A METHODOLOGY PROPOSAL FOR A REAL DRIVING CITY CYCLE IMPLEMENTATION IN CHASSIS DYNAMOMETER FOR EMISSION TESTS

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Abstract. *In this paper, PETROBRAS Research Center (CENPES) proposes a new methodology for real driving city cycle implementation in chassis dynamometer for emission measurement. The new cycle is an average traffic cycle, representative of a route performed during emission field tests in the city of São Paulo.*

Tests on emission laboratory with real driving city cycle will allow the assessment of, e. g., the effects of a new fuel formulation in local fleets under controlled conditions. Another possible application is emission inventory estimations of mobile sources without the need of the on-board equipment, which is generally an expensive method and has low repeatability due to traffic variations.

To generate the new cycle, 26 profiles of instantaneous speed data were acquired during the field tests and a medium speed distribution was calculated. For its implementation in the laboratory, analyses were made regarding gear shift points, conduction pattern and exhaust gases collecting phases.

The emission results obtained with this new cycle are analyzed and compared to those generated by the EPA FTP-75 cycle, upon which the Brazilian Standard ABNT NBR-6601 is based. The latter is used to certify light duty vehicles in the country. Following the EPA FTP-75 cycle, a brief assessment of the effects of cold start in tailpipe emissions is also presented.

The proposed methodology to reproduce a field route was efficient and can be used in future studies.

Keywords*: Emission Tests, Methodology, On Board, Chassis Dynamometer*

1. Introduction

An important source of atmospheric pollution is related to mobile emission, since vehicular fleets around the world are growing continuously. This general concern is the motivation for many countries around the world to dedicate considerable effort in the definition of environmental legislations to regulate vehicular exhaust gases emission limits. Those are directly related to engine and catalytic converter systems technologies, fuel specifications and vehicle maintenance policies.

In order to monitor and quantify these emission sources, some measurement methods were developed and are currently in use. Depending on the application, vehicular emission measurements can be made by a specific method (Frey *et al.*, 2001, Frey and Unal, 2002).

Chassis and bench dynamometer tests are carried out in laboratory facilities and are performed under controlled conditions, following a specific driving cycle built to simulate road operation. Driving cycles are supposed to represent stops, accelerations, decelerations, idle and cruise modes into a unique speed *versus* time profile. This method is strongly indicated when repeatability is mandatory. On the other hand, it may under predict certain events that impact the exhaust emissions and could only be reproduced by the car running on the streets, such as high accelerations, driver behavior variations an so on. Dynamometer tests are generally used in the development of fuels and vehicles, vehicle certifications and in-use vehicle inspection.

Remote emission tests are made by using infrared (IR) or ultraviolet (UV) spectroscopy and are able to measure pollutant concentrations when a vehicle passes through the sensor installed on the roadway. The main advantage of this method is its ability to measure a large number of on-road vehicles, with relative low costs. However, it can only provide an instantaneous estimation in a specific location. It is often applied on emission monitoring to evaluate inspection and/or maintenance programs effectiveness, identification of potential high emission vehicles and in emission factors development.

On-board emission measurements are the most realistic method to portray the actual on-road emission behavior, since data are collected while in-use vehicles are in real world conditions. Its major gain is to obtain the variations while road characteristics, driver behavior, traffic conditions, vehicle location, environment variations and even unexpected events may interfere the travel performing. It is the most desirable method to be applied in studies regarding the development of emission factors and emission inventories in order to assess global emissions for a given city or region. However, these studies normally require a large number of vehicles and many different route paths to be representative enough of local conditions, therefore being highly costly. Efforts are being devoted to produce lower-cost equipment. On-board emission tests are not applicable when some repeatability level is required, exactly due to the on-road variations which make each trip unique.

In 2004, PETROBRAS has taken part in the Brazilian phase of a joint research project aimed to raise environmental information related to light-duty vehicles in some of the main South American cities as guidelines to develop local environmental policies (Carvalho and Melo, 2004). Tests were made by using an on-board equipment set to obtain, in a second-by-second basis, values for CO, HC, NOx and CO_2 emission levels and speed *versus* time information of a local fleet running under local conditions in the city of São Paulo. The equipment and measurements were under a foreign technical group responsibility.

