UNIVERSIDADE DE SÃO PAULO

Instituto de Astronomia, Geofísica e
Ciências Atmosféricas

ANDRÉ LUIZ SILVA FORCETTO

DESENVOLVIMENTO DE UM SISTEMA PORTÁTIL DE BAIXO CUSTO PARA MEDIÇÃO DE EMISSÕES DE VEÍCULOS FLEXFUEL

DEVELOPMENT OF A LOW-COST PORTABLE SYSTEM TO MEASURE EMISSIONS FROM FLEXFUEL VEHICLES

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Development of a low-cost portable system to measure emissions from flexfuel vehicles

Doctoral thesis for the graduation program in Meteorology of the Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo

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“Toda boa dádiva e todo dom perfeito vem do alto, descendo do Pai das luzes, em quem não há mudança nem sombra de variação” – Carta do Apóstolo Tiago, capítulo 1.17

“Every good and perfect gift is from above, coming down from the Father of the heavenly lights, who does not change like shifting shadows” – Letter of Apostle James, chapter 1.17

“E disse Deus: ‘haja luz!’” – Livro de Gênesis, capítulo 1.3

“And God said, ‘Let there be light’” – Book of Genesis, chapter 1.3

ABSTRACT

Large urban centers such as the Metropolitan Area of Sao Paulo are subject to the pollution of soil, water, and air, where vehicles are an important source of atmospheric pollutants. In Brazil, the automotive fleet is mainly composed of flexfuel cars, fueled with ethanol as well as gasoline in any proportion. The control of the emissions and measurement of Emission Factors (EF) from vehicles is done by diverse methods, for example, in-tunnel experiments, remote sensing, standardized laboratory tests, and by the real driving emissions (RDE) test, running the vehicle in the roads coupled to a Portable Emissions Measurement System (PEMS). Furthermore, the RDE test was included in the new phases of the PROCONVE (Brazilian Program to Control Air Pollution from Automotive Vehicles) for homologation proposals. However, commercial PEMS are costly, heavy, and hard to be customized, while low-cost sensor technology is becoming even more available and, reliable. Thus, this research had the goal of developing a compact and low-cost PEMS, able to be applied in flexfuel vehicles. The low-cost PEMS was evaluated in vehicular emissions laboratory, reaching coefficients of determination R^2 above 0.94 for CO_2 and CO and 0.73 for THC. The data from real-world tests performed with the low-cost PEMS were condensed in EF, indicating relevant tendencies for improving mathematic models for pollutant emissions from vehicles. The results, in comparison to the values from standardized laboratory tests, point to an increase above 50% in the emissions at low urban speeds, at high accelerations and vehicle-specific power (VSP) demand, and close to 10 times increment for cold start emission. The most representative EF parameters were the vehicle speed and the VSP, with R^2 close to 0.90 for tendency curves expressed by first- and second-degree equations. The final result was a light, small dimensions, liable system, expending only a fraction of the value of a commercial device, and these characteristics could ease future academic research on vehicle emissions, including motorcycles.

Key-words: Atmospheric pollution, vehicular emissions, RDE, PEMS, low-cost sensors

RESUMO

Grandes centros urbanos, como a Região Metropolitana de São Paulo, estão sujeitos à poluição do solo, água e ar, onde os veículos são uma importante fonte de poluentes atmosféricos. No Brasil, a frota de automóveis é composta principalmente por carros flexfuel, abastecidos tanto com etanol como com gasolina, em qualquer proporção. O controle de emissões e medidas de Fatores de Emissão (Emission Factors - EF) produzidas por veículos são feitos por diversos métodos, por exemplo, experimentos em túneis, sensoriamento remoto, testes padronizados em laboratório e por meio do ensaio de emissões em tráfego real (Real Driving Emissions – RDE), rodando o veículo nas ruas, acoplado a um sistema portátil de medição de emissões (Portable Emissions Measurement System – PEMS). Além disso, o ensaio de RDE foi incluído nas novas fases do Programa

Brasileiro de Controle de Poluição do Ar por Veículos (PROCONVE) para fins de homologação do veículo. Porém, os PEMS comerciais são caros, pesados e difíceis de ser customizados, enquanto que a tecnologia de sensores de baixo custo está cada vez mais disponível e confiável, portanto, essa pesquisa teve como objetivo o desenvolvimento de um PEMS compacto e de baixo custo, apto a ser aplicado em veículos flexfuel. O PEMS de baixo custo foi avaliado em laboratório de emissões veiculares, alcançando coeficientes de determinação R^2 acima de 0,94 para CO_2 e CO e de 0,73 para THC. Os dados dos testes em tráfego real, executados com o PEMS de baixo custo foram condensados em Fatores de Emissão (Emission Factor – EF), que possibilitam indicar tendências relevantes para o aperfeiçoamento de modelos matemáticos para emissões de poluentes por veículos. Os resultados, em comparação com os valores obtidos em ensaios padronizados de laboratório, apontam para o aumento de cerca de 50% das emissões nas baixas velocidades urbanas, em elevadas acelerações e altas demandas de potência específica veicular (Vehicle Specific Power – VSP), e próxima de 10 vezes maior em quando o motor está frio. Os parâmetros de EF mais representativos foram a velocidade do veículo e o VSP, com R^2 próximo de 0.90 para curvas de tendência expressas por equações de primeiro e segundo grau. O resultado final foi um sistema leve, com dimensões reduzidas e confiável, que requereu o dispêndio de somente uma fração do valor de um equipamento comercial, e essas características poderão facilitar futuras pesquisas acadêmicas sobre poluição veicular, inclusive de motocicletas.

Palavras-chave: Poluição atmosférica, emissões veiculares, RDE, PEMS, sensores de baixo custo

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ABBREVIATIONS

ABNT – Brazilian Association for Technical Normative (*Associação Brasileira de Normas Técnicas*)

AFR – Air-fuel rate

BRAMS-SPM – Brazilian Regional Atmospheric Modeling System with Simplified Photochemical Module

CARB – California Air Research Board

CETESB – Environmental Company of Sao Paulo State (*Companhia Ambiental do Estado de São Paulo*)

CONAMA – Brazilian National Council for Environment (*Conselho Nacional de Meio Ambiente*)

COPERT – Computer Program to calculate Emissions from Road Transport

CVS – Constant volume sampling

DIY – Do-it-yourself

E22 – fuel blend with 78% gasoline and 22% ethanol

E100 – pure (100%) ethanol biofuel

ECU – Electronic Control Unit

EF – Emission Factor(s)

FID – Flame Ionization Detector

FTP-75 – Federal Test Procedure #75

GHG – Greenhouse Gases

GPS – Global Positioning System

HDV – Heavy-duty vehicle(s)

HW – Hardware

IAG-USP – Institute of Astronomy, Geophysics and Atmospheric Sciences of the Universidade de Sao Paulo (*Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo)*

IBAMA – Brazilian Institute for Environment and Renewable Nature Resources (*Instituto Brasileiro de Meio Ambiente e Recursos Naturais Renováveis*)

IBGE – Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística*)

LCS – Low-cost sensor(s)

LCP – Low-cost PEMS

LCV – Light Commercial Vehicle(s)

LDV – Light-duty Vehicle(s)

MASP – Metropolitan Area of São Paulo

MOVES – Motor Vehicle Emission Simulator

NDIR – Non-dispersive infrared detector

NEDC – New European Driving Cycle

OBD – On-Board Diagnostics

OECD – Organization for Economic Cooperation and Development

PEMS – Portable Emissions Measurement System

PROCONVE – Program to Control Air Pollution from Automotive Vehicles (*Programa de Controle da Poluição do Ar por Veículos Automotores)*

PM – Particulate matter

PN – Particle number

RDE – Real Driving Emissions

RPA – Relative positive acceleration

SMOB – On-board Monitoring System (*Sistema de Monitoramento On-Board)*

SW – Software

U.S. EPA – United States Environment Protection Agency, also EPA for short

VEIN – Vehicular Emission Inventory

VSP – Vehicle Specific Power

WLTC – Worldwide Harmonized Light Vehicles Test Cycle

WRF-Chem – Weather Research and Forecasting System with Chemistry

WRF-CMAQ – Weather Research and Forecasting System with Community Multiscale Air Quality Modeling System

CHEMICAL COMPOUNDS

CH_4 – Methane

CO – Carbon monoxide

CO_2 – Carbon dioxide

HC – Hydrocarbons, also: THC – total hydrocarbons

NMHC – Hydrocarbon except methane

NMOG – Non-methane organic gases

NOx – Nitrogen oxides

O_3 – Ozone

ROG – Reactive organic gases

SO_2 – Sulfur dioxide

THC – Total hydrocarbons; also: HC – hydrocarbons

VOC – Volatile organic compounds

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INTRODUCTION

The Metropolitan Area of São Paulo (MASP) has gone in the 1900s through a huge and non-organized population and urban growth, which brought concerns about water, soil, and air pollution (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021a; PEREIRA, 2012). This accelerated industrialization attracted to Sao Paulo people from other cities and States in Brazil, in a way that MASP was accounted in 2015 as the tenth bigger metropolitan area in the world, according to the Organization for Economic Cooperation and Development (OECD) (OECD/EUROPEAN COMMISSION, 2020). Formed by Sao Paulo City plus 38 other cities around, MASP is gathering more than 22 million people living in 7,944 km2, that means about half of Sao Paulo State's inhabitants are concentered in only 3.2% of its territory (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, 2021). Just in Sao Paulo City, the vehicular fleet rose up from 1.6 million in 1980 (PINHO, 2015) to almost 6 million vehicles in 2021 (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, 2022).

Vehicles are the main source in MASP of primary air pollutants and other compounds which are involved in the formation of secondary pollutants, such as ozone and fine particulate matter, as well as the main source of Greenhouse Gases (GHG) (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b). Due to the high level of atmospheric pollution in MASP and other Brazilian big cities, such as Belo Horizonte, Rio de Janeiro, Curitiba, and Porto Alegre, the Brazilian Federal Government started in the 1980s a program establishing progressive reduction in the limits of emissions from light and heavy-duty vehicles, following the pattern of those implemented in the USA and Europe (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, 2011).

Since the beginning, the measurement and control of vehicle emissions all around the world is made by standardized laboratory tests. This method has good repeatability and reproducibility but it is criticized for lacking representativeness and being subject to fraud. There are registers of many cases where the vehicle was approved in the homologation tests, but when on the streets presented a huge increase in pollutant emissions (ARCHER, 2016; GERMAN, 2016).

To have a better evaluation of their emissions, vehicles started to be tested in real-world conditions (Real Driving Emissions – RDE), coupled with a Portable Emissions Measurement System (PEMS). The PEMS is composed of laboratory-grade gas analyzers, exhaust flowmeter, GPS, and some additional resources, measuring the pollutants produced by the vehicle while running on the roads. Usually, they can measure carbon dioxide (CO_2) and regulated pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), and, depending on the governmental requirements, the number of particles (PN) and/or total hydrocarbons (THC) (AVL, 2022; HORIBA, 2022).

Research justification

Real-world emission data is relevant not only for type-approval proposals, and to help automotive engineers in the evaluation of engine calibration maps, but also for improving air quality models and emission inventories. The small amount of RDE data is reflected in the divergences between emission inventories, in-field atmospheric measurements and air quality models, where adjustments must often be introduced in these mathematic models, raising the emission values from homologation tests, in order to obtain a better adherence of calculated levels of pollutants in a region, when compared with those actually measured by air quality control stations. The need for RDE data becomes more significant when considering the influence of flexfuel cars as the main source of hydrocarbons, which will influence the ozone levels in the metropolitan areas, as well as the near absence of studies on motorcycle emissions on the streets.

However, a commercial PEMS is hard to be customized, heavy, bulky, and costly. A complete system can weigh more than 200 kg, considering the PEMS, gas bottles, batteries, and accessories, with an acquisition cost close to US$ 300k, therefore its intrinsic characteristics are limiting the spread of this resource. For example, due to the current design, the PEMS is difficult of being assembled and even used on the streets in motorcycles, due to the risk of expensive repairs in case of an accident. Thus, it is necessary to search for alternatives that may be cheaper, but still functional, easy to handle, customized, and able of producing results with reasonable accuracy.

Research goals and hypothesis proposal

This research aims to develop a low-cost PEMS, focused on the application in flexfuel vehicles powered with Otto engines, i.e., passenger cars fueled with pure ethanol or gasoline with 22-27% ethanol, mixed in any proportion. This system shall be light and with reduced dimensions, to be handle and mounted even in small, compact cars. It must also be an open-source project, easily reproduced and customized by others, including a possible future application in motorcycles. The hypothesis to be analyzed is that a low-cost PEMS is liable to be applied in academic research of real-world vehicular emissions.

Thesis organization

This thesis has the following organization: Chapter 1 brings a bibliographic review about atmospheric pollution, real driving emissions, and the instrumentation required to measure them, Chapter 2 presents the research methodology, Chapter 3 brings the process for development of the low-cost PEMS, Chapter 4 discusses the Vehicle Specific Power (VSP) as a complementary metric for RDE, Chapter 5 contains the results from RDE tests and Chapter 6 analyses the Emission Factors from these RDE data.

1. LITERATURE REVIEW

1.1 Atmospheric pollution

Air pollution is the presence of contaminants in the atmosphere, such as dust, gas, smoke, vapor, etc., in quantities and duration enough to harm human well-being and health, fauna, flora, and to damage material goods (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021a; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021a). The pathway of exposure to air pollutants is mainly through the respiratory system and, sometimes, by the skin and mucous membranes. Some hazardous substances can reach the bloodstream and impact almost the whole body, where the most affected organs are the lungs, heart, and brain (WORLD HEALTH ORGANIZATION, 2021a).

The effects of air pollution are being noticed since ancient Rome but, after the Industrial Revolution in the 19th Century, this concern raised to higher levels, in line with the increasing emissions (JACOBSON, 2002). Events of intense acid smog associated with the burning of coal plus the presence of fog and/or radiative temperature inversion were recorded many times in London in the 1800s and 1900s. The worst episode happened in December/1952, accounting for 4,000 deaths attributed to pollution and with an estimated particulate peak concentration of 4,460 µg/m^3 (JACOBSON, 2002). For comparison, the WHO guidance level in 2021 for PM_{10} in 24-hour exposure is only 45 µg/m^3 (WORLD HEALTH ORGANIZATION, 2021b). Diversely than these short and severe events, sunny cities like Los Angeles in the early 1900s faced almost daily a persistent layer of chemically formed pollution, called photochemical smog, whose sources are gases from factories and vehicles and which does not require fog or smoke for its formation (JACOBSON, 2002).

According to WHO (WORLD HEALTH ORGANIZATION, 2021a), more than 90% of humans are exposed to air pollution concentrations that exceed the safe level recommended, mainly in low- and middle-income countries, and the more susceptible group are children, elders, and pregnant women. An estimated 4.2 million deaths are linked to outdoor pollution and 7 million to the joint effects of indoor and outdoor air pollution exposure every year. Air pollutants are associated with 43% of mortality and morbidity from chronic obstructive pulmonary disease, 25% from ischemic heart disease, 24% of deaths from stroke, 17% of deaths from acute lower respiratory infection, and 29% of deaths from lung cancer. The main public health concern relays on particulate matter (PM), ozone (O_3), CO, NOx, and sulfur dioxide (WORLD HEALTH ORGANIZATION, 2021a, 2021b).

Beyond the effects on humans, pollutants can affect the environment in many ways: in general, pollution impact on the ecosystems includes loss of species diversity, and plants living in high ozone levels have a reduction in photosynthesis, slow growth, and increased risk of to be damaged by insects and severe weather (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021b), excess of SO_2 can damage plants foliage and reduce growth (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021c), NOx can form secondary particulate matter and acid rain, harming lakes and forest. The excessive nitrogen dissolved in the coastal waters causes algae to grow faster than ecosystems can handle, reducing oxygen levels and leading to the death of fishes (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021d).

1.2 O_3 formation mechanism

The chemistry of the photochemical smog and the mechanism for ozone formation was discovered by Arie Haagen-Smit, a professor at the California Institute of Technology, in 1952. He produced O_3 in the laboratory from the mixture of oxides of nitrogen and reactive organic gases in the presence of sunlight (JACOBSON, 2002; SCHWEHR, 2009).

O_3 is formed in the troposphere as background concentration in a called photo stationary state, where the reactions in the atmosphere produce O_3 in the same amount that is depleted (JACOBSON, 2002). This ozone background concentration is seasonal, depending on the availability of precursors and sunlight, reaching higher levels in the summer (SCHULTZ et al., 2017), varying in the troposphere from 40 to 120 $\mu g/m^3$ (JACOBSON, 2002).

