vehicles powered with ethanol-gasoline blends compared with conventional vehicles powered by regular (commercial) gasoline blends. Of particular interest were the fuel economy of the vehicles and the characterization of their emissions.

METHODS

Fuel economy was estimated for two different groups of vehicles considering normal driving patterns in the MMA. The first (Group 1) consisted of four internal combustion engine Honda Civics (1.8 L and 2.0 L displacement) and one Honda Hybrid Civic (1.3 L). The second group (Group 2) included a Nissan (1.8 L), a VW (1.4 L) and a Jeep (2.4 L). The fuel economy of the first group was only estimated for regular (unleaded) gasoline (87 octanes), while the second group used regular gasoline and its corresponding 5% v/v and 15% v/v gasoline-ethanol (E05R and E15R, respectively) blends and premium (unleaded, low sulfur) gasoline (92 octanes) with the same v/v blends with ethanol (E05P and E15P, respectively). Fuel economy for Group 1 vehicles was estimated for city and out-of-city road usage from fuel tank loads; when possible, on-board vehicle computer millage records were also registered. Fuel-economy for Group 2 vehicles was calculated from in-tank fuel volume differences between the start of the test and end of the test. In these cases, a known amount of fuel was loaded to the empty vehicle tank (the tank was disassembled), and after the test the fuel deposit was purged to obtain the final fuel volume (again, disassembling the tank).

Emission characterization was performed for three different modes (cold-starts, hot-starts and real-world driving cycles) for one of the Honda Civics with conventional-engine (1.8L) from Group 1, the Hybrid Honda Civic (1.3L) and all the vehicles in Group 2. Each group was studied with the fuel types described above. Pollutant concentrations in the automobile's exhaust were measured with a Snap-On AL293-001 (Kenosha, WI) portable gas analyzer. The device is capable of determining the concentrations of total hydrocarbons (THC), O_2, CO, CO_2 and NO_x.[14,15] The range, precision and resolution of the device are presented in Table 1.

Table 1. Measurement characteristics of the gas analyzer used for emissions testing.

Compound	Range	Precision	Resolution
THC	0-30,000 ppm	±3%	1 ppm
O_2	0-25%	±5%	0.01 ppm
CO	0-15%	±3%	0.01 ppm
CO_2	0-20%	±3%	0.01 ppm
NO_x	0-5,000 ppm	±4%	1 ppm

Cold-start emissions are of interest since it has been demonstrated that high emissions occur during the first 90-300 seconds after the engine has been started.[11,16] Cold-start emissions were characterized during the first 90 seconds after the engine was started, after 12 hours of being turned off.[11] During hot-starts, emissions can also be high and thus they are of interest. Hot-start characterization was performed 10 minutes after the vehicles were turned off.[12] In both cases, sampling began 10 seconds after the vehicle was turned on to purge gases from the system. Real transit characterization was performed on a city driving cycle based on the FTP. The cycle included a section of multiple accelerations (low transit), constant mid velocities (suburban transit, approximate velocity of 60 kph) and constant high velocities (freeways).[13] The driving cycle was 14.7 km long.

Emission factors were calculated assuming ideal gas behavior of the combustion gases and considering the engine characteristics of the vehicle being tested, as expressed in Equation 1.

Equation (1) $$E_i = \frac{1}{d}\int_{t_o}^{t_f} D\left(\frac{rpm}{2}\right)\left(\frac{y_i P}{RT} M_i\right) dt$$

where,

E_i = emission factor for species i (mass emitted per distance travelled)
D = engine fuel-air mixture displacement
rpm = revolutions per minute of the engine
y_i = mole fraction of the pollutant in the exhaust
P = ambient pressure
R = ideal gas constant
M_i = molecular weight of species i
d = distance travelled in the test

Equation (1) was integrated for the duration of the tests (t_o to t_f) considering that the time interval between the sampled data was 1 s. When calculating the emission factors for the cold- and hot-start tests, Equation (1) is modified to report only mass emitted for the duration of the tests (90 s) by eliminating the distance travelled term.