As the company was also interested in evaluating some specific fuel comparisons under local conditions, more accurate experiments under controlled conditions were necessary. Then, a methodology to simulate the route performed during the field tests on a chassis dynamometer was developed and implemented on CENPES.

Based on a data set of 26 valid speed profiles recorded during the tests and on the gear shift points specified for each vehicle, an average cycle was generated. Despite acceleration behavior is an important factor that affects vehicular emissions, this information was not available on the data set. The main purpose was not to obtain the most representative cycle for the city of São Paulo but, to simulate the only trip route used in the field tests. As only one driver has made the trips, following the gear shifts tables, it was accepted that the generated average cycle would be enough for the laboratory tests purposes.

This paper presents the methodology applied to create the new cycle, named SP04, and to implement it on a chassis dynamometer of CENPES. It also presents some comparisons between the results obtained with SP04 and EPA FTP-75 cycles. An analysis of the cold start effect in emission is also presented.

2. Emission Legislation

The Brazilian vehicular emission legislation is regulated by the National Environmental Council (CONAMA) that is an institution of the Ministry of the Environment (MMA). In 1986 a program called PROCONVE (Motor Vehicle Air Pollution Control Program) was introduced in order to establish pollutant emission levels based on tests results carried out on a chassis dynamometer following the Brazilian Standard ABNT NBR 6601, which is based on the EPA FTP-75 cycle, performed in km/h. PROCONVE is a program coordinated by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA). Currently, PROCONVE is in its Phase IV, whose limits for light-duty vehicles are listed in Tab. 1. This phase will be fully implemented in 2007.

Table 1. PROCONVE phases with respective vehicular pollutant emission limits.

Phase	Year	CO (g/km)	HC (g/km)	NOx (g/km)	CO idle (g/km)	Aldehydes (g/km)
I	1988	24.0	2.1	2.0	3.0	-----
II	1992	12.0	1.2	1.4	2.5	0.2
III	1997	2.0	0.3	0.6	0.5	0.03
IV	2007	2.0	0.16	0.25	0.5	0.03

3. Brazilian Fuels and Vehicles

Brazilian fuel specifications are established by the National Petroleum Agency (ANP). Three different motor fuels are currently available in the national market as follows:

- Gasohol (E25) – Blend 75% gasoline and 25% anhydrous ethanol;
- Hydrated Ethanol; and
- Compressed Natural Gas (CNG).

Based on these three fuel types, the national light-duty vehicles market is shared by: gasohol (E25) dedicated engines; hydrated ethanol dedicated engines; converted engines to run with CNG; and flex-fuel engines that are able to run with any blend of gasohol (E25) and hydrated ethanol.

4. Field Tests

The original project test schedule was planned to accomplish on-board measurements in light duty vehicles during one week. The equipment and measurements were under a Canadian technical team responsibility that was only available during this period. 25 tests were originally scheduled.

Based on this limited format, a vehicle matrix was established considering all vehicles types, PROCONVE phases, vehicle sale volumes and the current São Paulo fleet composition.

Additionally to the main scope of the project, PETROBRAS identified an opportunity to obtain some comparative information for Brazilian fuels under local conditions. As comparative tests would be necessary to obtain these results, it was decided that the simulation of the on-road route on the chassis dynamometer should be done.

The test route was defined considering the work site location. This place was used to prepare the vehicles and to install the equipment before each trip. Five alternative routes were evaluated and classified according with time and distance in free flowing and congested traffic conditions. This analysis was made by running five different cars for each route during an entire day. Figure 1 shows a schematic map with the route in the city of São Paulo.

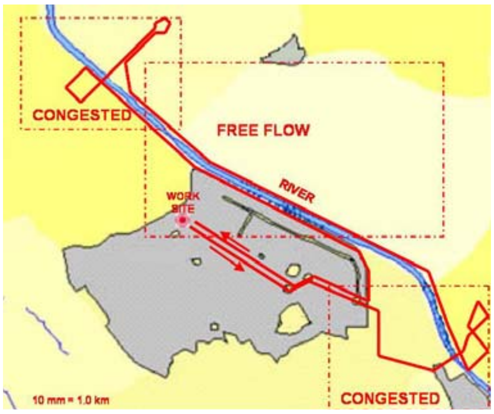

Figure 1. Map of the field test region, showing the route in the city of São Paulo.