The presence of reactive organic gases (ROG) and NOx in the atmosphere unbalanced these reactions because ROG are decomposed in the troposphere into peroxyl radicals, which react with NOx in the presence of sunlight, producing O_3 (JACOBSON, 2002). The ROG are defined by California Air Resources Board (California ARB or simply CARB) as any photochemical reactive carbon compound and they are also called volatile organic compounds (VOC) by the United States Environment Protection Agency (U.S. EPA), but it is included in this definition that VOC has a vapor pressure greater than 0.1 mmHg (SCHWEHR, 2009).

The concentration of O_3 in the atmosphere is influenced by temperature, solar radiation below 420 nm, wind speed, relative humidity, and other meteorological factors (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021e).Beyond these factors, the O_3 formation process depends on the VOC/NOx ratio. A NOx-limited atmosphere is when the proportion between VOC and NOx is higher than 8 parts per million per carbon unit (ppmC1) of VOC for 1 part per million (ppm) of NOx because NOx concentration rules the O_3 production. In the opposite way, if the VOC/NOx ratio is below 8:1, it is named VOC-limited atmosphere, to reduce O_3 levels it is necessary to reduce VOC emissions (JACOBSON, 2002).

1.3 Atmospheric pollution in the Metropolitan Area of Sao Paulo

The fast-growing of Sao Paulo City and neighboring cities brought co-related environmental problems which led, first, to start the measurement of sulfur dioxide (SO_2) and smoke in the 1960s and, in a second moment, the assembly of an automatic monitoring network in MASP for monitoring SO_2, PM_{10}, O_3, NOx, CO and other air pollutants (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021a).

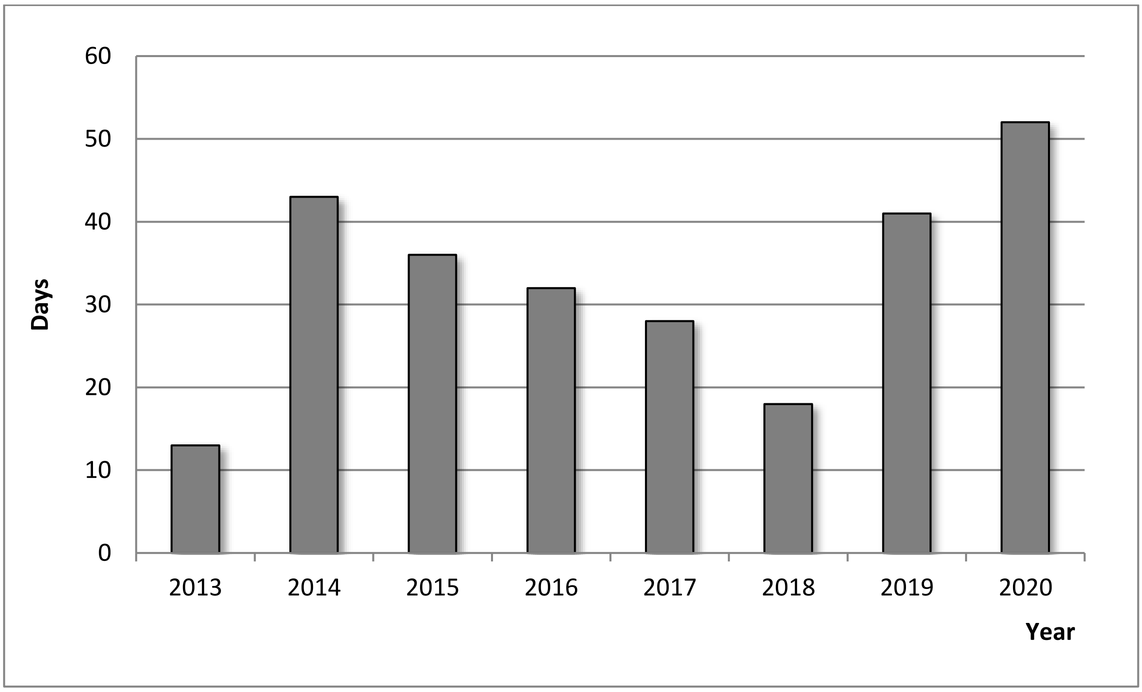
Thanks to joint efforts of the Brazilian Federal Government and Sao Paulo State Government, some programs to control air pollution are in action: since the 1980s it was adopted oil with lower sulfur content, natural gas, or electricity for industrial processes. After the 1990s is available low-sulfur Diesel oil for trucks and buses and it was encouraged the use of ethanol biofuel in passenger cars. The Program to Control Air Pollution from Automotive Vehicles (*Programa de Controle da Poluição do Ar por Veículos Automotores* – PROCONVE) was introduced in the 1980s for light-duty vehicles (LDV), light commercial vehicles (LCV), heavy-duty vehicles (HDV), and motorcycles, setting progressively lower emissions limits for NOx, PM_{10}, CO and hydrocarbons (HC) (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, 2011). Although the MASP (and Brazilian) fleet more than doubled in the last 30 years, the emissions of primary pollutants are being reduced (ANDRADE et al., 2017; INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, 2011). However, there are still concerns about O_3 and

$PM_{2.5}$ levels. In particular, ozone concentration in MASP does not show tendency for reduction along the years (ANDRADE et al., 2017; COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021a; ORLANDO et al., 2010).

The Brazilian final standards for criteria pollutants are close to Europe and USA limits and WHO recommendations but, for now in the year 2022, it is implanted an intermediate less restrictive phase. For O_3, the Brazilian current interim limit is 140 µg/m^3 for 8 hours and the final limit, when adopted, will be 100 µg/m^3 or 50 ppb for 8 hours (CONSELHO NACIONAL DO MEIO AMBIENTE, 2018a), this limit is 120 µg/m^3 for 8 hours and 25 days/year in Europe (EUROPEAN COMMISSION, 2021), and in the USA is 70 ppb or 140 µg/m^3 for 8 hours (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021f). WHO recommendation for air quality is below these values, O_3 concentration should be lower than 100 µg/m^3/8 hours and 4 days/year (WORLD HEALTH ORGANIZATION, 2021b).

However, in 2020 the CETESB air monitoring network registered more than 50 days in the MASP when even the interim limit was exceeded in at least one station, as shown in Figure 1 (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b).

Figure 1 – Number of days exceeding O_3 standard in the MASP (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b) ***(adapted)***



Chemical transport models applied to the MASP atmosphere by Martins, Orlando, and Vela showed that the O_3 formation is, on average, VOC-dependent (MARTINS, 2006; ORLANDO et al., 2010; VELA, 2013) but Ibarra-Espinosa pointed out that the concentration of NOx, VOC, and CO are not uniformly distributed, with high NOx levels in the motorways around MASP due to the traffic of heavy-duty trucks and, in the downtown area, a higher concentration of CO and VOC from LDV and motorcycles (IBARRA-ESPINOSA et al., 2020).

The main O_3 precursors in MASP, in order of concentration, are formaldehyde, acetaldehyde, propane, isoprene, and 2-butane (ALVIM, 2013) and, considering the O_3 formation potential, they are aldehydes, alkenes, aromatics, and alkanes (ORLANDO et al., 2010). Although both studies do not measure ethanol, Orlando (ORLANDO et al., 2010) reported that this concentration in MASP atmosphere is high, due to the use of biofuel for LDV. Ethanol has a low potential for O_3 formation but it is easily decomposed by OH to acetaldehyde, which is a strong O_3 precursor (JACOBSON, 2002), and more, substances generated by an incomplete burn of ethanol in vehicles, such as ethene, ethane, and ethyne, have also elevated potential of O_3 formation (SICILIANO et al., 2021).

Alkenes represent 45% of VOC concentration but this family of compounds has lower reactivity than the others. Isoprene is itself responsible for an increase of 15% in O_3, although must be considered that it is emitted from anthropogenic and natural sources, being the last one the most important (ORLANDO et al., 2010).

1.4 Vehicles as pollutant source

The air pollutants in metropolitan areas have mainly anthropogenic origin, from mobile sources, e.g., cars and trucks, stationary sources (cooking, factories, landfills, refineries, power plants, etc.), or indoor sources (building materials and cleaning products) (MACDONELL et al., 2013; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2022).

When Dr. Haagen-Smit unveiled the smog formation process, became clear that VOC and NOx from automobile exhaust plus sunlight were responsible for O_3 formation (JACOBSON, 2002). His research was the basement of today's air pollution regulations, as a consequence, California established in 1966 the first tailpipe emission standards in the USA, which were extended to all USA by the U.S. EPA 1967 Air Quality Act. CARB adopted yet in 1971 the first NOx standards for vehicles that led to the development of the exhaust catalyst (CALIFORNIA

AIR RESOURCES BOARD, 2021). Europe introduced the control of pollutants for homologation of vehicles in 1992, when Regulation 91/441/EC started the phase Euro 1, settling limits to CO, NOx, and HC (DELPHI, 2020).

CETESB reported that in MASP, for the year of 2020, vehicles were responsible for 96.4% of CO, 72.8% of HC, 64.9% of NOx, and 40% of PM_{10} emissions, as seen in Figure 2 (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b). The relative contribution by vehicle type, LDV, HDV, and motorcycles, is summarized in Figure 3. Beyond this, transportation was responsible in 2008 for the production in the Sao Paulo State of 36.3 Gg CO_2eq, or 26% of all GHG, where 10% of this total comes from LDV/LCV (COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO et al., 2011).

Figure 2 – Pollutants contribution in %, by source in MASP, in 2020 (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b) ***(adapted)***

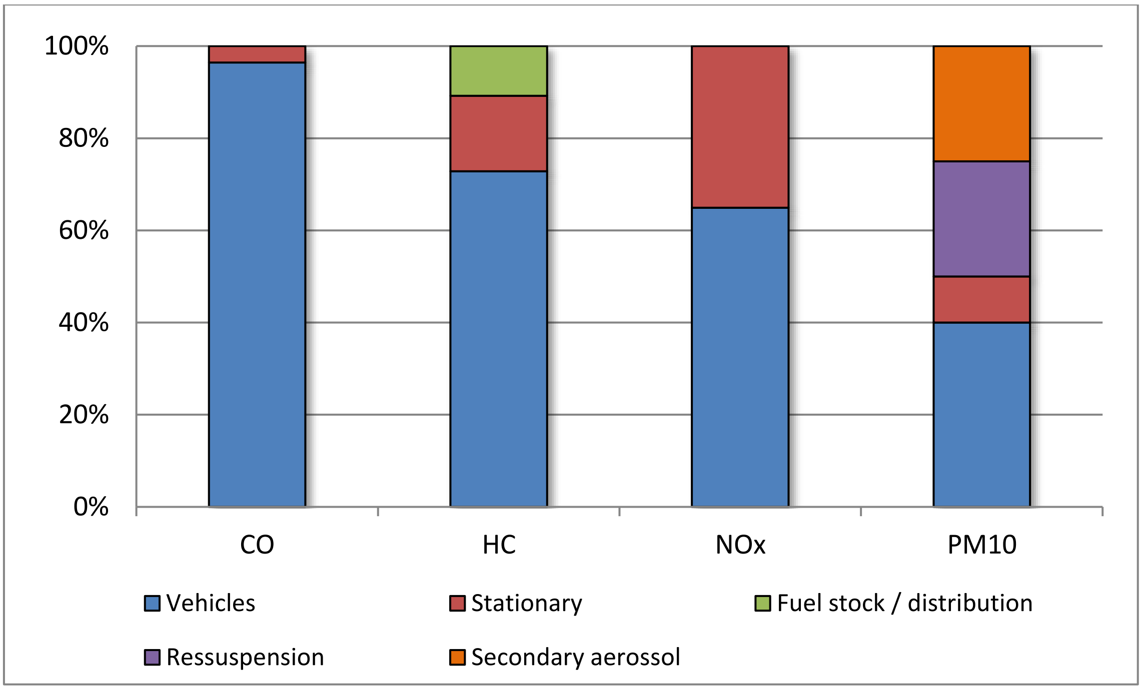
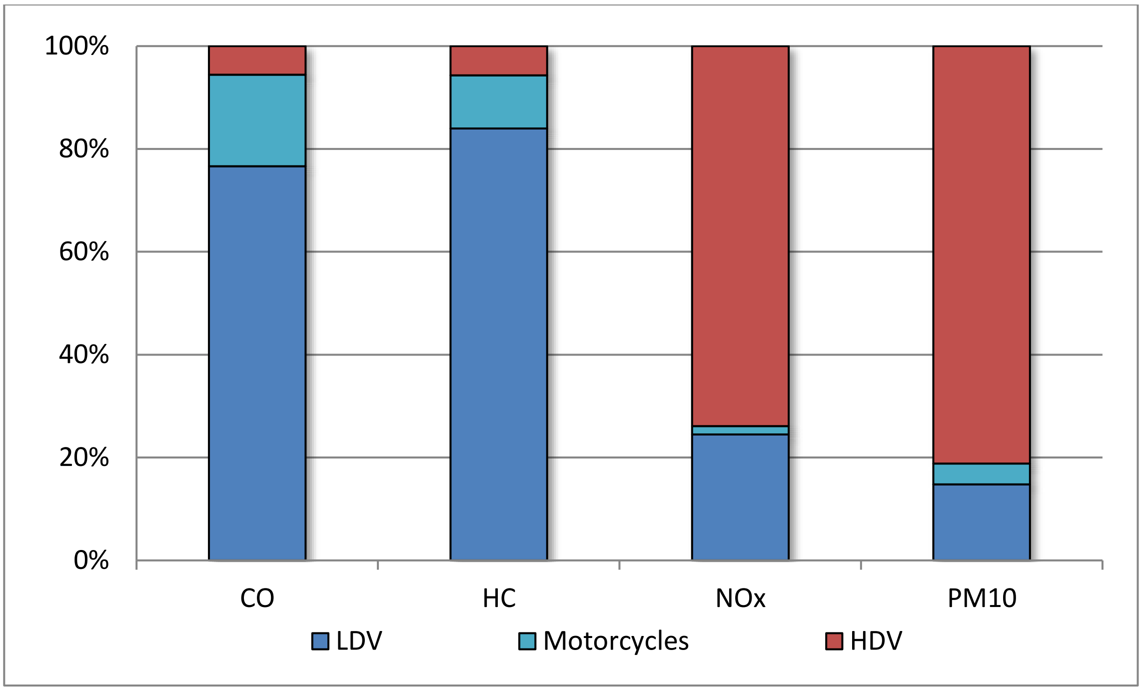


Figure 3 – Vehicle's relative contribution by type for pollutants in MASP, 2020 (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b) ***(adapted)***



As happened in the USA and Europe, the Brazilian National Council for Environment (Conselho Nacional de Meio Ambiente – CONAMA) implemented in the 1980s the PROCONVE, setting progressively more restrictive emissions limits along time for new cars, motorcycles, buses, and trucks, which must be evaluated by standardized laboratory tests (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, 2011). Table 1 presents a summary of pollutants regulatory standards for passenger cars fueled with gasoline in Brazil, in comparison with some other countries/regions.

Table 1 – Comparison of emissions limits applied in Brazil and other countries (DELPHI, 2020)

Country or region	**Started in (year)**	**Level**	**THC (mg/km)**	**NMHC (mg/km)**	**NOx (mg/km)**	**CO (mg/km)**
Brazil	2022	PROCONVE L7	-	NMOG + NOx: 80		1,000
USA	2017	Tier 3 Bin 70	-	NMOG + NOx: 44		1,056
Europe	2020	Euro 6d	100	68	60	1,000
China	2020	CN6a Type 1	100	68	60	700
Japan	2009	Post New Long Term	-	50	50	1,150
India	2020	Bharat Stage VI	100	68	60	1,000
South Korea	2009	K-LEV III ULEV70	-	NMOG + NOx: 44		1,060

Notes: NMOG: non-methane organic gases, **NMHC:** hydrocarbons except methane

The effectiveness of PROCONVE was demonstrate by Andrade et al. (ANDRADE et al., 2017), because the levels of CO, PM_{10}, sulfur dioxide and nitrogen dioxide in MASP atmosphere show progressive reduction from 1982 to 2015, according to new phases were implanted and despite the growing of the fleet, with exception to O_3, which keeps almost stable in all this period.

1.5 Methods to evaluate vehicular emissions

There are many different methods to evaluate vehicular emissions, each with its strong and weak points. The main methods are inside tunnel measurement, remote sensing, laboratory test with dynamometer, and RDE test.

1.5.1 Tunnel measurement

Experiments inside tunnels for determining CO_2 and pollutant emission factors is a well-established method that has been reproduced in different sites and countries in Europe, the Americas, and Asia, producing consistent results (AIT-HELAL et al., 2015; DALLMANN et al., 2012; HUANG et al., 2017; JAMRISKA et al., 2004). In this method, it is necessary to discount the contribution from the outside air, which can be done by measurements inside and outside the tunnel, or by measuring background values. The calculation of Emission Factors (EF) for the evaluated pollutants is done by measuring the pollutant concentrations, weighted with traffic flow data such as traffic volume, speed, and HDV x LDV ratio. Emissions in tunnels tend to be less influenced by other sources and/or photochemical reactions and the fleet evaluated is mixed in a such way that has good representativeness of real-world conditions, like as the use of commercial fuel (with possible contaminations) and vehicles age and maintenance conditions (NOGUEIRA et al., 2021). On the other hand, it is not possible to identify which or how many vehicles are surpassing the standards, nor to evaluate the specific influence of aged catalysts, bad conservation, fuel contamination, nor even if the vehicle catalyst is not warm enough (AGARWAL; MUSTAFI, 2021).