RESULTS

Fuel Economy Results. Fuel economy for the Hybrid Civic and the average from the conventional Civics of Group 1 was 16.5 km/L and 11.1 km/L, respectively. The results obtained for Group 2 are presented in Table 2. The average fuel economy of the conventional vehicles in Group 1 is similar to those of the vehicles 1 and 2 in Group 2 for both types of commercial gasoline free of alcohol.

Table 2. Fuel economy results for Group 2.

Gasoline blend	Vehicle 1 (1.4 L)	Vehicle 2 (1.8 L)	Vehicle 3 (2.4 L)
Regular	10.86 ± 0.08	9.53± 0.12	6.61± 0.22
Premium	10.15 ± 0.10	9.33± 0.05	7.28± 0.09
E05R	10.48± 0.12	9.11± 0.06	6.34± 0.07
E05P	9.89± 0.04	9.06± 0.08	7.26± 0.03
E15R	9.79 ± 0.13	8.88± 0.20	6.27± 0.12
E15P	9.66± 0.09	8.82± 0.05	7.06± 0.05

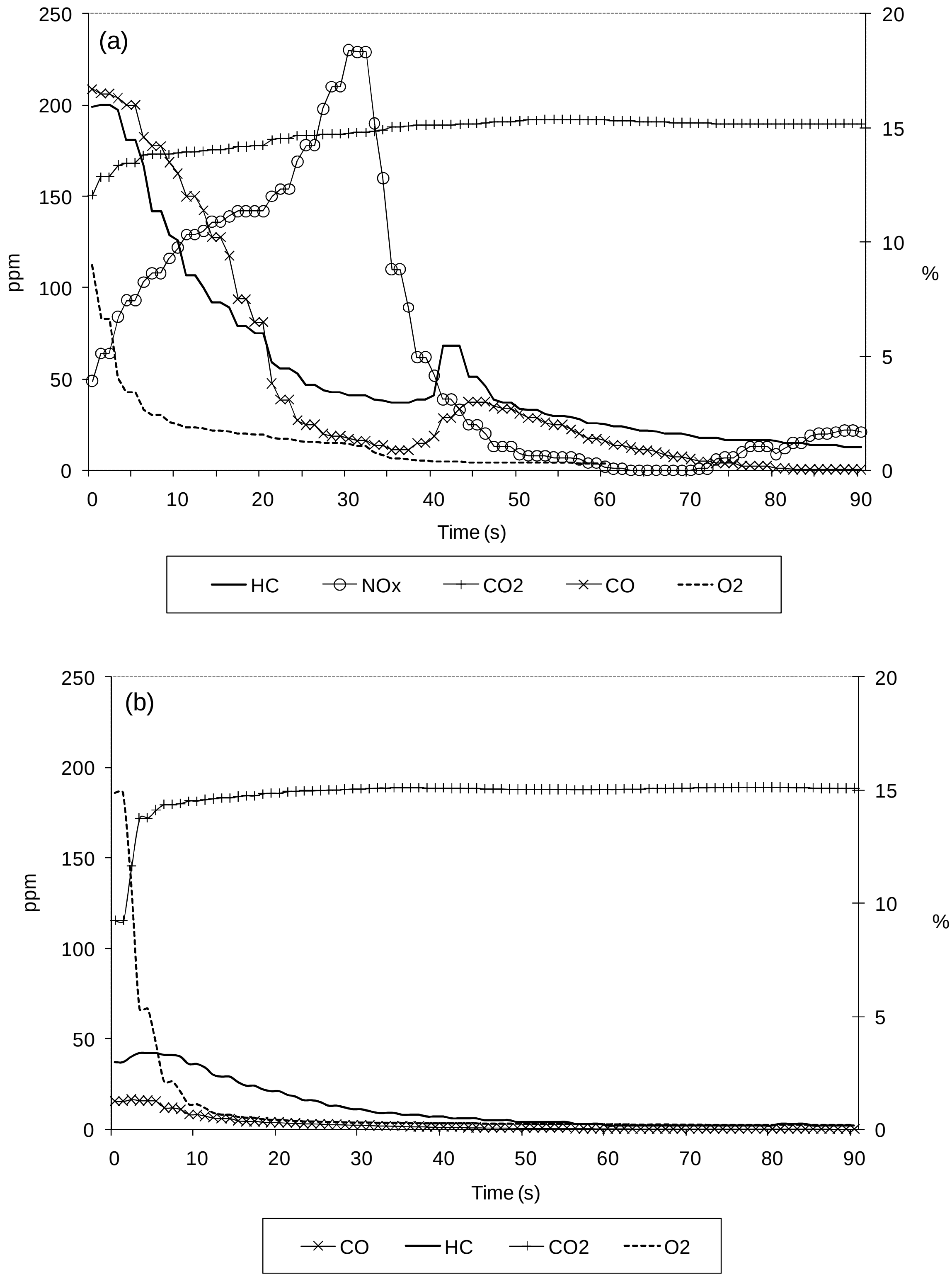
The hybrid vehicle had a fuel economy 48.6% higher than the average of the conventional vehicles in Group 1. In comparison with Group 2, it was 51.9%, 73.1% and 149% higher for vehicles 1, 2 and 3, respectively, when using regular gasoline (87 octanes) which was the only one used to test the hybrid automobile. When comparing the fuel economies of Group 2 vehicles, there was a statistically significant difference (95% confidence) when using the different gasoline type and blends. Table 3 presents the percent difference in fuel economy when comparing each type of gasoline-ethanol blend with respect to the commercial gasoline fuel (either Regular or Premium). The decreased fuel economy, especially for the 15% v/v ethanol-gasoline blend, is probably due to the lower heating value obtained when adding the alcohol.[7]