The equipment output records provided emission values of CO, HC, NOx and CO_2, as well as speed *versus* time profiles for each trip. The speed data acquisition was made by using a speed sensor based on the Doppler Effect that was available in the equipment set. In order to minimize the influence of the driving pattern, only one driver drove all vehicles, following the gear shift points established for each car. Acceleration information was not available on data records, however as the objective was not to build the most representative route for the city of São Paulo, but to simulate the test route on the dynamometer, it was considered that the available information would be enough for this purpose.

5. Cycle Development

5.1. Cycle Definition Methodology

At the end of tests, the route to be simulated in the chassis dynamometer was recorded into 26 speed *versus* time profiles and one cycle should be built from these data. The first approach was to calculate an average profile based on the available data. A quick analysis have shown that each speed data was very similar. However, idle, acceleration, cruise and deceleration events did not occur at the same instant on each test run, due to traffic variations. The elapsed trip time ranged between 36.2 minutes and 67.4 minutes.

Thus, it would be necessary to create a way to standardize the profiles. It was made by calculating histograms, one for each data set, representing speed level percentage distributions based on 10 km/h intervals. Average speed, total distance and elapsed trip time values were also assessed for each trip data. After this analysis, an average histogram and mean values for the above characteristics were calculated. Figure 2 shows the calculated average histogram, where "Trip %" is the percentage of each speed level occurrence during each test trip.

In addition, the sum of square errors (SSE) between each histogram and the average one was performed. The SSE was calculated by the sum of the squared differences between each speed category percentage (v_i) and the corresponding speed category of the average histogram ($\bar{v}_i$) as shown in Eq. 1.

$$SSE = \sum_{i=1}^{n} \left(v_i - \bar{v}_i\right)^2 \qquad (1)$$

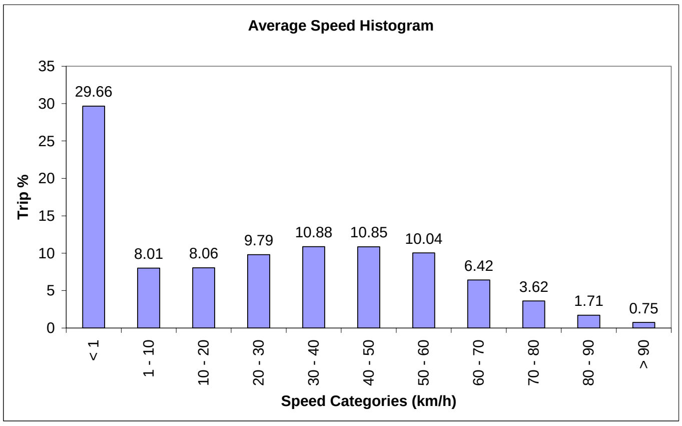

Figure 2. Average route speed histogram based on 26 test speed profiles

The cycle that best portrays the test route has to match the average histogram, the average values of average speed, trip distance and trip time and also the lower SSE value. The criterion to select the average cycle was to compare the above parameters with those previously calculated for each trip speed profile. Table 2 shows a summary of each data set characteristics including percentage differences between the characteristics of each trip and the corresponding mean values.

Table 2. Data set characteristics for the 26 trips in the field tests.