The tunnel study performed in 2018 by Nogueira et al. in MASP also brings historical values of emission factors from previous studies, confirming the tendency of reduction in the EF and pollutant concentrations, although the values found were systematically higher than those reported by CETESB in the Vehicles Emission Inventory Report (COMPANHIA

AMBIENTAL DO ESTADO DE SAO PAULO, 2022a; NOGUEIRA et al., 2021). For comparison with the EF from Nogueira et al., it was taken from CETESB inventory an average of the EF applied in the last 10 years before the period of each study, and the results are summarized in Table 2. These values are based on type-approval laboratory tests with a correction factor due to vehicle deterioration (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022a).

Table 2 – Comparison between EF for LDV from tunnel experiments performed in MASP in 2001, 2004, 2011, and 2018, with CETESB vehicular emissions inventory (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022a; NOGUEIRA et al., 2021)

In-tunnel measurements			**CETESB**			
Year	**NOx (g/km)**	**CO (g/km)**	**Period**	**NOx (g/km)**	**CO (g/km)**	**HC (g/km)**
2001	1.30	16.0	**1991-2001**	0.49	3.4	0.46
2004	1.60	14.6	**1994-2004**	0.27	1.6	0.25
2011	0.30	5.8	**2001-2011**	0.07	0.5	0.10
2018	0.14	2.5	**2008-2018**	0.02	0.3	0.05

Complementary, the EF average for motorcycles in the period of 2008-2018 in the CETESB inventory is 0.06 g/km for NOx, 0.8 g/km for CO, and 0.13 g/km for THC, or approximately 3 times the EF for LDV (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022a). Despite the motorcycles are a relevant source of pollutants, they are not accounted for separately by Nogueira et al. (NOGUEIRA et al., 2021), nor in the other studies cited before (AIT-HELAL et al., 2015; DALLMANN et al., 2012; HUANG et al., 2017; JAMRISKA et al., 2004).

1.5.2 Remote sensing

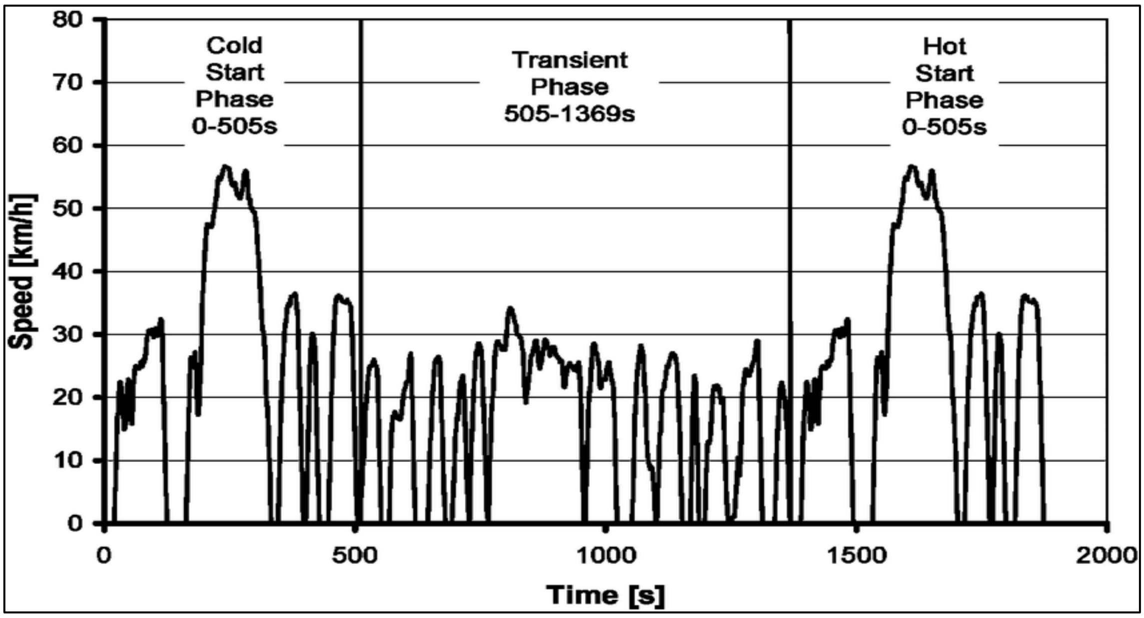
This method consists of measuring vehicle emissions by spectroscopy, where a light source above the road or on the roadside projects a beam to a detector on the other side that interacts with the air compounds. Sensors and cameras coupled to the remote sensing device register vehicles' speed, acceleration, and license plates, allowing to access manufacturer, model, year, fuel type, and other basic data. Usually, it measures NOx, CO, and CO_2 but some devices are still able to measure PM, HC, and ammonia. Remote sensing based on laser instruments has high accuracy and is less subject to variations.

Remote sensing can evaluate hundreds or more vehicles in the real-world, depending on the traffic flow in the site with minimal interference in the traffic flow or driving conditions. Data analysis can evaluate the influence of temperature, age, or acceleration. This method is useful for improving inspection/maintenance programs, and identifying individually high emitters or a group of defective car models. Some limitations of remote sensing are that the measurements are difficult under rain and snow and can be cross-influenced by other cars with a high level of emissions and it is needed a site with mild acceleration and/or slope because high, negative, or no speed variation can distort the results. Remote sensing is also a small sample of the roads from the region where the evaluation is made, depending on further data about the influence of topography and traffic flow for a more comprehensive analysis (AGARWAL; MUSTAFI, 2021; BORKEN-KLEEFELD; DALLMANN, 2018).

1.5.3 Laboratory tests

CARB introduced in the 1970s a test cycle for evaluating and controlling the pollutants from light-duty vehicles (LDV) in dynamometer, under controlled conditions and to verify their compliance with the regulated standards, as represented in Figure 4, called Federal Test Procedure #75, or FTP-75 for short. This cycle is a variant of the U.S. EPA Urban Dynamometer Driving Schedule cycle, reproducing a typical urban-rural trip in Los Angeles metropolitan area and it was adopted for type-approval proposals in the USA, Canada, South Korea, and Australia (WWW.DIESELNET.COM, 2019). The Brazilian normative for LDV laboratory test, ABNT NBR 6601, is based on the FTP-75 test cycle procedure (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2021). A shorter variant for this cycle is the FTP-74, but the vehicle starts with engine warm, usually above 70 °C, and runs only the hot start phase, followed by the transient phase.

Figure 4 – Federal Test Procedure #75 (FTP-75) test cycle (DELPHI, 2020)



The Europe test cycle used to be the New European Driving Cycle (NEDC), presented in Figure 5, but it was replaced after 2017 by the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), Figure 6. For the development of the WLTC, it was recorded real-world in-use speed and acceleration of passenger cars from Europe, India, Japan, South Korea, and United States, to build a more realist cycle for global use (TUTUIANU et al., 2014; WWW.ALPHABET.COM, 2019). Besides Europe, WLTC is yet applied or under implementation for type-approval proposals in Japan, China, South Korea, and Russia (WWW.ALPHABET.COM, 2019).

Figure 5 – New European Driving Cycle (NEDC) test cycle (DELPHI, 2020)

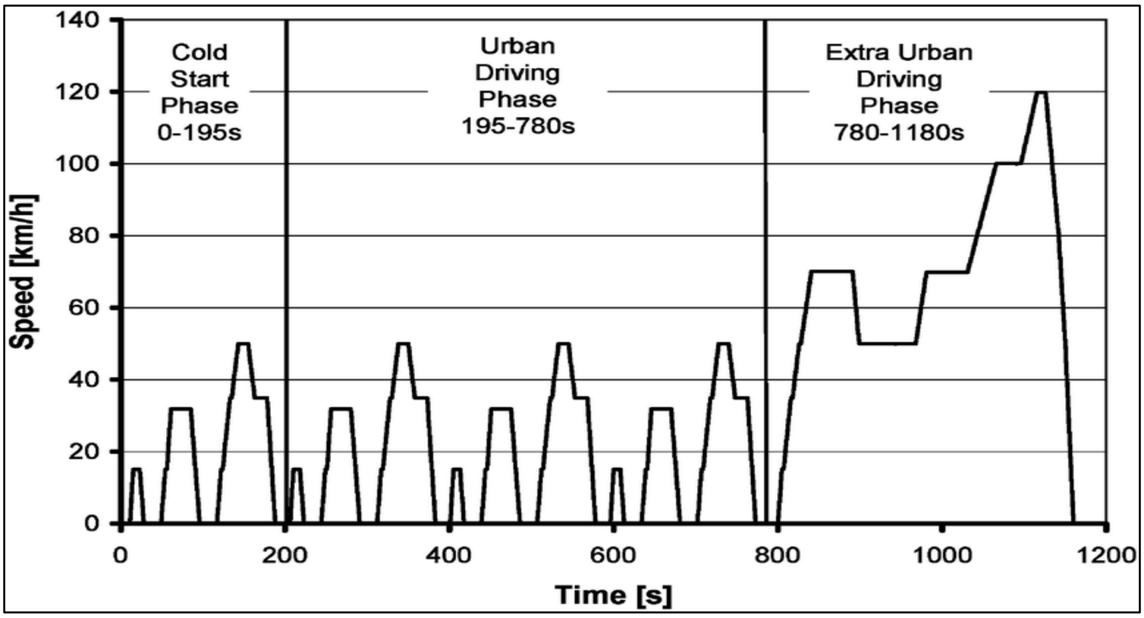
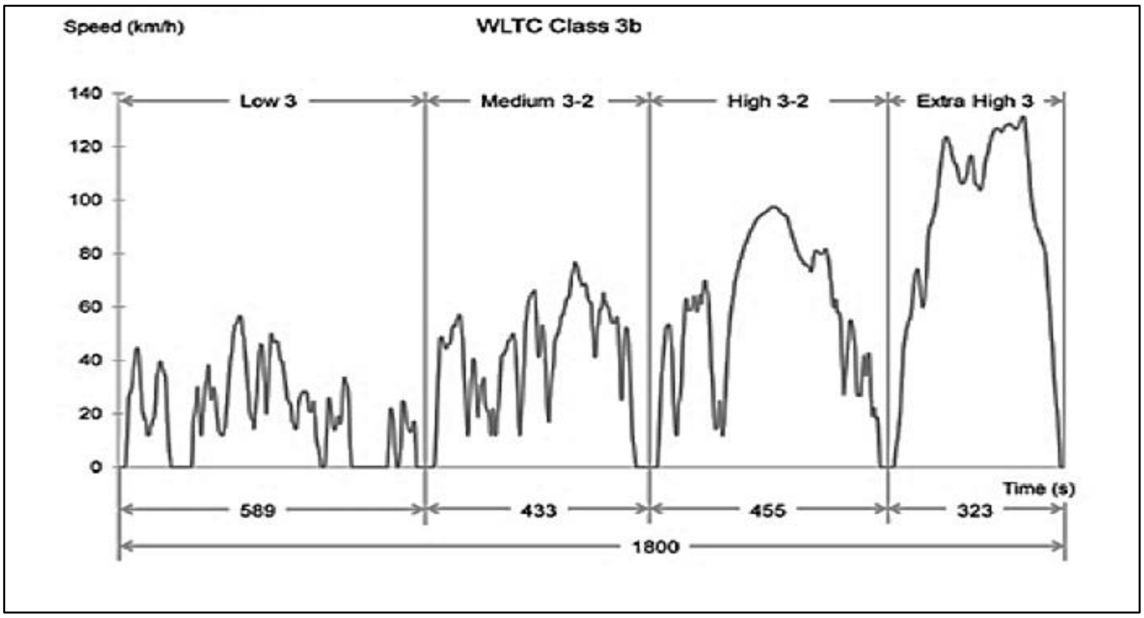


Figure 6 – Worldwide Harmonized Light Vehicles Test Cycle (WLTC) (DELPHI, 2020)



Laboratory tests have good repeatability and reproducibility, even among different sites. For example, the Brazilian Fuel Efficiency Program accepts a variation of just 5% for CO_2 emission from tests performed with the same vehicle in the same laboratory and 8% when made in different laboratories (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS RENOVÁVEIS, 2014). However, this method is criticized for lacking representativeness because, in fact, many studies point to Diesel passenger cars emitting NOx in real-world from 2 to 25 times higher than the regulatory limits and CO_2 up to 50% higher than in the laboratory tests (FRANCO et al., 2014; KADIJK et al., 2016; MILLER; FRANCO, 2016; TAKAI; ISHII, 2016; THOMPSON et al., 2014), and gasoline vehicles have problems related to cold start emission and CO_2 up to 90% higher (KHAN; FREY, 2018; MAY; BOSTEELS; FAVRE, 2014).

These divergences are attributed to some reasons: firstly, test cycles just represent an average of traffic conditions and vehicle load (POURESMAEILI; AGHAYAN; TAGHIZADEH, 2018; TUTUIANU et al., 2014), second, the dynamometer reproduces a flat road, so with no grade (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2019, 2021; VARELLA et al., 2019), third, they are executed under mild temperature, diverse than the variations that are found in the daily real-world (FRANCO et al., 2014). Other factors not considered in the laboratory tests include vehicle mileage, variations in the commercial fuel quality, actual driver behavior, traffic jams, air conditioning usage, and, worse, some divergences can be found due to the presence of fraudulent resources. For example, it was reported the use by some manufacturers of one software (SW) in the engine's Electronic Control Unit (ECU) for the type approval process and another different SW for running on the roads (FRANCO et al., 2014; GERMAN, 2016; THOMPSON et al., 2014). At least, Emission Factors for governmental inventories can diverge from real-world because they consider a deterioration compensation in the EF that is based on tests made by running cars on close tracks or in dynamometers under well-controlled maintenance, best fuel quality, and low-profile driver behavior (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2011).

Diverse strategies were reported by German and Archer when manufacturers explore gaps in the laws for achieving the regulatory emissions limits, but in some cases, they are fraudulent (ARCHER, 2016; GERMAN, 2016):

- Thermal window: the pollutant control system works only in a narrow range of temperature, and it is deactivated when out of this interval. Sometimes, it is just a strategy to protect the engine in extreme ambient conditions, which is legal, but in some suspicious cases the system for control the pollution only works when the temperature is in laboratory conditions (20-30°C).

- Hot restart: when the engine is turned on with the coolant temperature above 70°C, the anti-pollution system does not work. This condition is illegal and particularly used in the

WLTC test because in this cycle the vehicle starts with the engine cold and the cycle is performed without stops.

- Shut off after 22 minutes: the entire system turns off after this time. It is considered as defeat device because all laboratory tests long about 20 minutes.

- Test recognition: it is feasible in two different situations: first, legal, some vehicles have a "dynamometer mode" because some features, such as traction control, ABS, airbag control, and others must be inactivated to make possible the car to be driven in a laboratory. The second one, illegal, is when the SW in some way recognizes that the vehicle is in test and chooses a calibration map in the ECU exclusively to this condition, which is different from the used on regular driving, with the proposal of having fewer emissions and better consumption average exclusively in the laboratory.

1.5.4 Real Driving Emission test

In the USA, on-road measurements are done since 2005 for evaluating heavy-duty vehicle (HDV) emissions and for monitoring and defeating device chasing of LDV (ENGELJEHRINGER, 2019; HE; YANG, 2017). In the European Union, Regulation 715/2007 (EUROPEAN COMMISSION, 2007) points out the need of reviewing laboratory cycle NEDC to one closest to real traffic conditions, that is the WLTC, and assigned that real-world emissions should correspond to what is measured in the laboratory, recommending the development of a specific procedure for RDE, with the vehicle being tested in the roads coupled to a PEMS. The need for a more comprehensive real-world evaluation of vehicle emissions gained momentum after the issue involving some Diesel vehicles emitting in streets 5 to 20 times more than in a laboratory, due to the use of alternative and/or fraudulent ECU mapping (BALDINO; MUNCRIEF; KODJAK, 2017; GIECHASKIEL et al., 2016; THOMPSON et al., 2014; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2016a).

Europe started experimental RDE tests for HDV in 2004, becoming part of the type-approval process in 2009 (WEISS et al., 2011). LDV started to be tested in RDE after 2016 for monitoring and since 2018 for regulatory proposals (EUROPEAN COMMISSION, 2016a). In the RDE, vehicles run on streets and roads, subjecting them to real-world variables, such as traffic conditions, driver behavior, variable topography, and a larger temperature range than inside the laboratory.