Table 3. Percentage decrease in fuel economy for Group 2 vehicles with respect to the corresponding commercial fuel.

Gasoline	Vehicle 1 (1.4 L)	Vehicle 2 (1.8 L)	Vehicle 3 (2.4 L)
E05R	3.5%	4.5%	4.1%
E05P	2.6%	2.9%	0.4%
E15R	9.9%	6.9%	5.2%
E15P	4.8%	5.5%	3.0%

Cold- and Hot-Starts Emission Factors: Emission levels during one of the cold-start and hot-start emissions test for the hybrid vehicle are shown in Figure 2 to exemplify the type of behavior obtained in these type of tests. As it can be observed, the concentrations tend to be higher during cold-starts and they take longer to stabilize. The same behavior was observed for all the vehicles studied, even when ethanol-gasoline blends were used.

Figure 2. Pollutant concentrations during cold-starts (top panel) and hot-starts (bottom panel) for the hybrid vehicle. In both panels: CO_2 and O_2 in %; CO in % × 100, and HC and NO_x in ppm (for the hot-start test NO_x levels were below the detection limit of the device).



For Group 1, CO, THC and NO_x emission factors (EF) estimated for cold-starts were higher than those obtained for hot-starts (Table 4), whilst CO_2 emissions were higher during the hot-start tests. This is a result of the higher temperature of the engine which promotes a more efficient combustion and better catalytic converter functioning during the second test.[17,18] Comparing technologies, the emissions from the hybrid vehicle were typically less than the emissions from the conventional vehicle. A similar result was obtained for vehicles in Group 2: all EF were lower in the hot-start tests with respect to the cold-start tests for the same fuel blend. CO_2 emissions tended to be higher when the commercial fuel blend was used and lower with a 5% v/v ethanol blend. NOx tended to be lower when using ethanol in the fuel (a marginal increase was obtained for the hot-start tests using the E05P blend). THC tended to decreased in all cases with the exception of the cold-start tests using the E05P blend. CO had a more erratic behavior.

Table 4. Emission factors (grams per episode; i.e., 90 s) for cold- and hot-starts of Group 1 vehicles: Hybrid vehicle (HV) and conventional vehicle (CV). Engine *rpm* were set to 1500 in all tests.