RUN ID	**1#1**	**1#2**	**1#4**	**1#5**	**2#1**	**2#2**	**2#3**	**2#4**	**2#5**	**2#6**	**3#1**	**3#2**	**3#3**
Average Speed (km/h)	23.45	36.38	37.87	26.36	24.84	28.38	22.32	20.96	26.92	21.53	24.75	21.90	29.00
Trip Length (km)	21.94	21.98	25.02	23.06	23.52	21.51	21.28	23.55	23.55	23.44	20.89	20.89	21.45
Trip Time (min)	56.15	36.25	39.65	52.50	56.82	45.48	57.20	67.40	52.50	65.32	50.63	57.24	44.37
% Average Speed	-14.25%	33.05%	38.49%	-3.60%	-9.16%	3.79%	-18.39%	-23.34%	-1.57%	-21.26%	-9.48%	-19.91%	6.06%
% Trip Lenght	-2.17%	-2.00%	11.55%	2.82%	4.87%	-4.10%	-5.14%	4.99%	5.00%	4.50%	-6.88%	-6.85%	-4.39%
% Trip Time	11.20%	-28.20%	-21.48%	3.97%	12.54%	-9.93%	13.29%	33.49%	3.98%	29.37%	0.28%	13.37%	-12.13%
SSE (%)	50.55	182.51	244.16	31.62	36.72	54.16	153.21	306.59	55.16	120.71	55.40	76.22	28.42
RUN ID	**3#4**	**3#5**	**3#6**	**4#1**	**4#2**	**4#3**	**4#4**	**4#5**	**4#6**	**5#1**	**5#2**	**5#3**	**5#4**
Average Speed (km/h)	33.48	32.04	22.10	***26.80***	32.88	27.27	34.70	25.25	21.23	23.87	28.40	29.67	28.62
Trip Length (km)	25.24	23.12	22.14	***22.35***	21.73	19.02	24.83	22.58	22.51	20.70	22.22	23.08	21.61
Trip Time (min)	45.23	43.30	60.10	***50.04***	39.65	41.85	42.93	53.66	63.61	52.02	46.93	46.66	45.30
% Average Speed	22.42%	17.18%	-19.18%	***-1.99%***	20.24%	-0.28%	26.90%	-7.66%	-22.36%	-12.71%	3.86%	8.51%	4.66%
% Trip Lenght	12.51%	3.09%	-1.32%	***-0.36%***	-3.13%	-15.21%	10.69%	0.67%	0.33%	-7.74%	-0.96%	2.88%	-3.66%
% Trip Time	-10.42%	-14.25%	19.02%	***-0.90%***	-21.47%	-17.12%	-14.97%	6.27%	25.97%	3.03%	-7.05%	-7.59%	-10.28%
SSE (%)	55.99	59.73	56.85	***12.62***	73.56	175.03	74.13	91.48	131.77	24.47	36.59	84.96	48.73

According to the selection criteria, the trip data that better fitted with the mean cycle was the run ID 4#1, which means that it is related to “Day 4 – Vehicle 1”. After selection, this speed profile was modified and adjusted in order to better fit the mean values. Table 3 shows a comparison between the calculated mean characteristic values and its correspondent at the original 4#1 cycle and at the modified 4#1 cycle. Also, percentage differences for each characteristic and SSE values are listed. It can be noticed that the SSE value was reduced from 12.62% to 3.43%. The modified speed profile was then named SP04 and considered as the defined cycle to simulate the field route.

Table 3. Comparison between the average distribution (reference), the original 4#1 and the modified 4#1 (SP04) data.

Parameters	**Average (reference)**	**Original 4#1**	**Modified 4#1 (SP04)**
Average Speed (km/h)	**27.35**	26.80	**27.94**
Trip Length (km)	**22.43**	22.35	**22.35**
Trip Time (min)	**50.49**	50.04	**51.00**
% Average Speed	-----	-1.99%	**2.16%**
% Trip Lenght	-----	-0.36%	**-0.35%**
% Trip Time	-----	-0.90%	**1.01%**
SSE (%)	-----	12.62	**3.43**

Figure 3 shows a comparison between the calculated average speed profile and the SP04 cycle histograms. It is easily noticed that the speed distribution is very similar considering both profiles.

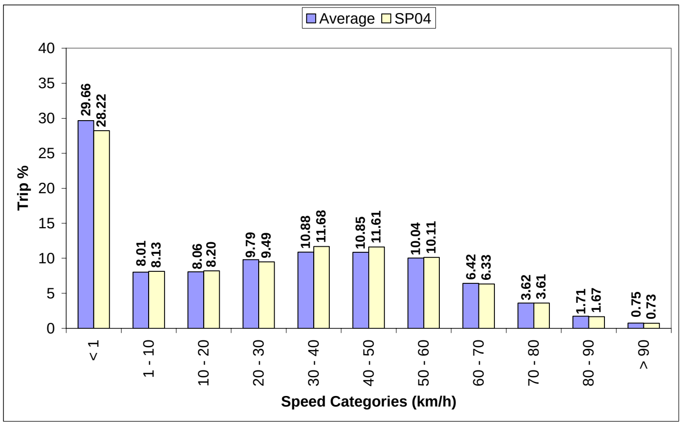

Figure 3. Comparative speed histograms showing the average profile and SP04 cycles.