RDE Europe is defined by Regulation 2016/427, named “Pack 1” and it was complemented by Regulations 2016/646 (Pack 2), 2017/1154 (Pack 3), and 2018/1832 (Pack 4), settling the step-by-step to prepare car and instruments, how to execute the RDE test, which limits must be attended for ambient temperature, altitude, required instruments, calculations, criteria to evaluate driving dynamics and emissions limits to NOx and number of solid, non-volatile, particles between 23 nm and 10 µm, while CO_2 and CO are only measured and reported but not regulated (EUROPEAN COMMISSION, 2016a, 2016b, 2017, 2018). The recommended instruments for a regulatory PEMS are similar to those used in the laboratory, such as chem-luminescence or non-dispersive ultra-violet analyzer for measuring NOx, light-scattering particulate counter for PN, non-dispersive infrared detector (NDIR) for CO_2 and CO and Flame Ionization Detector (FID) for THC. A flowmeter, usually based on the Pitot tube, gives the exhaust gas flow and the traveled distance and altitude is obtained by a Global Positioning System (GPS) device (EUROPEAN COMMISSION, 2016a).

RDE has been adopted or is under implementation by many countries such as South Korea, China, Japan, India, and Brazil (DELPHI, 2020). The United Nations Economic Commission for Europe is working to define a worldwide RDE procedure, based on European RDE and called United Nations Regulation for RDE (UNR RDE) (UNECE, 2020). Some countries made adaptations in the RDE procedure and parameters, according to the local needs. For example, China adopted an extended limit for altitude of 2,400 m above sea level and Japan has only urban and rural trips in the test (ENGELJEHRINGER, 2019).

In Brazil, RDE started in 2022 with the new homologation steps PROCONVE L7, for monitoring, and L8, after 2025, for type-approval (CONSELHO NACIONAL DO MEIO AMBIENTE, 2018b). As happened in other countries, the procedure was adapted for the typical Brazilian conditions, to be closer to the real world and be effective to control vehicle emissions. The RDE Brazil is based on the European RDE, in Table 3 is presented a comparison between European and Brazilian procedures.

Table 3 – Difference between European and Brazilian RDE procedures (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a, 2016b, 2017, 2018)

PARAMETER	**RDE Europe**	**RDE Brazil**
Altitude (moderate)	0-700 m	0-1,000 m
Altitude (extended)	700-1,300 m	1,000-1,300 m
Cumulated positive altitude gain	0-1,200 m / 100 km – usually far below the limit	600-1,200 m / 100 km – usually close to the upper limit
Ambient temperature (moderate)	0-30°C	15-35°C
Ambient temperature (extended)	-7 to 0°C and 30 to 35°C	10 to 15°C and 35 to 40°C
Trip share	Urban 29-44% Rural 29-43% Motorway 29-43%	Urban 55-75% Rural 25-45% No motorway
Trip duration	90-120 minutes	60-120 minutes
Reference speeds	Mean speeds from WLTP: P1: phase 1 (18.9 km/h) P2: phase 2 (56.7 km/h) P3: phase 4 (92.0 km/h)	Mean speeds from FTP-75: P1: phase 2 (25.82 km/h) P2: phase 3 (41.03 km/h) P3: 90 km/h
CO_2 reference points (g/km)	WLTP CO_2 phases 1 (P1), 2 (P2), and 4 (P3)	FTP-75 phases 2 (P1) and 3 (P2 and P3)
CO_2 reference mass (kg)	WLTC CO_2 total mass x 0.5	FTP-75 phases 2 and 3 mass
Fuel	Commercial: Gasoline E10, Ethanol E85, Diesel B7	Reference: Gasoline E22, Ethanol E100, Diesel B7
Pollutants evaluated	NOx and PN. CO and CO_2 only reported	NOx, CO, NMOG[1] and CO_2 (for efficiency)

Note: 1) In the RDE Brazil, the PEMS measures the THC. NMOG is calculated after the run, based on the NMOG/THC ratio from laboratory homologation tests (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022).

The RDE has two main advantages over the laboratory tests: it is more realistic because the vehicle is effectively running on the roads (FRANCO et al., 2014), and more difficult to fraud the test since it is done under random traffic conditions, larger temperature range and variable duration longer than 20 minutes (MILLER; FRANCO, 2016). Disadvantages or drawbacks of RDE are: (i) low repeatability and no reproducibility due to the random traffic conditions and driver behavior (LEATHERMAN, 2018; SMITH, 2015), (ii) as the trip is longer than the laboratory cycles, and the main emissions are concentrated in the cold start (MANZOLI, 2009), the influence of the pollutants produced in the cold phase in the overall results are diluted, (iii) the PEMS is still costly, heavy and big, often a commercial system is more expensive than US$300k and weighs about 150 to 200 kg, including batteries, gas bottles and other accessories (FRANCO et al., 2014; KADIJK et al., 2016), and (iv) the PEMS is a "*turn-key*" system (AVL, 2022; HORIBA, 2022), where any modification requires a substantial input of time and money if it is possible to be done.

There are a variety of alternative PEMS being developed, aiming to be cheaper and lighter, and some of them are already commercially available. Almost all of them are based on electrochemical sensors or ECU data and the exhaust flow is calculated upon ECU data to dismiss the Pitot exhaust flow meter. The simplest PEMS measures only NOx but the most recent and complete models are also able to control CO_2, CO, THC, and PN at an affordable cost, about US$50k, or almost five times less than a commercial system (3D-ATX, 2020; GLOBAL MRV, 2020; NGK SPARK PLUG CO, 2020).

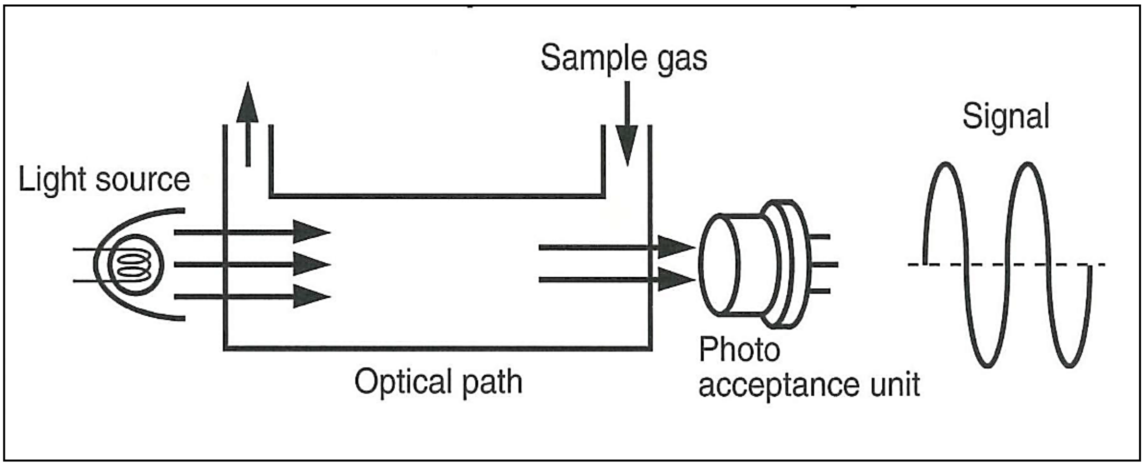
1.6 Low-cost sensors for air monitoring

Laboratory-class analytical instruments for air monitoring have good sensibility and reliability but they are considered expensive, bulky, and complicated to maintain and operate, thus limiting the building of networks for air quality control. Usually, the strategy is to install a few stations to cover an area and extrapolate the results through computational dispersion pollutant models. Low-cost sensors (LCS) become an easier and cheaper alternative for implementing hazard-warning systems, and for more detailed air pollutants measurement at the micro-scale neighborhood level. LCS is not as accurate as traditional analyzers, although LCS networks can compensate for their lower accuracy by producing large amounts of data that can be spatially interpolated, better detailing the complexities of an urban environment (KUMAR et al., 2015). The challenges of LCS development pass by robust mechanical, electric and electronic design to lead to vibration, interferences, and environmental stresses. Other issues are the lack of calibration of LCS, which can result in significant errors when in ambient conditions, and high cross-influence of other gases for

NOx and O_3. Despite this, LCS for CO can reach a coefficient of determination R^2 above 0.86 (CROSS et al., 2017). Their performance can be enhanced by machining learning, where the sensors form an artificial neural network and mathematic tools, such as Principal Compound Analysis (PCA), that are helpful to improve the self-calibration, signal response curves and reduce noise (MOREIRA, 2014; PENZA, 2018; REITENBACH, 2016).

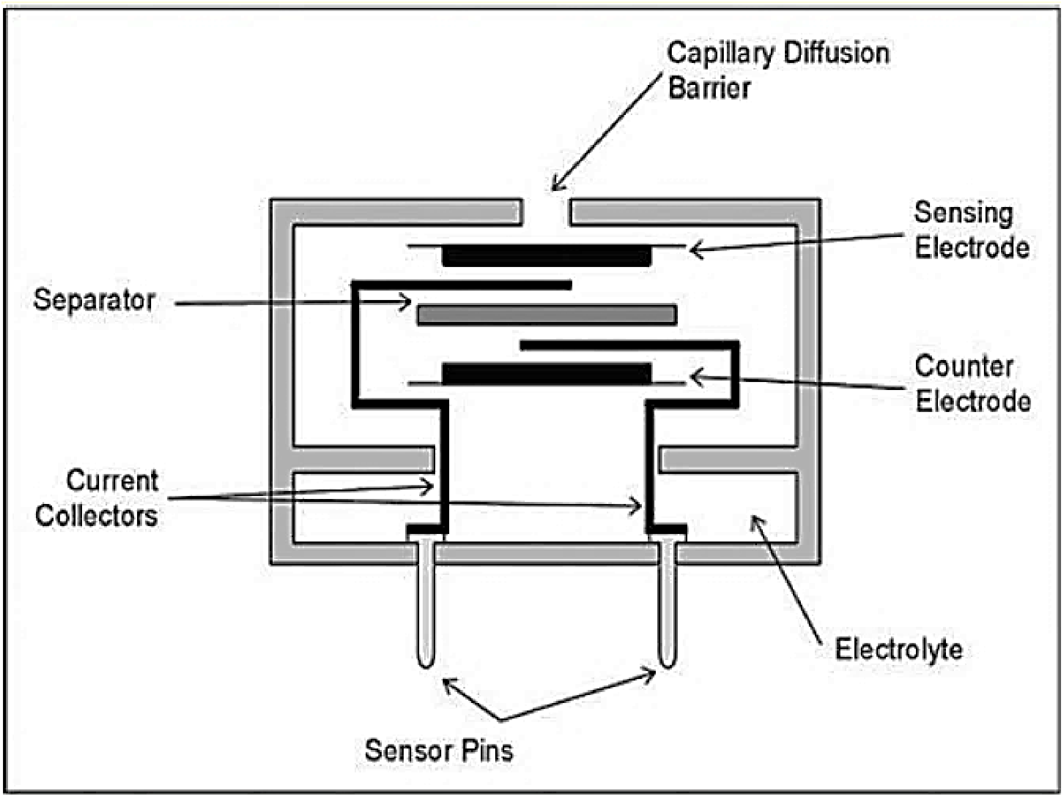
According to MacDonell et al. and Martinho, the LCS can be classified by their detection technique (MACDONELL et al., 2013; MARTINHO, 2014), which are spectroscopy and chemical interaction. In spectroscopy, a light beam crosses the sample or the airflow and the sensor can identify compounds based on their absorption spectra, light dispersion, or chemical-specific light emission. Examples of the spectroscopy categories are light scattering detectors for particulate matter and infrared and ultra-violet detectors for gaseous compounds, such as CO_2, CO, ammonia, VOCs, and others. Figure 7 brings an example of a non-dispersive infrared detector working scheme.

Figure 7 – Non-dispersive Infrared sensor schematic work principle (GASTEC CORPORATION, 2022)



In the chemical technology, the most common working principles are electrochemical and electro-catalyst. The electrochemical sensor has an electrolyte reacting with the gaseous substances to be measured and it creates an electric potential between the electrodes, Figure 8 shows the internal construction of a CO electrochemical sensor. This kind of LCS has low power consumption, good linearity, and precision, with a spam life of more than 2 years, but it is sensitive to changes in the ambient temperature and humidity, there is cross-influence of other gases beyond that is being evaluated and some of them have limited range of measurement.

Figure 8 – CO electrochemical sensor schematic construction (CRETESCU; LUTIC; MANEA, 2017)



Electro-catalyst sensor, also called chemo-resistive or metal-oxide semiconductor, has a metal oxide, usually tin oxide, that is heated, reacts with the substance to be measured and this reaction results in a change of the sensor conductivity, and the heating requires less than 1 W to work. This technology is more sensitive to ambient conditions and to the cross-influence of other gases than electrochemical sensors. Beyond this, water condensation and silicon vapor can damage the internal components (ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD, 2015a). Other issues are the poor accuracy in low gas concentrations and the non-linear variation of conductivity, demanding more efforts for correlating the response curve to the gas concentration. Figure 9 brings the example of an electric-catalyst sensor, model MQ-6, which is indicated for flammable gases, e.g. THC, and Figure 10 shows the internal components and electric circuit, where terminals H receive electric current to heat the sensor, which is mounted between terminals A and B. These terminals are connected to an electronic board that converts the variance in the sensor resistance or voltage to discrete values, and so, the pollutant concentration can be calculated.

Figure 9 – Example of an electro-catalyst sensor, MQ-6 model (CANDIDO, 2017)

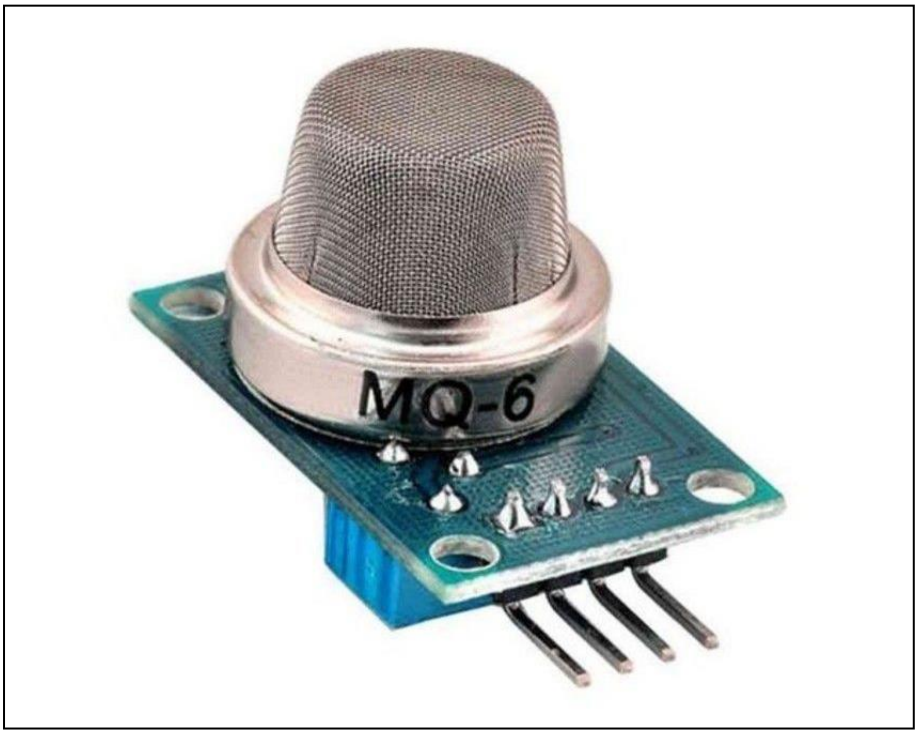
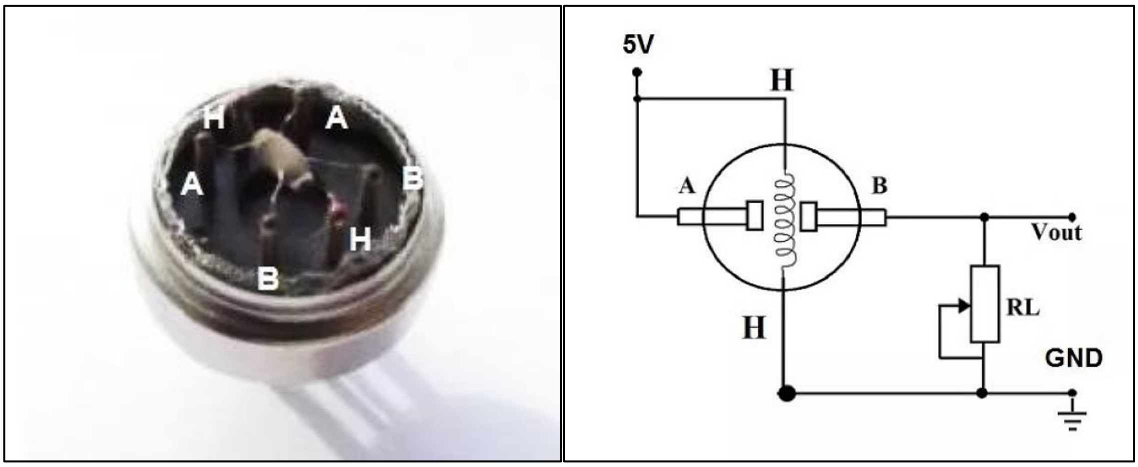


Figure 10 – Inside view of an electro-catalyst sensor and its schematic circuit (CANDIDO, 2017)



Note: A-B: circuit for gas measurement, H-H: sensor heating, RL: variable resistor for response adjusts.