	Cold-starts		**Hot-starts**	
Pollutant	**HV (21 samples)**	**CV (10 samples)**	**HV (14 samples)**	**CV (10 samples)**
CO_2	325.2	369.2	330.1	437.9
CO	0.59	2.33	0.27	0.19
THC	0.21	1.62	0.01[a]	0.04
NO_x	0.06	0.95	b.d.l.[b]	0.16

[a] A high percentage of measurements were close or below the device detection limit; [b] Below detection limit.

Table 5. Average emission factors (grams per episode; i.e., 90 s) for cold- and hot-starts of Group 2 vehicles. Each type of fuel was sampled 5 times in each vehicle. Engine *rpm* were left to attain idle speed levels (~800 rpm).

Fuel-type	**Cold-Start**				**Hot-Start**			
	CO_2	**CO**	**THC**	**NO_x**	**CO_2**	**CO**	**THC**	**NO_x**
Regular	319.5	19.4	0.73	0.27	242.7	10.8	0.22	0.10
E05R	290.8	20.0	0.65	0.20	235.1	9.6	0.22	0.06
E15R	293.0	21.5	0.39	0.15	233.4	15.7	0.20	0.10
Premium	296.9	15.6	0.54	0.15	255.0	2.56	0.25	0.05
E05P	275.0	14.4	0.69	0.12	245.6	2.7	0.22	0.05
E15P	287.1	10.1	0.38	0.09	249.8	1.9	0.11	0.04

Driving Cycle Emission Factors: Pollutant emissions behavior during the in-city driving cycle is exemplified in Figure 3. In the graphs, the major difference between the hybrid and conventional vehicles occurs during the low transit sections. During these periods, the vehicles undergo a stop-and-go mode. In particular, the hybrid vehicle, when stopped, shuts down the burning of gasoline. Thus, the levels of CO_2 emitted drop to near 0% and the oxygen increases to nearly 20%. The tests for Group 2 vehicles presented similar behavior as the conventional vehicles in Group 1.

Emission factors for vehicles in Group 1, for the three sections of the driving cycles, are presented in Table 6. In every case, the emissions from the hybrid vehicle are lower than the emissions from the conventional one. In addition, CO_2 emission was the lowest in low speed transit (frequent breaking and accelerating), in both vehicles. The emission factors for the entire driving cycle for Group 2 vehicles are presented in Table 7. It can be observed that CO_2 and NOx emissions tend to drop as there is a higher percentage of ethanol on the fuel mixture, while CO tends to increase. THC has a more erratic behavior: increases when the regular gasoline is used and decreases when the premium gasoline is used.

Figure 3. Emissions during real-world driving cycles for Group 1 vehicles: Hybrid Vehicle (top panel) and Conventional Vehicle (bottom panel). CO, NOx and HC in (ppm); CO_2 and O_2 in (%).