5.2. SP04 *versus* FTP-75 cycles comparison

Figure 4 presents both SP04 and FTP-75 cycle represented. It is noticed that the FTP-75 cycle is basically divided into two major periods. The first one begins with a 505 second transient phase with cold start, followed by a 864 second cruise phase. After that, the engine is turned off for 600 seconds. The second period begins with a 505 second transient phase with hot start that has the same trace of the first one with cold start. The 864 second cruise phase is not run again, but the result obtained in the first period is considered again for the pollutant gases calculation. This period is mentioned in Fig. 4 as “FTP-75 (virtual)”. On the other hand, the SP04 cycle was generated without phase divisions.

In the FTP-75 cycle, each pollutant gas emission *(Y_{MP})*, in g/km, is calculated by Eq. 2, where Y_{CP}, Y_C and Y_{HP} are the measured emission, in grams, for each pollutant in the cold transient, the cruise and the hot transient phases, respectively and D_{CP}, D_C and D_{HP} the distances of each correspondent phase, in kilometers. As mentioned, the terms Y_C and D_C appear in both portions of Eq. 2.

$$Y_{MP} = 0.43\left(\frac{Y_{CP} + Y_C}{D_{CP} + D_C}\right) + 0.57\left(\frac{Y_{HP} + Y_C}{D_{HP} + D_C}\right) \tag{2}$$

In the SP04 cycle, each pollutant emission is calculated by dividing the total emitted mass, in grams, by the total cycle length, in kilometers.

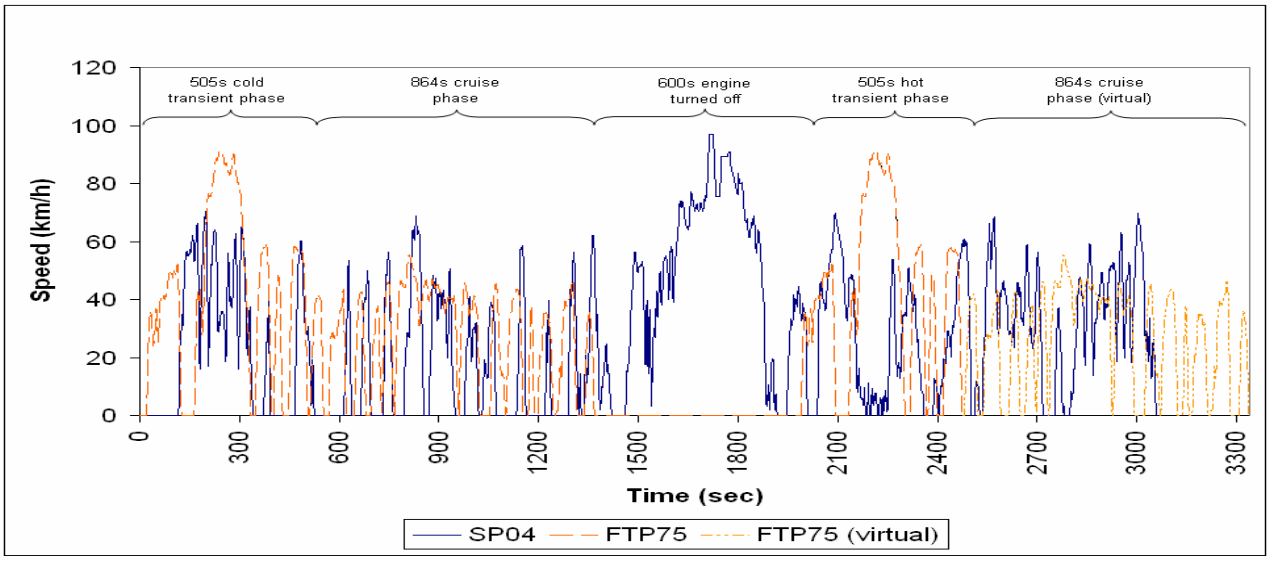

Figure 4. The SP04 cycle in comparison with the EPA FTP-75.