1.6.1 Low-cost sensors for PEMS applications

Vehicular application of LCS has diverse and specific requirements than those for ambient air monitoring: pollutants concentration varies largely because in cold start and accelerations exhaust gas concentrations of THC, CO, and NOx can be higher than 10,000 ppm but they drop to almost zero when in steady speed and the catalyst is hot. Furthermore, the exhaust gas usually reaches temperatures above 100 °C, with high humidity levels due to water generation in the combustion process.

Several research projects have been developed, applying LCS to measure vehicular pollutants from the exhaust gas, making use of automotive NOx and/or PN sensors, as those used by car manufacturers for controlling the catalyst and particulate filter efficiency in passenger cars (KADIJK et al., 2016), data from the On-board Diagnostics (OBD) (POWVER, 2020), repair-shop brand gas analyzer (MANZOLI, 2009; VOJTISEK-LOM; JAMES T COBB, 1997) and electrochemical and/or NDIR sensors (VOJTISEK-LOM et al., 2020). Available commercial versions of LCS PEMS are also named mini-PEMS, small PEMS, or SEMS (Smart or Sensor Emission Measurement System), Table 4 presents the working principles and technical characteristics of some available systems.

Table 4 – Examples of PEMS with low-cost sensors and their main features

Manufacturer or Researcher	Working principle and pollutants evaluated	Exhaust flow measurement	Distance
RESEARCH			
Vojtisek-Lom (1)	NDIR: CO_2, CO, THC Electrochemical: NOx, O_2	OBD data calculation	OBD data
Manzoli (2)	NDIR: CO2, CO, THC Electrochemical: NOx, O2	OBD data calculation	GPS
Kadijk (3)	Automotive electrochemical sensors: NOx, O2	OBD data	OBD data
Powver (4)	OBD data: NOx	OBD data	GPS
COMMERCIAL			
3D-ATX (5)	NDIR: CO_2, CO Electrochemical: NOx, O_2 Ionization/ scattering: PN, PM	Not specified	Not specified
Global MRV (6)	NDIR: CO_2, CO, THC Electrochemical: NOx, O_2 Scattering: PM Tunable Diode Laser: NH_3	OBD data calculation	GPS
NGK (7)	Automotive electrochemical sensors: NOx, O_2 Diffusion charging: PN	OBD data calculation	OBD data

Notes: ***(1)*** (VOJTISEK-LOM et al., 2020)***,*** ***(2)*** (MANZOLI, 2009)***,*** ***(3)*** (KADIJK et al., 2016)***,*** ***(4)*** (POWVER, 2020)***,*** ***(5)*** (3D-ATX, 2020)***,*** ***(6)*** (GLOBAL MRV, 2020)***,*** ***(7)*** (NGK SPARK PLUG CO, 2020)***.***

These instruments bring interesting resources for research, where many of them are being used not only for passenger cars or trucks but in snowmobiles, All Terrain Vehicles, and other unusual applications. They have yet some limitations: just one model can measure THC, and those with PN sensors count all kinds and sizes of particles, not only non-volatile particles between 23 nm and 10 µm, as required in the regulatory method, so the results are not equivalent. At least, they are all “black boxes”, where the SW driving the system is locked on and can only be modified by the manufacturer, making hard to customize it. One more point not clear is if any of them can work in flexfuel cars.

Therefore, diverse factors are acting simultaneously in Brazil, regarding RDE: the rising control of the pollution from vehicles in the real world, the development of a procedure for RDE according to the Brazilian conditions demanding a deep knowledge about how the PEMS works, what are the PEMS strong and weak characteristics, the Brazilian LDV fleet composed by flexfuel cars where a regular PEMS measuring NOx and PN does not match the local needs and, finally, the availability of reliable low-cost sensors. So, in this context, the development of a low-cost PEMS in Brazil focused on to be applied in gasoline-ethanol vehicles becomes relevant.

2. METHODOLOGY

The steps for the development of the low-cost PEMS, hereinafter named LCP, have to consider the kind of vehicles being studied and which are the pollutants of interest. In sequence, the general design concepts for the system will guide the selection of available options of hardware (HW) and SW, sensors, and other complementary instruments. At least, it is planned the actions needed to build, develop, test, and validate the LCP and how analyze the data from the LCP tests.

2.1 Research scope

2.1.1 Target vehicles

The Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* – IBGE), the federal bureau responsible for data and information about Brazil, counts a growing fleet in the country, estimating in 2011 more than 70 million vehicles and, for 2021, about 111 million, a rise of 57%. From these, in 2021, 73.1 million (66%) of them are LDV/LCV, 8 million (7%) are HDV and 30.3 million (27%) are motorcycles (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, 2022). Just in Sao Paulo City can be found close to 7.2 million (10%) of all Brazilian LDV/LCV (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, 2022). In Brazil, LDV is typically a small hatch, 4-5 passengers, with 1,000-2,000 cm3 flexfuel engines. Some international examples of them are the Fiat Uno, Chevrolet Opel Corsa, Ford Fiesta, and Hyundai I-20, among others.

CETESB report for air pollution quality (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b) points out that 97% of LDV/LCV in MASP have Otto engines and more than 70% of them are flexfuel. Only 3% are diesel-fueled vehicles because this fuel is allowed only for some LCVs and mainly for HDV because diesel fuel has lower taxes than gasoline and ethanol for reducing freight prices and buses fares (PETROBRAS, 2021), remembering that, despite their lower participation in the fleet, diesel-fueled LCV and HDV are the main sources of PM and NOx.

The notation used for the gasoline-ethanol blend is based on the ethanol content, i.e., pure gasoline is named E0, which means a complete absence of ethanol, conversely, 100%

ethanol is E100. The commercially available fuels are E22 and E100, but the ethanol contents in the E22 can have a variation between 18% to 27%, thus between E18 to E27, depending on the seasonal availability of the biofuel (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022b). The choice between E22 or E100 by the owners of flexfuel vehicles is based on the commercial equivalent price, because ethanol usually costs less than gasoline but has a 30% higher consumption, and based also on personal preferences, like as environmental consciousness or range between fueling (SALVO; HUSE, 2013). For reducing the dispersion in vehicle homologation results, the E22 in laboratory tests must have a variation of only +/-1% in ethanol content, so between E21 to E23 (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, 2011).

Therefore, this research is focused on flexfuel passenger cars, fueled with E22 and E100. CETESB granted the use of one vehicle from its own fleet in the tests, that complains these characteristics:

- Manufacturer: Volkswagen
- Model: Gol City 2015
- Year of production: 2014
- Pollutant control level: PROCONVE L6, close to Euro 5
- Gross weight: 996 kg
- Engine: 1,000 cm3, indirect injection, flexfuel, 56 kW
- Power-to-mass ratio: 56.3 W/kg
- Accessories: air conditioner, hydraulic steering
- Usage: approximately 88,000 km at beginning of the tests
- Conservation status: done periodical maintenance and repairs, all systems working regularly, but with some corrosion inside the exhaust pipe.

This car is the best-seller model in the Brazilian market, with more than 5 million units sold from the 1980s to 2020s, in different versions and generations. In 2003, it becomes the first flexfuel car sold in Brazil (ROZEN, 2020), thus it is representative for the Brazilian fleet.

2.1.2 Target pollutants

As discussed before in 1.3, LDV/LCV are relevant sources of GHG, and are the main source of CO and VOC in MASP, acting together with NOx from HDV and industries, plus solar light to form O_3. However, Otto vehicles exhaust emission is not so significant for $PM_{2.5}$ and secondary aerosol as HDV (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2021b), therefore the pollutants to be studied here are CO_2, CO, and THC.

2.2 General low-cost PEMS design guidelines

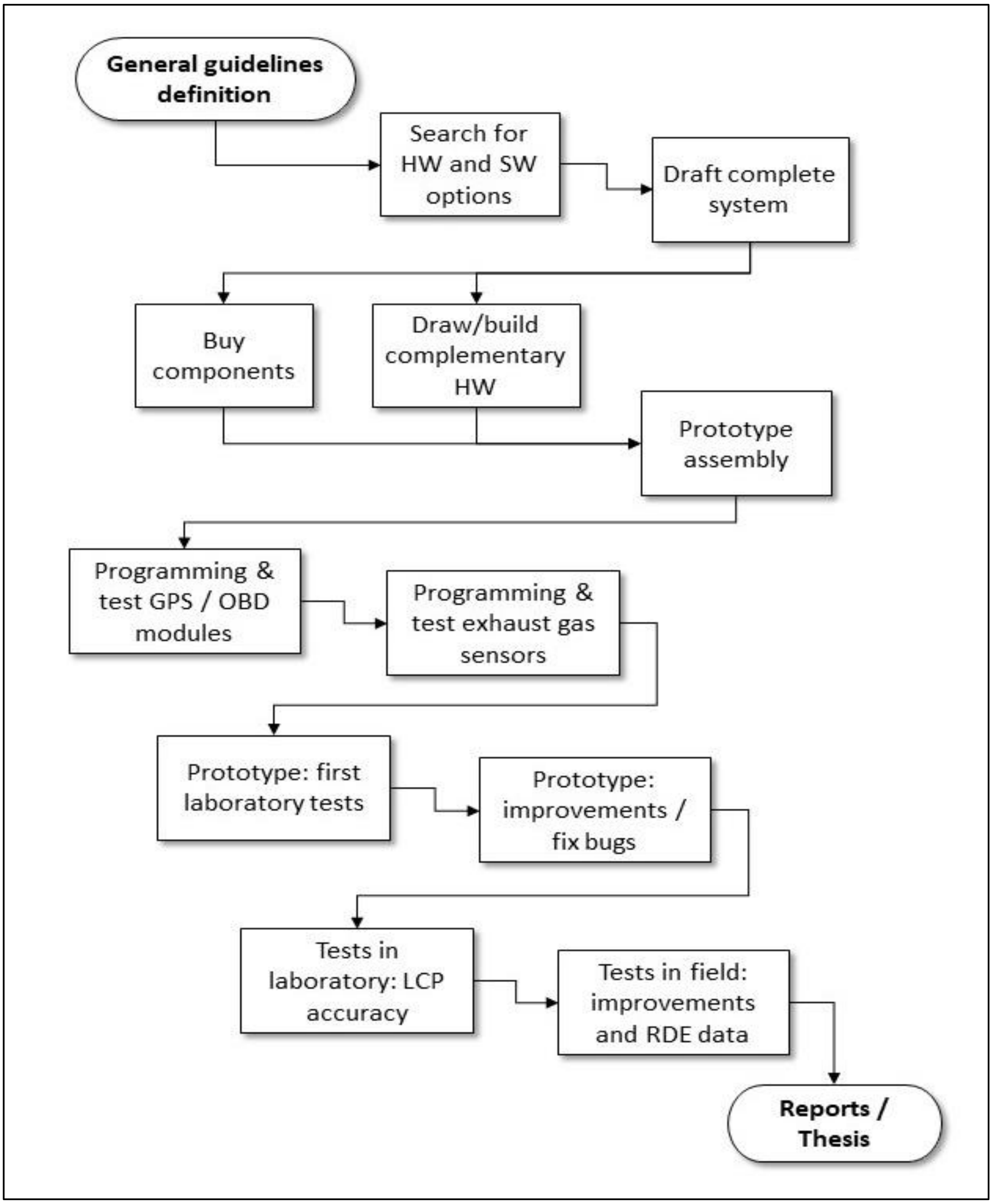
Cross recommends some important characteristics for LCS instruments, which are helpful to guide the LCP design: a robust mechanical construction, avoiding vibrations and leakages, low-noise circuitry, electronic filters for removing transients, and a method for converting sensor signal to concentration (CROSS et al., 2017). Following this path, the LCP must be as simple as possible and robust, with reinforced electrical cabling and connections, having attention to interferences from the engine and other sources. Additional care must be taken for electrochemical and electro-catalyst sensors, avoiding being exposed to temperatures above 50°C and relative humidity over 90% (ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD, 2015b, 2015a). For reducing the sampled gas temperature and humidity and meet the sensors manufacturer's requirements, the gas is mixed to ambient air, in a similar way that is done in the laboratory facilities. The dilution principle is based on intakes for sample and ambient air intakes with different areas, and the actual ratio can be determined by the CO_2 concentrations in the exit of the system, after the blower, comparing the value when the ambient air intake open, as designed, and with it closed, allowing just exhaust gas coming in the tube.

At least, to keep the costs as low as possible, computational resources are concentrated in a low-cost all-in-one computer Raspberry, that runs executable programs with the high-level program language Python, which has a large and comprehensive library for different applications, freely available in the internet forums. Other options for HW to reduce costs are to measure the exhaust flow through OBD data, instead of a Pitot tube sensor, a low-cost GPS device for positional data, and use of electric energy from the vehicle for the suction pump, reducing the need for large batteries to power the LCP. This pump must have low energy consumption, enough to not influence the vehicle emissions, considering at the same time that the absence of heavy batteries to power up the LCP helps in not affecting the emissions.

2.3 Plan of action

The LCP development follows the steps according to the diagram exposed in Figure 11:

Figure 11 – Diagram for planning the low-cost PEMS development



2.4 Data analysis

2.4.1 Evaluation of the Low-cost PEMS accuracy

In order to determine the system accuracy, the LCP is tested in the CETESB laboratory of vehicular emissions and the results from LCP are compared with those from the test cell instruments. CETESB is an active participant in the Brazilian laboratory correlation group for vehicular pollution, a team that is composed of vehicle manufacturers, auto parts suppliers, and research institutes, working to improve the reliability of their facilities through periodic tests among themselves, where CETESB is the benchmark for the others.

This laboratory is located at the company headquarters, in Sao Paulo City, and has a chassis dynamometer with non-dispersive infrared analyzers for CO_2 and CO, a chemical luminescence detector for NOx, a FID for THC, and another for CH_4. Beyond the test bench, the laboratory has a Shed chamber for evaporative testing and chromatographs to measure aldehydes and unburned ethanol (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022b).

The RDE procedures recommend just a validation test, where it runs a homologation test cycle, e.g., WLTC or FTP-75, and the divergence from PEMS and laboratory results must be lower than pre-defined tolerances, as shown in the Table 5. Distance is an important parameter, since the vehicle emissions are measured in grams per kilometer. In field, the PEMS makes use of the GPS to register the trip, and the normative determines that its accuracy must be checked up against the ECU values, which is verified, on this turn, by the comparison to the laboratory reference (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a).

Table 5 – PEMS validation test: tolerances from normative (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022c; EUROPEAN COMMISSION, 2016a)

Parameter	**Permissible tolerances**
CO_2	+/- 10 g/km or +/- 10% of the laboratory reference, whichever is larger
CO	+/- 150 mg/km or +/- 15% of the laboratory reference, whichever is larger
THC	+/- 15 mg/km or +/- 15% of the laboratory reference, whichever is larger
Distance	+-/ 250 m of the laboratory reference

CETESB has also an internal procedure for correlation between vehicular laboratories, which determines that at least three tests are performed under the same conditions for car setup and test cycle and the results are checked with Student's T-test for small samples, which is adequate for evaluating two or more data set produced in different events or laboratories but under similar circumstances (COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022c).

To determine more comprehensively the LCP accuracy, the vehicle must be tested in the laboratory under diverse conditions, for example with the engine starting hot, warm, and cold, intentionally producing different values from one test to another. When the vehicle is running in the test cell, the emissions are measured at the same time by the laboratory instruments and LCP.

The laboratory reports present the results in g/km, but according to the RDE normative (ABNT, EC 427), the PEMS measures pollutant concentration in ppm, plus distance and exhaust flow, and these data must be post-processed after the test in order to calculate the final results in g/km. However, the low-cost sensors usually do not deliver directly ppm concentration but a value representing the variation in the resistance or voltage in the presence of the pollutant, therefore equations must be developed to transform these reads in useful values, able to be post-processed and used in the analysis.

The LCP accuracy is determined by the Pearson analysis, which is more representative in this case, when is done the comparison of one set of results from the laboratory with the second set from the LCP. Its accuracy is expressed by the Coefficient of Determination R^2, which is the square of Pearson Correlation Coefficient R, obtained by the Excel tool regression data analysis, with a confidence level of 95%.