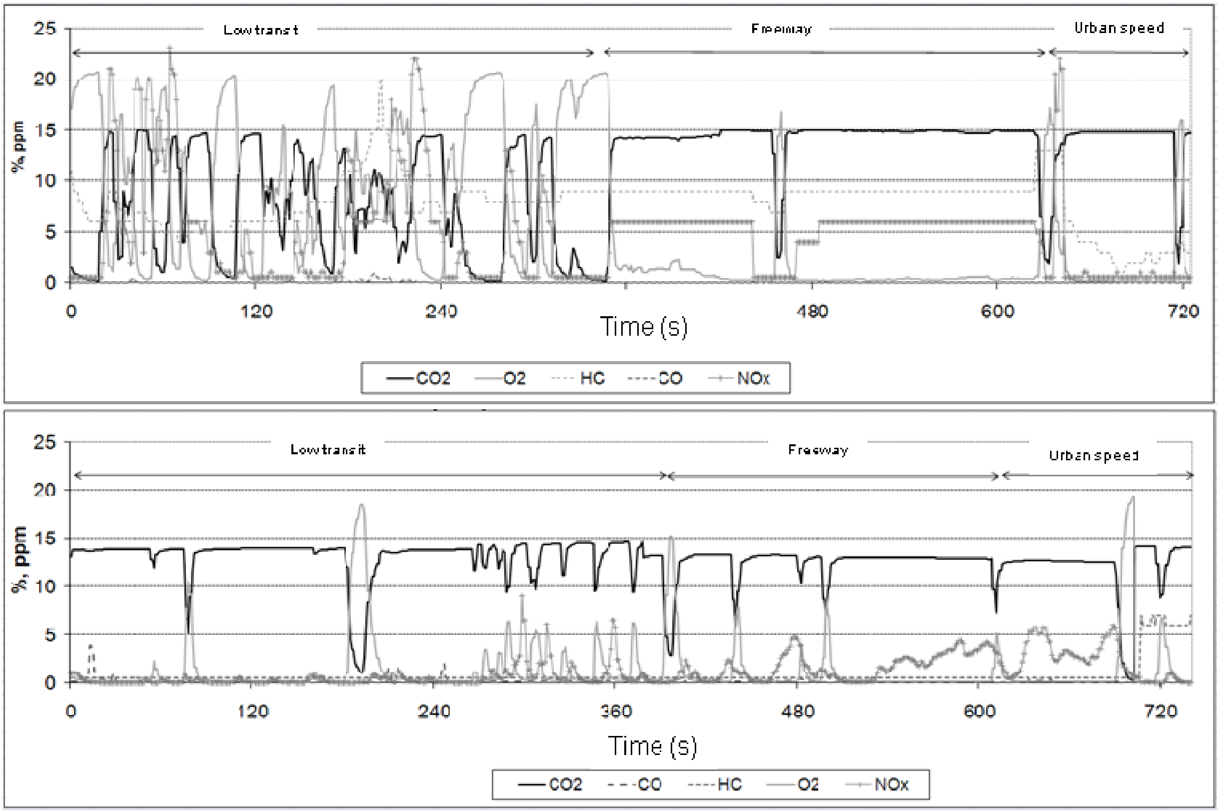


Table 6. Emission factors (g/km) for Group 1 vehicles when driven in the "real-world" driving cycle.

Pollutant	HV Low transit	HV Urban speed < 60 kph[a]	HV Freeway ~ 80 kph	CV Low transit	CV Urban speed < 60 kph	CV Freeway ~ 80 kph
CO_2	165.9	204.4	210.2	288.9	347.5	366.8
CO	0.2	0.2	0.2	0.7	0.8	1.5
THC	0.02	0.03	0.02	0.1	0.1	0.02
NO_x	b.d.l.	b.d.l.	b.d.l.	0.4	0.3	0.3

[a] kph: kilometers per hour.

Table 7. EF (g/km) for Group 2 vehicles in-city driving mode.

Fuel	Pollutant			
	CO_2	CO	THC	NOx
Regular	241.3	2.18	0.02	0.11
E05R	238.8	3.20	0.03	0.07
E15R	196.2	3.53	0.03	0.09
Premium	236.1	0.66	0.05	0.18
E05P	242.0	2.18	0.02	0.11
E15P	211.2	4.19	0.03	0.10

CONCLUSIONS

The highest fuel economy found during this investigation was that of the hybrid vehicle studied. Gasoline-ethanol mixtures showed a decrease in fuel economy of 0.4%-4.5% and of 3.0%-9.9% for the 5% v/v and 15% v/v mixtures being evaluated. Further research would clarify if this tendency remains with larger vehicles. The emission of pollutants found for the different vehicles showed that the lowest emissions were obtained for the hybrid vehicle. Emissions of CO_2 and NOx decreased when using gasoline-ethanol fuel mixtures, while CO emissions tended to increase. THC presented an erratic behavior with respect to the fuel mixture used. Even though the amount of vehicles used in this study was very small, results gives indication of what could be expected if the technologies and fuel blends explores are used massively in the MMA.

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KEYWORDS

Mobile sources
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