Table 4 shows a summary of comparisons between the SP04 and the FTP-75 cycles regarding to average speed, trip distance and time and execution details such as cold start existence, preconditioning and emission calculation. In this comparison these values were calculated considering the "virtual" cruise phase and they are shown with and without its 600 seconds with the engine turned off.

Table 4. Summary of comparisons between the SP04 and FTP-75 cycles.

Parameters	**EPA FTP-75 (w/ 600s turned off)**	**EPA FTP-75 (w/out 600s turned off)**	**SP04**
Average Speed (km/h)	25.85	34.12	27.94
Trip Lenght (km)	23.97	23.97	22.35
Trip Time (min)	55.63	45.63	51.00
Cold Start	Yes		No
Preconditioning	At least 12 hours before test		Immediately before test
Emission Calculation	weighted (cold and hot phases)		total mass / total lenght

Besides the way to calculate the pollutant emissions, two other important differences between the cycles are related to preconditioning and cold start. In the FTP-75 cycle, vehicles are preconditioned at least 12 hours before test and begin with a cold start. This preconditioning is an execution of the cold transient and cruise phases. In the SP04 cycle, this same preconditioning procedure is performed immediately before the test begins. So, the test begins with the engine already warmed up. It was because in the field tests, emission measurements started after a preconditioning to adjust the equipment.

5.3. Cycle implementation in the laboratory

The SP04 cycle, defined as detailed before, was then applied to the CENPES chassis dynamometer. The system that controls the dynamometer and the pollutant analyzers was programmed with new files containing the trace data, in a speed *versus* time format, and the gear shift tables.

The equipment is provided by three pairs of bags that are filled with exhaust gases diluted in ambient air. These bags are dimensioned to receive the exhaust of each FTP-75 cycle phase. Additionally, there are two different venture nozzles that control each bag filling flow rate. During the FTP-75 execution, the first and third pairs of bags are filled through a venture nozzle with 0.849 m^3/h (30 scfh) flow capacity, while the second pair uses a 0.368 m^3/h (13 scfh) venture nozzle.

As the SP04 was generated without phases division, the volumetric capacity of one pair was not enough to receive the entire exhaust gas amount, due to its complete duration of 3060 seconds. So the three pairs of bags were used to acquire the exhaust gases, and the filling duration of each one was set at 1025, 990 and 1045 seconds using, all of those, the 13 scfh venture nozzle. This configuration was adjusted to make the bags shifting coincide with an idle condition.

6. Tests and Results

6.1. Vehicles and fuels

The tests with the SP04 and FTP-75 cycles were performed using two different vehicles with different fuels as follows. These vehicles and fuels were used in the field tests too:

- Vehicle 1 – Gasohol dedicated engine, 1.8L, 4 cylinder, 16 valves, 134 HP, 15000 km, 2003, tested with 100% regular gasohol (E25).
- Vehicle 2 – Flexible fuel engine, 1.6L, 4 cylinder, 8 valves, 97 HP, 10000 km, 2003, tested with 100% regular gasohol (E25) and 100% hydrated ethanol.

- Regular Gasohol (E25) – blend of 75% regular gasoline with 25% anhydrous ethanol. MON = 83.1, RON = 97.7 and sulfur content of 0.1077%, in mass.
- Hydrated Ethanol – Alcohol content of 92.8%.

Both were tested to obtain at least three results being valid and statistically consistent.

6.2. Results

Figure 5 shows the results of CO, HC, NOx and CO_2 obtained with vehicle 1.