Therefore, it is planned to do 10 tests with E22 and 10 more with E100, following the cycle FTP-74. It determines that the engine must start hot, i.e., with water coolant above 70°C but, to increase the emissions during the tests and enlarge the range of evaluation of the LCP, some of the runs are done with the engine below 70°C. The FTP-74 has two advantages over the homologation standard FTP-75: is shorter and does not require an interval between tests, saving time, which allows doing more tests in fewer days. Table 6 shows the plan for LCP evaluation and compares it with the other procedures.

Table 6 – Procedures for PEMS evaluation: comparison with RDE normative and CETESB interlaboratory correlation procedure (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, 2022c; EUROPEAN COMMISSION, 2016a)

	RDE normative	**CETESB interlaboratory correlation**	**LCP accuracy evaluation**
Quantity	1 test	3 or more tests, one fuel	10 tests with E22, plus 10 with E100
Test cycle	WLTC or FTP-75	ABNT NBR 6601 (FTP-75), cold start, interval of 12 to 36 hours between tests	FTP-74, hot (> 70 °C) and warm (> 35° C) start, no interval
What is measured	CO_2, CO, NOx, THC, distance covered in the test	CO_2, CO, THC, NMHC, NOx, optionally fuel consumption	CO_2, CO, THC, distance

2.4.2 RDE tests

The RDE tests are performed according to the Brazilian normative ABNT 17011 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022) in routes starting from CETESB vehicular laboratory in Sao Bernardo do Campo and finishing close to this place, in travels of approximately 45-48 km, being about 28-30 km in the city and more 17-18 km in the road, under real traffic and diverse ambient conditions. The results are compared to those from laboratory tests executed following the Brazilian normative ABNT 6601 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2021). Although the RDE tests lack statistical significance, due to having been done with just one vehicle, they are still important for indicating tendencies of how accurate or representative the RDE and laboratory tests are.

2.4.3 Emission Factors

A more comprehensive analysis is done for determining emission factors (EF) for diverse parameters, such as ambient temperature or vehicle speed. The EF should be considered with some care, due to the same concern reported in 2.4.2, that it has been analyzed over results from just one vehicle, although they remain interesting because indicate tendencies for vehicle behavior regarding pollutant emissions.

Mathematic models for estimating vehicle pollution, for example, the Computer Program to calculate Emissions from Road Transport (COPERT) from European Union and the Motor Vehicle Emission Simulator (MOVES) from U.S. EPA, usually consider the average emission of CO_2 and pollutants from homologation tests, combining these values by vehicle's size, production year, technology for pollution control, estimated mileage, kind of fuel and its consumption (KOUPAL et al., 2003; LASKOWSKI et al., 2021; NTZIACHRISTOS et al., 2009; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2002). In Brazil, an example of a model is the Vehicular Emission Inventory (VEIN), developed by Sergio Ibarra-Espinosa when a doctorate student in IAG-USP. This SW makes use of EF from CETESB reports from homologation tests, weighted in its calculations by cold start and hot exhaust emissions, traffic volume, composition, and speed, among other variables (IBARRA-ESPINOSA, 2017).

The Institute of Astronomy, Geophysics and Atmospheric Sciences of the Universidade de Sao Paulo (*Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo* – IAG-USP) works with the Brazilian Regional Atmospheric Modeling System with Simplified Photochemical Module (BRAMS-SPM), the Weather Research and Forecasting System with Chemistry (WRF-Chem) and the Weather Research and Forecasting System with Community Multiscale Air Quality Modeling System (WRF-CMAQ). They include data from vehicular emission models, such as VEIN and others, where the main parameters are the intensity of use, or daily mileage in kilometers, for different types of vehicles and EF in g/km or grams per liter of fuel consumed (g/l), estimated from in-tunnel campaigns or, when not available, from CETESB reports based on homologation tests (ANDRADE et al., 2015).

Although laboratory tests are an important data source for pollutant models, they are generated in ideal conditions, such as mild temperature, no traffic jams, standardized cycles with not-so-hard acceleration, and no road grade, i.e., a plain route. For improving the accuracy of the models, it is necessary to introduce some compensation factors upon the emission rates. For example, MOVES takes mainly into account the average speed and VSP (KOUPAL et al., 2003; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2002) and COPERT considers variations in ambient temperature, acceleration, vehicle speed and engine temperature (NTZIACHRISTOS et al., 2009).

In the EF analysis, the data from all RDE tests will be gathered in one single file for E22 and another one for E100 and second-by-second emissions of CO_2, CO, and HC in g/km and g/l of fuel consumed will be classified by ambient temperature, vehicle speed, acceleration, VSP, and engine temperature.

The EF are expressed in relative values, so they are the ratio between the results measured in the RDE test in comparison to those from the laboratory tests, sorted according to the parameter that is being studied. The references for CO_2, CO, and THC are the average values from laboratory tests according to the Brazilian normative ABNT 6601 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2021).

For the engine temperature analysis, the classification criterion follows the RDE normative, when the engine is considered cold when its coolant is below 70°C and hot when above this temperature (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a). Regarding VSP, this parameter is separated into bins with the same criteria adopted by U. S. EPA in the mathematic model MOVES, as shown in Table 7.

Table 7 – VSP modal definition adopted by U.S. EPA in the MOVES mathematic model (KOUPAL et al., 2003; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2002)

VSP mode	**Definition (W/kg)**		**VSP mode**	**Definition (W/kg)**
1	VSP < -2		**8**	13 <= VSP < 16
2	-2 <= VSP < 0		**9**	16 <= VSP < 19
3	0 <= VSP < 1		**10**	19 <= VSP < 23
4	1 <= VSP < 4		**11**	23 <= VSP < 28
5	4 <= VSP < 7		**12**	28 <= VSP < 33
6	7 <= VSP < 10		**13**	33 <= VSP < 39
7	10 <= VSP < 13		**14**	VSP >= 39

3. SYSTEM DEVELOPMENT

In Figure 12, there is the draft or schematic design of the LCP and in Figures 13-14 the pictures from the early steps of assembling. The working concept is based on sampling the exhaust raw gas, reducing its temperature as it is passing in the hose. Condensation is separated and the gas is diluted with ambient air, cross a dilution tunnel to homogeneous the mixture, and pollutants concentration are measured by the sensors.

Figure 12 – Schematic design of the low-cost PEMS developed in this thesis

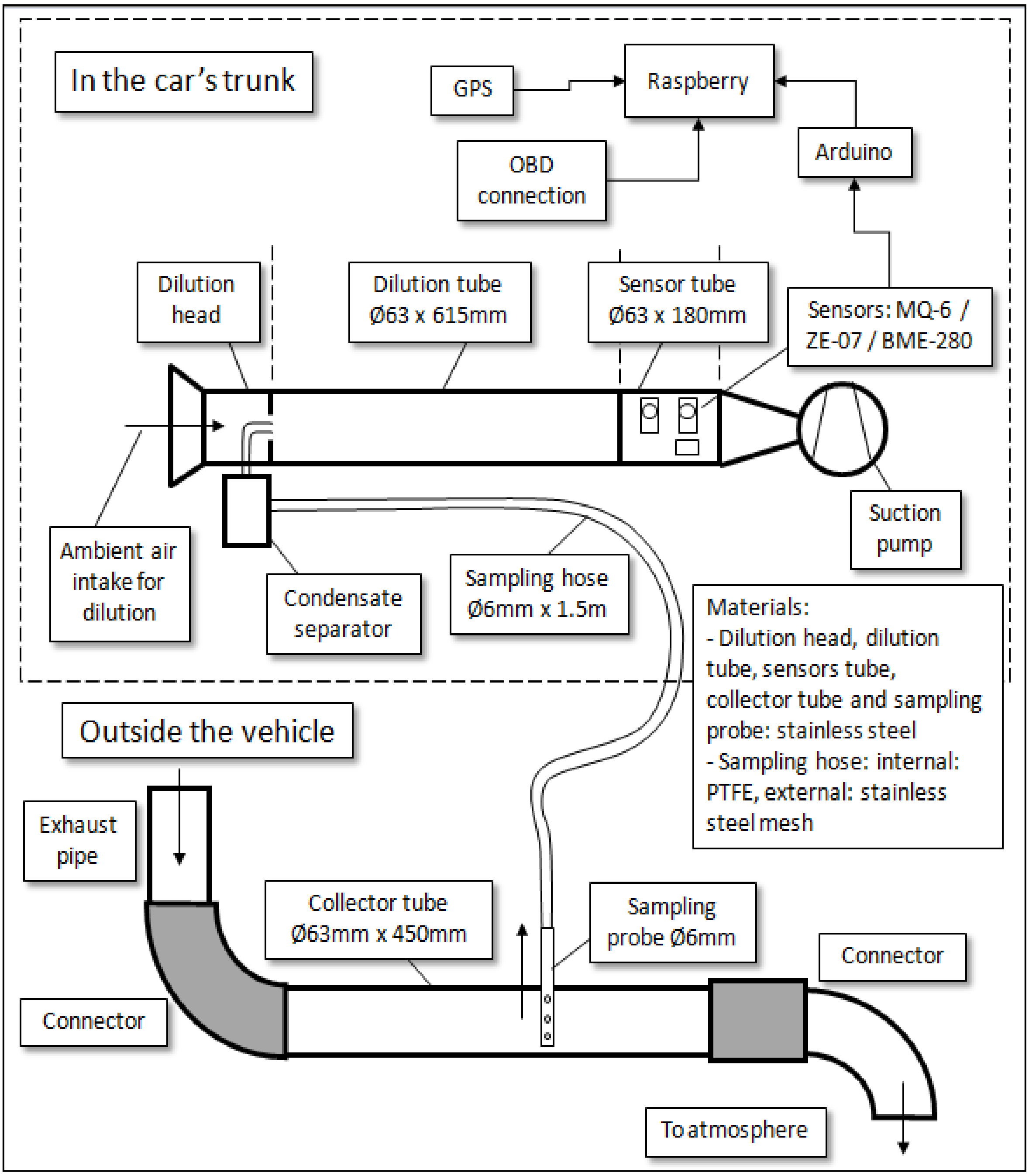


Figure 13 - Low-cost PEMS - early stage of assembling

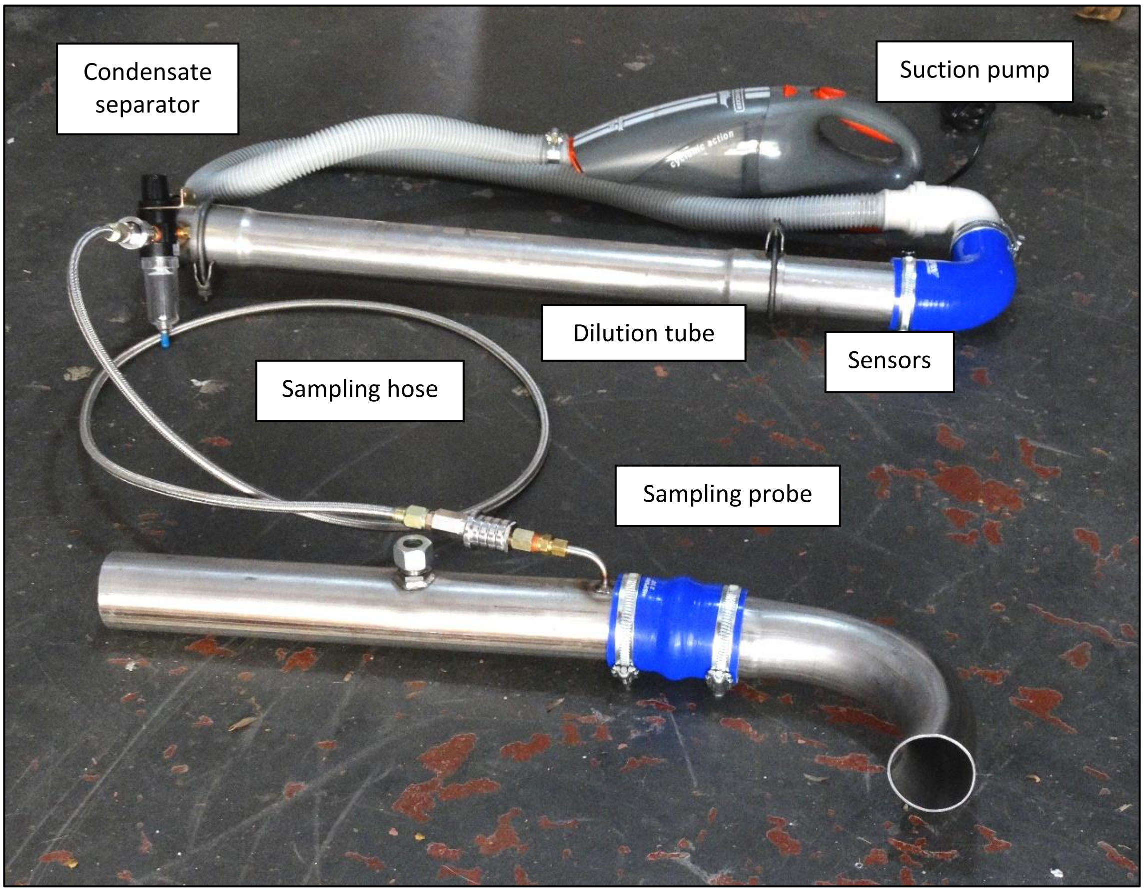
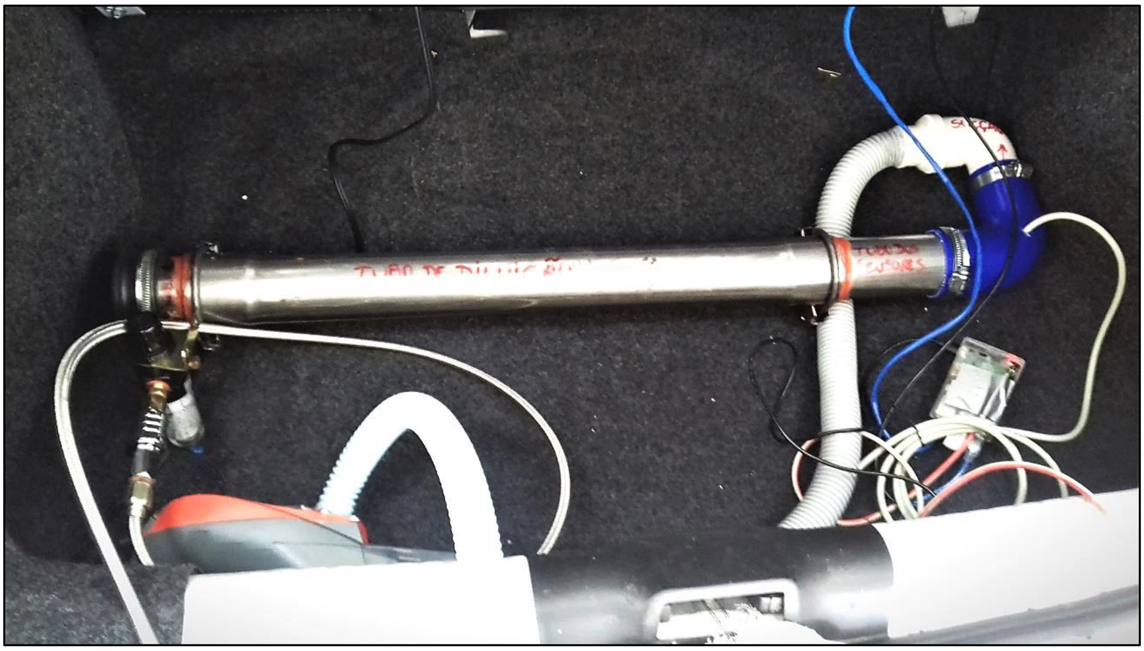


Figure 14 - Low-cost PEMS – early assembly stage – in the vehicle's trunk



3.1 Software and hardware development

3.1.1 Software and hardware definition

The first SW tested was LabVIEW, and despite an available academic version free of charge for USP, it is paid. This SW is versatile and easy to program by graphical icons, but there are some drawbacks: it requires a robust computer to run, the free academic version needed an internet connection to validate the login, limiting its use in the field, the same graphical programming language that is easy to work became difficult to lead with large and complex programs and this SW is not friendly-integrated with hardware from other manufacturers than National Instruments, the developer of LabVIEW.

The second option revealed to be adequate to this project, which was to develop a program based on Python programming language, which is a high-level, interactive, dynamic typing and easy to learn, inside a communitarian model of development, so, without acquisition costs. It needs few resources of HW, allowing the use of a Raspberry, a small low-cost single-board computer that runs a free operational system based on Linux. This device is light and small, approximately the same size as a credit card, and has low electric power consumption.

For saving Raspberry computational resources, the pollutant sensors were linked to an Arduino Leonardo, which is an open-source, single-board platform, with limited memory capacity but still able to read the sensors, doing minimal signal processing, and communicating with Raspberry to send pollutants concentration data.

3.1.2 Selection of sensors, assembling, and connection with Raspberry

The cheapest devices available in the Brazilian market are the electro-chemical sensors, popular in “do-it-yourself” (DIY) electronic projects, which can be connected to an Arduino or Raspberry to do home automatization, fire alarm, breathalyzer, and for ambient air quality monitoring networks, as discussed before in Chapter 1.5. As a consequence of their popularity, many examples of programs for them are easily found in C+ and Python.

The specific application of low-cost sensors in the LCP is more challenging. While ambient monitoring usually is most focused on NOx, PM, and sometimes, CO, in flexfuel vehicles THC is relevant, although under this classification a large range of compounds can be found, such as aldehydes, ethane, ethene, butane, and propane, among others, in different proportions depending on the fuel that is burning (ALVIM, 2013; SICILIANO et al., 2021).

The first sensors tested were the models MQ-7 for CO, MQ-3 for ethanol, MQ-2 for THC, and MQ-4 for CH_4, all of them manufactured by Zhengzhou Winsen Co. In parallel, a sensor from Bosch, model BME-280 (BOSCH SENSORTECH GMBH, 2018), was mounted on the sensors plate to monitor air temperature, pressure, and humidity inside the LCP, because the low-cost sensors can be damaged if the temperature exceeds 50°C and relative humidity is higher than 90%, as mentioned before in Chapter 2.2.

This first set did not produce satisfactory results, with high dispersion in low pollutant concentrations and hard cross-influence from other gases, therefore a second set was tested, with an electrochemical sensor for CO, model ZE-07, and a MQ-6 for THC, both made by Zhengzhou Winsen Co (ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD, 2015b, 2015a). They still have limitations, the ZE-07 measurement range is limited to 500 ppm and has yet some sensibility to CH_4, and MQ-6 technical data recommends this model for measuring liquefied petrol gas, not exhaust gas. Despite this, they produced applicable results, which are discussed in Chapter 5. Some sensors were not used in this research, for example, for NOx were not found any low-cost option in the Brazilian market for Arduino applications, for PM was considered but not applied, because it was out of the scope of this project, and for CO_2 it was not necessary, due to its concentration is being calculated from ECU data.

The BME-280 is plugged in the Arduino Leonardo by its digital channel, delivering directly the temperature, pressure and humidity measurements (BOSCH SENSORTECH GMBH, 2018). Diversely, CO and THC sensors are able to dialogue with Arduino in two ways, by digital and by analogical output. In the digital way, the sensor reads the pollutant concentration, but returns to Arduino just if it exceeds (1) or not (0) a previously set value, adjusted through a variable resistor in the sensors board. In the analogical connection, the electronic board continuously measures the sensor resistance or voltage and attributes a value for this read. When the pollutant concentration changes, the output value also changes, however it is not representing the gas concentration, but the variance in the sensor resistance (ZHENGZHOU

WINSEN ELECTRONICS TECHNOLOGY CO. LTD, 2015a, 2015b). These analogical reads have a delay in comparison with data from the OBD and GPS, due to the time required to the exhaust gases leave the engine, go through the exhaust pipes and mufflers up to the vehicle's rear, be sampled and diluted by the LCP and measured by the sensors, that have themselves a response time. The analogical reads must also be converted to pollutant concentration in ppm, and this is done in a step after the RDE test and before all data be post-processed. The determination of this delay and the process to conversion raw values in ppm pollutant concentration is detailed in the Chapter 5.

3.1.3 Python programming

The core or the basic structure for the Raspberry program was a SW developed by graduation students in Automotive Electronics from Faculdade de Tecnologia de Santo Andre, Santo Andre/Brazil, for a system so-called On-board Monitoring System (*Sistema de Monitoramento On-Board* - SMOB). SMOB was created by Gonçalves, Ortega, and Santos for monitoring vehicles, taking data from the OBD and a GPS device, and sending this information to an online monitoring service (GONÇALVES; ORTEGA; SANTOS, 2018). The Raspberry read these signals, writes a text sentence and sends it by a cell phone 4G internet connection to a site for monitoring the vehicle.

As in LCP the on-line monitoring is not necessary, this part was cut off, but other data gathered by SMOB from the GPS device and engine OBD are still interesting, such as engine rotational speed, vehicle speed, intake air temperature, intake air pressure, distance traveled, engine coolant temperature, ambient temperature and ethanol concentration.

From here, the SMOB program was complemented to supply the needs of the LCP. First, the LCP program gets the lambda factor (λ). When $\lambda = 1$, the air-fuel ratio (AFR) is in stoichiometric proportion, which means that there is enough mass of air to burn completely the fuel. For example, every gram of pure gasoline (E0) requires 14.5 grams of air, for regular Brazilian gasoline E22 this ratio is 13.5:1, and for ethanol E100 is 11:1. An enriched mixture has more fuel than the stoichiometric, with λ lower than 1, and for lean mixtures λ is greater than 1 (BOSCH, 1993). In Otto engines, the three-way catalysts require that λ be kept in between 0.9 to 1.1 for better efficiency. Eventually, this ratio can change, for example, in accelerations or if the engine is cold, when ECU enriches the AFR to deliver more power or to avoid combustion failures. In contrast, during decelerations the ECU cuts off the fuel completely, so λ goes to infinite (BOSCH, 1993; HARANTOVÁ; OTÁHALOVÁ; KASANICKÝ, 2019; VARELLA et al., 2019).

After collected the OBD data, the LCP program processes them to determine the exhaust flow mass. As defined in the RDE procedure (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a), the method to calculate exhaust flow mass through mass air flow plus the AFR is expressed in Equation 1:

$$q_{mew} = q_{maw} \; x \; (1 + \frac{1}{(AFRst \; x \; \lambda)}) \quad (1)$$

Where q_{mew} is the instantaneous exhaust mass flow [kg/s], q_{waw} is the instantaneous intake airflow mass rate [kg/s], *AFRst* is the stoichiometric AFR for the in-use fuel and λ is the lambda value. The vehicle used in the LCP development does not have an intake airflow sensor, so this data must be obtained by calculations based on the Perfect Gas Law (WWW.BRITANNICA.COM, 2022), expressed in Equation 2:

$$P \; x \; V = \frac{m}{M} \; x \; R \; x \; T \quad (2)$$

Where *P* is the air pressure, *V* is the volume of the air, *m* is the mass of the air, *M* is the molar mass of the air, *R* is the Universal Gas Constant, and *T* is the air temperature. Reorganizing this to define air mass:

$$m = \frac{P \; x \; M \; x \; V}{R \; x \; T} \quad (3)$$

To achieve the air mass flow of a four-stroke engine, Equation 3 is multiplied by the rotational speed of the engine, times the volumetric capacity of the engine, as shown in Equation 4:

$$q_{maw} = \frac{P \; x \; M}{R \; x \; T} \; x \; RPM \; x \; \frac{CC}{2} \quad (4)$$

Where *P* is the intake air pressure [mbar], *M* is the molar mass of the air, 29.08 g/mol, *R* is the Universal Gas Constant, 8.314 m^3.Pa/mol.K, *T* is the intake air temperature [K], *RPM* is the engine rotational speed [min^{-1}], and *CC* is the cubic capacity of the engine [cm^3], which is divided by 2 because Otto engines get ambient air just one time every two rotations.

Finally, combining Equations 1 and 4, plus the engine volumetric efficiency *Rv*, and applying the necessary adjustments for the different units, it has Equation 5, which is used in the LCP program:

$$q_{maw} = 29.15\ x\ 10^{-9}\ x\ \frac{P}{(T + 273{,}15)}\ x\ RPM\ x\ CC\ x\ Rv\ x\ (1 + \left(\frac{1}{AFRst\ x\ \lambda}\right)) \quad (5)$$

Other points in the LCP program that demanded attention were the need to keep each loop running one time per second or faster, as determined in the RDE normative (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a). It was necessary to apply some programming resources to attain this 1 Hz target: first, the SMOB makes use of a method, or Python add-in software, for the GPS data reader that acquires data only at each 4 to 5 seconds, so this method was changed to another one, faster. Second, the first GPS device used in LCP was not able to capture the coordinates as fast as needed, and it was replaced to another one, a model Ublox NEO-6M able to take latitude, longitude, altitude, and co-related data at 5 Hz, from the global navigation satellite systems GPS (USA), GLONASS (Russia), and Galileo (Europe) (U-BLOX, 2011). Third, the SW was divided into threads, which is simply to execute instructions simultaneously, in parallel, for saving time.

The pollutant sensors are connected to the Arduino which runs a stand-alone program in C+ language, reading the sensors' signals. The Raspberry makes a data request to Arduino, which answers with a text sentence. All data from OBD, GPS, and Arduino are joined by Raspberry in a logging file with comma-separated values format (*.csv) and this information is post-processed out of the PEMS, by an add-in macro for Excel developed by Joint Research Centre from Ispra, Italy, called EMROAD (EUROPEAN COMMISSION, 2019). EMROAD is able to process *.csv data from diverse commercial PEMS but the AVL MOVE PEMS has the simplest file protocol, so this format was chosen for the LCP. Some other parameters, such as lambda, raw values from sensors and air pressure, temperature and humidity from inside the PEMS sensor tube, were added in each sentence recorded by the Raspberry.

The set Raspberry-Arduino is remotely controlled by a notebook, with a Virtual Networking Computing (VNC). VNC is an SW for replicating the desktop of one on the other, allowing operate the Raspberry without the need of a monitor, mouse, or keyboard, just some care is necessary in the configurations, e.g., to keep always the same IP protocol.

The programs that are running in the Raspberry and Arduino devices are supplied in Appendix 1 and 2, in Appendix 3 is detailed how to process the log file generated by the Raspberry and in Appendix 4 there is the check-list and LCP turning on and off procedure.

3.1.4 Fixing noise from Arduino measurements

A significant problem that happened during the development of the LCP is that the Arduino device presented a strong noise from the unplugged analogical channels. For example, when only one MQ sensor was connected to channel 2 and it was subjected to a small amount of ethanol, the signal output in channel 2 reflects itself in the others, as seen in Figure 15, even if anything else is connected. Another problem found was the instability of the output signal, as shown in Figure 16, varying even when just ambient air is being measured with no relevant pollutant concentration, or when testing in different channels.

Figure 15 – Signal response in channel 2 and noise from other channels

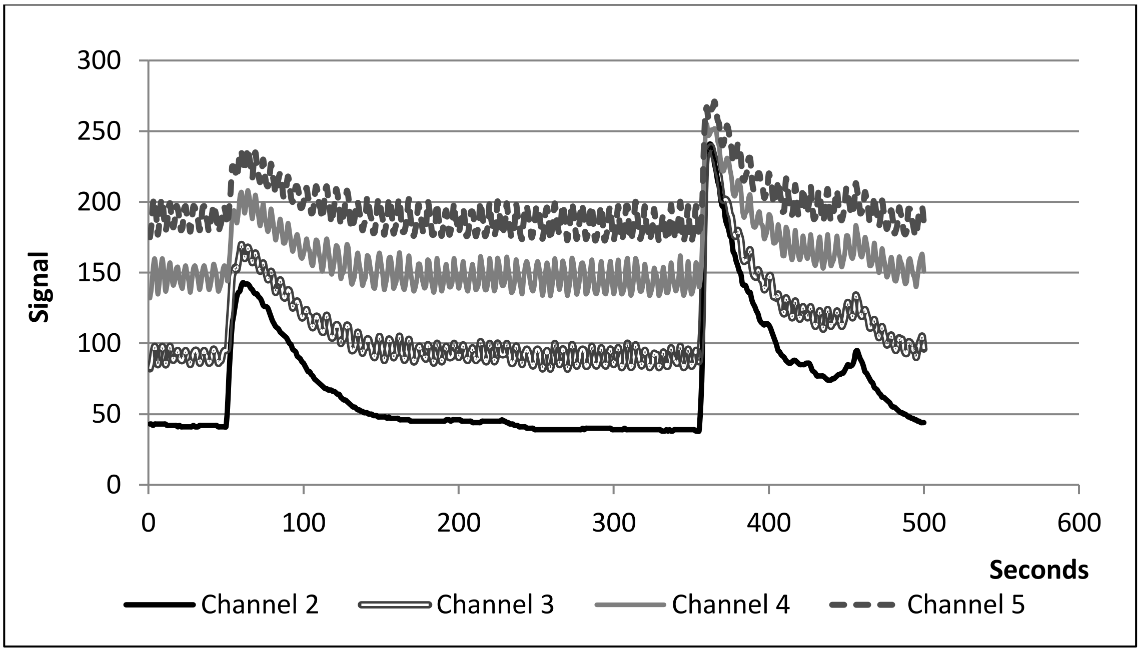
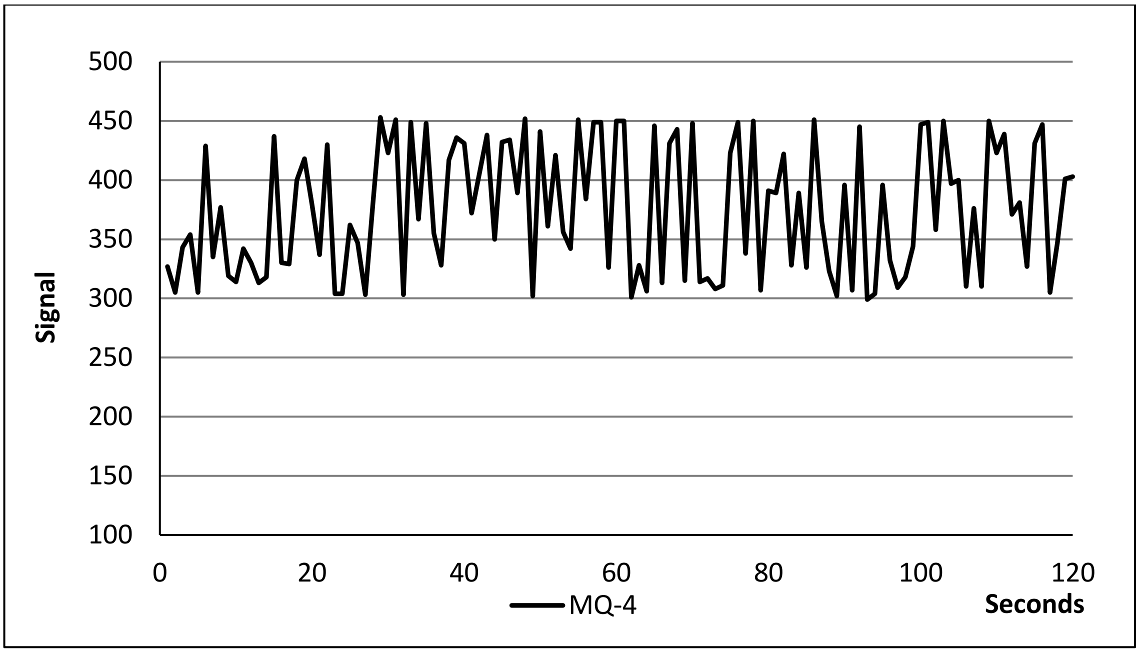


Figure 16 – Variation of the signal output of one channel along the time



Because Arduino is popular in DIY projects, there are many websites with tutorials and forums to discuss how to fix the most diverse problems. In www.labdegaragem.com was recommended to ground all unplugged channels, so the three sensors, MQ-4, ZE-07, and MQ-6, were connected in channels 0, 2 and 4 respectively, and it was introduced a wiring in the channels 1, 3 and 5 to connected to ground (0 V) (WWW.LABDEGARAGEM.COM, 2021). After this, the noise from unused channels was eliminated, as seen in Figure 17. The schematic wiring for Arduino and sensors without grounding the unplugged channels is shown in Figure 18, and Figure 19 has the same wiring plus ground connections, highlighted by a red cycle and represented by dashed lines. The symbols in the sensors are VCC for voltage input, GND for ground or zero Volt (0 V), AO for analogical output, and DO for digital output (not in use in this project), BME-280 is plugged in the Arduino by the digital channels SCL and SDA.