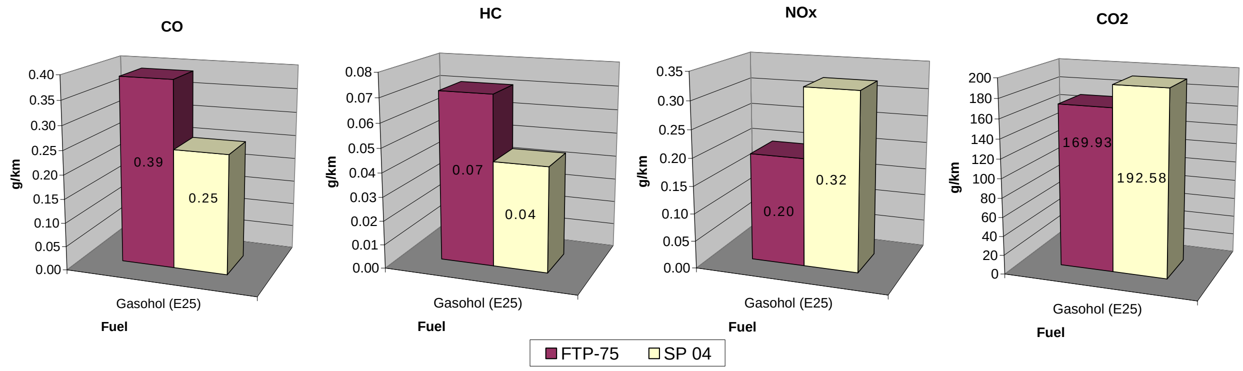

Figure 5. Pollutant emission levels of vehicle 1.

As can be noticed in Fig. 5, the CO and HC emission levels for the SP04 cycle are lower than in the FTP-75 cycle. It can be referred to the absence of the cold start in the new cycle. Higher temperatures in the engine chamber due to lower average speed in the SP04 cycle can explain the higher amount of exhausted NOx. Lower average speed can also explain the higher amount of CO_2 emission when the vehicles run the SP04 cycle.

In Fig. 6 are presented the results obtained by vehicle 2 running with two different fuels. This vehicle was tested with gasohol (E25) and hydrated ethanol.

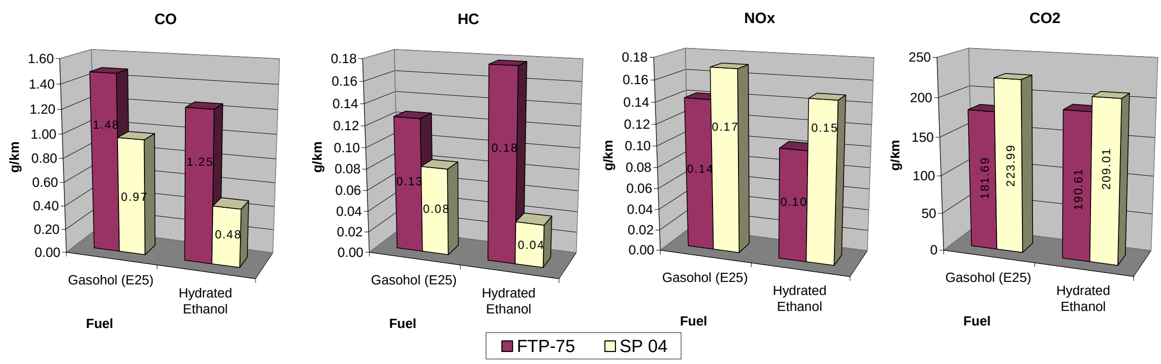

Figure 6. Pollutant emission levels of vehicle 2.

The trend shown in Fig. 5 for vehicle 1 was followed by the results of vehicle 2. The effect of the cold start was more evident when the vehicle 2 was tested with hydrated ethanol. For gasohol, the difference between the cycles was 34% while for hydrated ethanol was 62%. For HC, these values were respectively 38% and 78%.

6.3. Vehicle cold start effects on emission

Based on the FTP-75 and SP04 results, that were an indication of the cold start strong influence on emissions, an analysis was made on the FTP-75 results by isolating the cold start phase influence. It was done by replacing the obtained values for the factors Y_{CP} and D_{CP}, respectively by Y_{HP} and D_{HP} in the Eq. 2 and recalculating the emission results for each car / fuel binomial.

Figures 7 and 8 show the results. As can be noticed, CO and HC results show the large influence of the cold start on these pollutant emission. It can be also verified that vehicle 1 was more sensible to this effect than vehicle 2. On the other hand, it is observed that NOx and CO_2 are not affected by this running condition. In this case, vehicle 2 was more sensitive to NOx emission profile changes than vehicle 1.

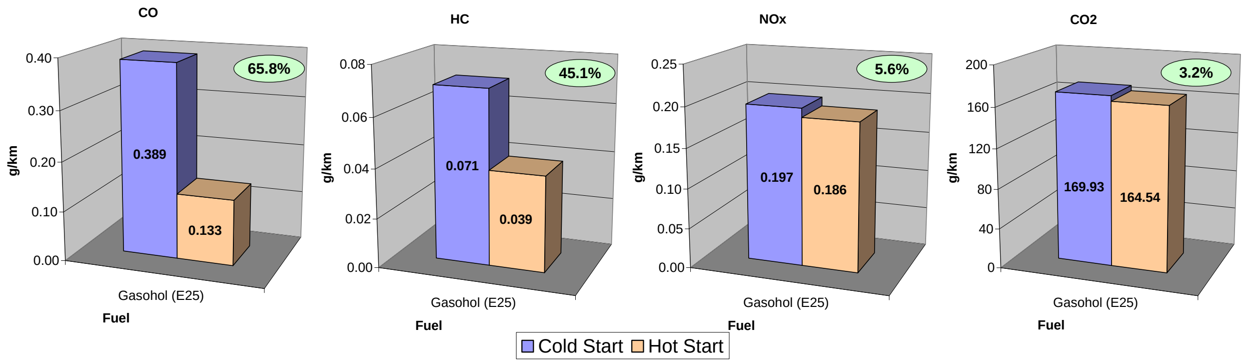

Figure 7. Cold start influence on emissions of vehicle 1.

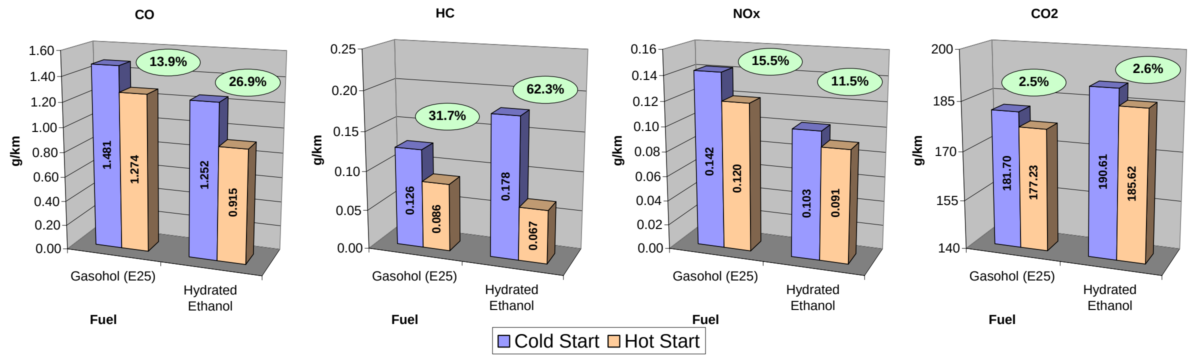

Figure 8. Cold start influence on emissions of vehicle 2.

7. Conclusions

The field route used in the São Paulo tests was successfully implemented and simulated on the CENPES chassis dynamometer. The proposed methodology to reproduce a field cycle was efficient and may be used in future studies.

Comparisons between the SP04 cycle and the currently used one in the Brazilian Standard (FTP-75) shows that the both cycle are reasonably similar. Although the goal of this work was not to define the most representative cycle of the city of São Paulo, SP04 cycle could represent a typical real world driving route in that city. The results were consistent for both cycles.

The cold start analysis confirmed its effect on CO and HC emissions. These levels are lower when the cold start phase is absent. Lower average speed in the SP04 cycle can explain the differences in NOx and CO_2 emission results.

CENPES is purchasing a similar equipment this year and new studies can be done in the future applying these experience and methodology.

8. References

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9. Responsibility notice

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