Figure 17 – Signal from channels 0, 2, and 4 after grounding unplugged channels

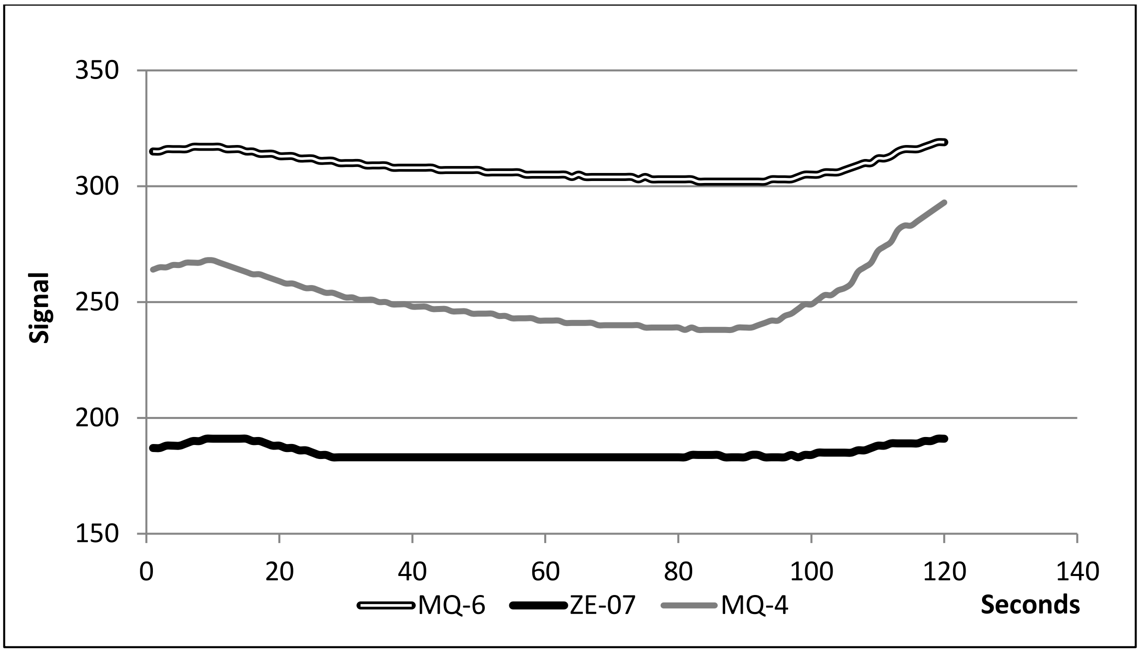


Figure 18 – Arduino wiring without grounding in A1, A3, and A5 channels (red circle)

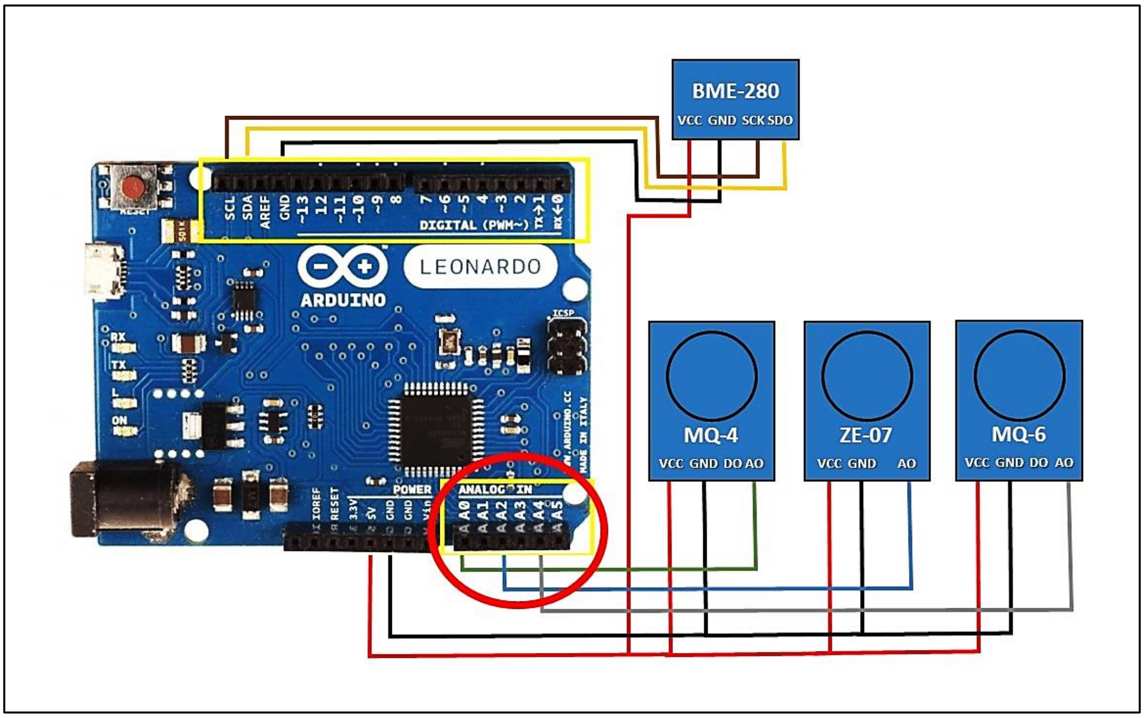
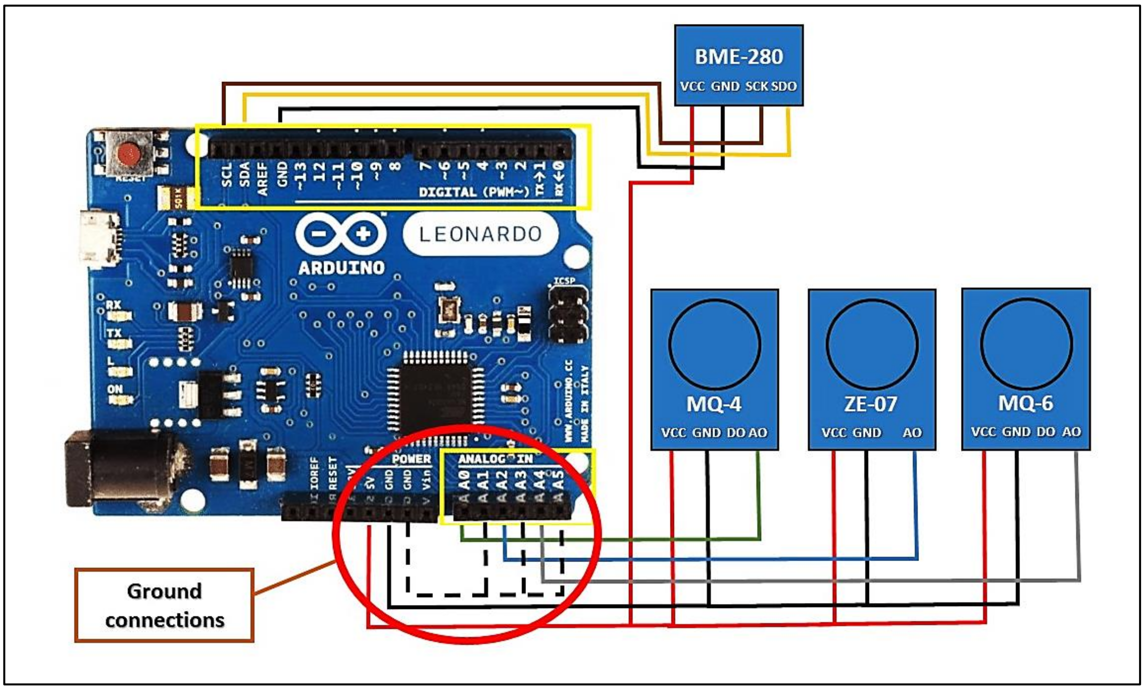


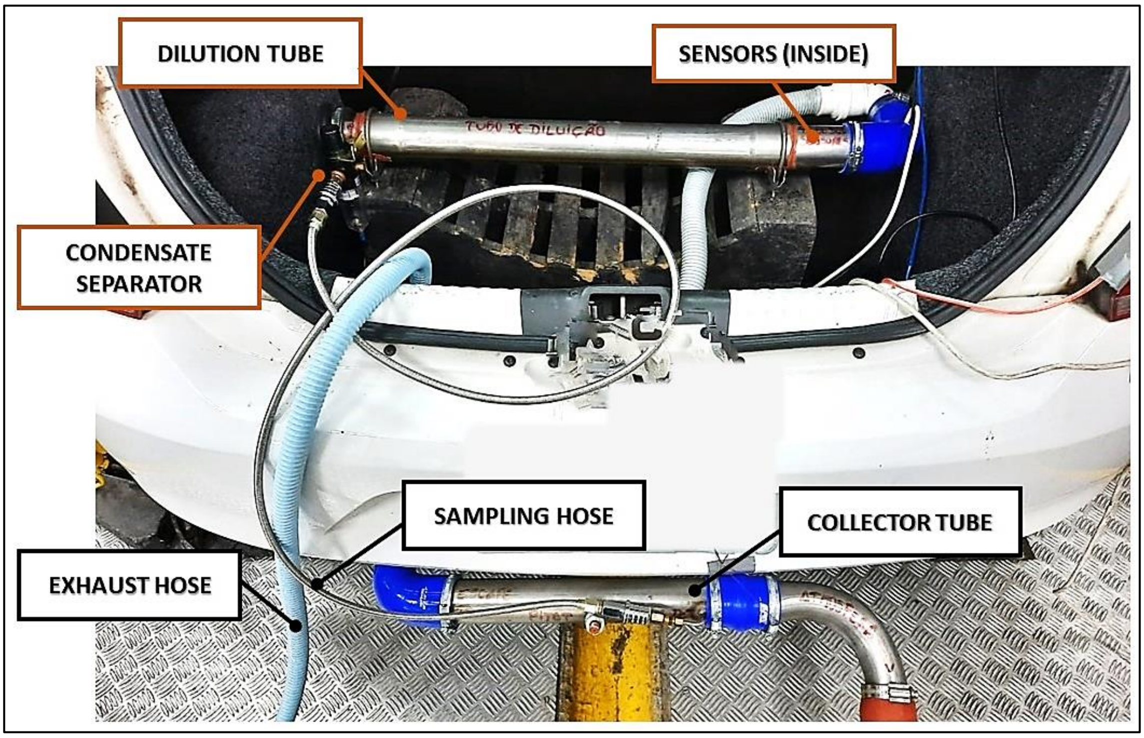
Figure 19 – Arduino wiring with grounding connections in A1, A3, and A5 channels (red circle)



3.1.5 Complementary hardware

As exposed in Chapter 1.5.1, exhaust gas is a harsh environment to gas sensors, with pollutants concentration varying from thousands of ppm in the cold start to almost zero when the catalyst is warm, plus temperatures above 100 °C and severe water condensation. Thus, the function of the complementary hardware is to collect, prepare and dilute the exhaust gas sample, passing it into the sensors and throwing it away, from the vehicle, as seen in Figure 20.

Figure 20 – Low-cost PEMS mounted in the test vehicle



The collector tube is assembled at the end of the exhaust pipe by silicon rubber connector. As electro-catalyst sensors are sensitive to silicon gases, it was necessary to “burn” the connectors, especially the one plugged at the end of the exhaust pipe. The process for this is easy and consists of running the car and letting the hot exhaust gas pass by the connectors for 30 minutes or more or to keep the rubber connectors on an oven at 180°C for 30-40 minutes.

The length and diameter of the collector tube, plus the position of the sampling probe are defined by the RDE normative (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a). The full length, considering the connectors before and after the collector tube and the exit tube, shall be more than eight times the tube diameter, thus bigger than 500 mm. The collector tube diameter must be the same or bigger than of the exhaust pipe, in order to avoid interferences in the exhaust gas flow. As the test vehicle has an Ø55 mm exhaust pipe, the collector tube has Ø63 mm (Ø 2.1/2”) x 450 mm, plus two Ø2.1/2” x 100 mm connectors and an Ø63 x 80 mm exit tube. The sampling probe is mounted inside the connector tube and its position, according to the normative, must be more than 200 mm far from the end of the collector tube.

The hose takes the gas sample from the probe to the dilution head, the separator removes the water condensed in the hose before mix the gas with atmospheric air in the dilution head, Figure 21. This head is connected with the dilution tube, which has a length enough to homogeneous and stabilizes the mixture, passing it by the sensors, Figure 22-23. The dilution tube design follows the ABNT NBR 6601 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2021) laboratory test normative, which determines that it must have a length of 10 times its diameter between the mixing point and the sensors. Thus, it consists of a Ø63 mm x 630 mm tube, plus the dilution head and sensors tube, making a total length of 750 mm. At least, a small vacuum cleaner works as a suction pump, sucking in the mixture and delivering it outside the car.

Figure 21 – Dilution head: mixer for exhaust gas sample with ambient air

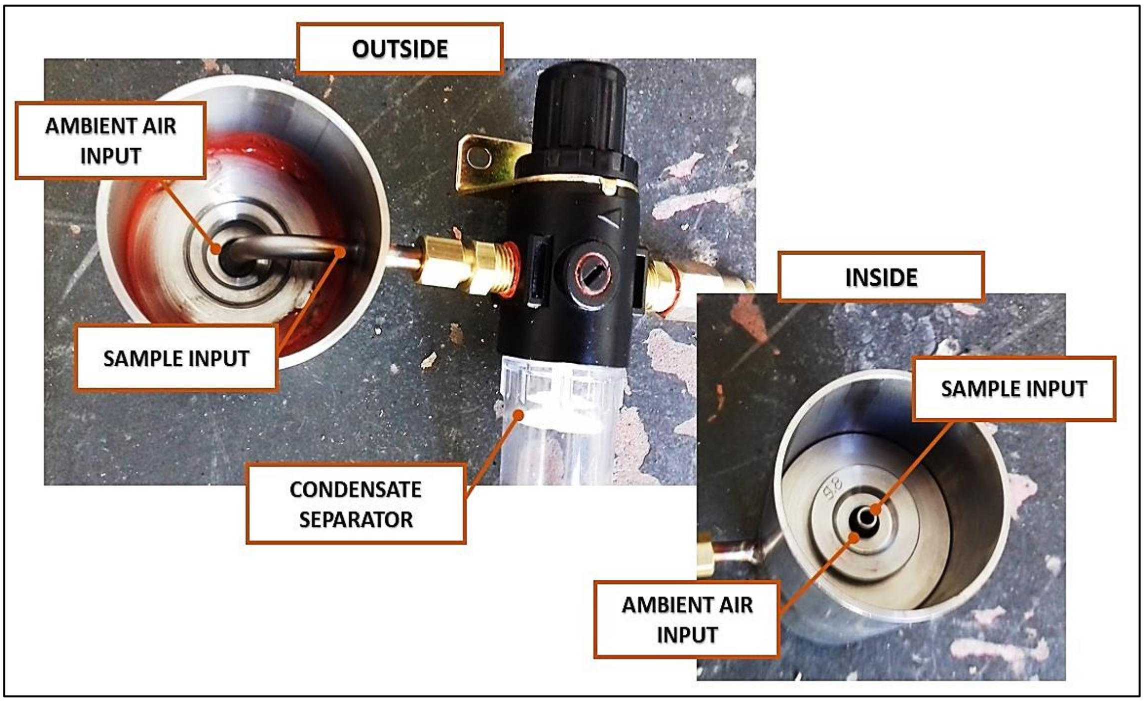


Figure 22 – Sensors board

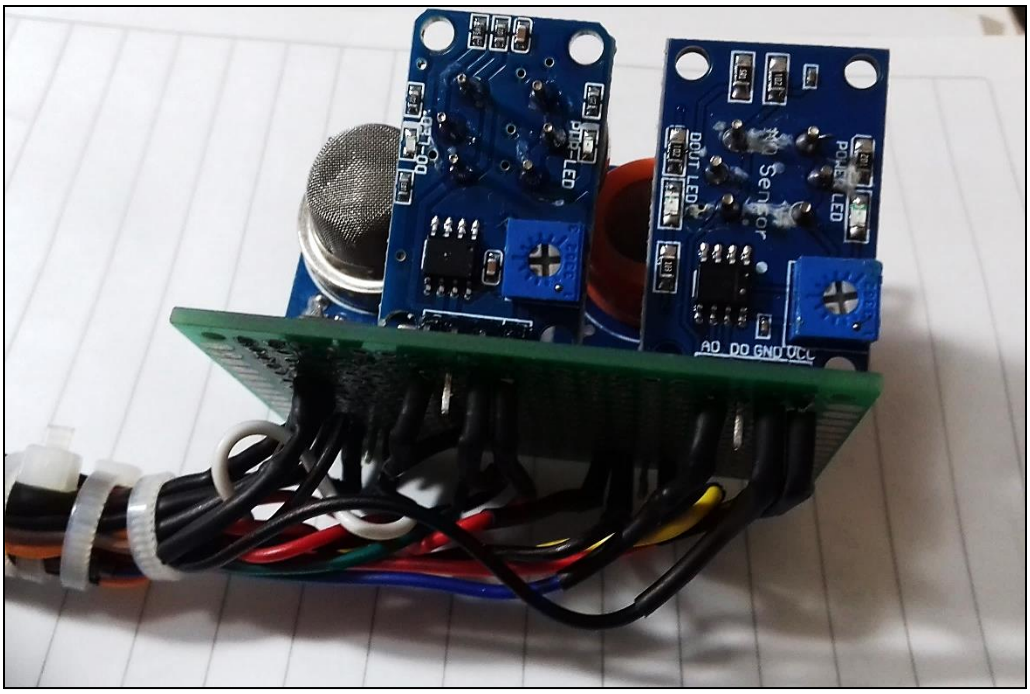
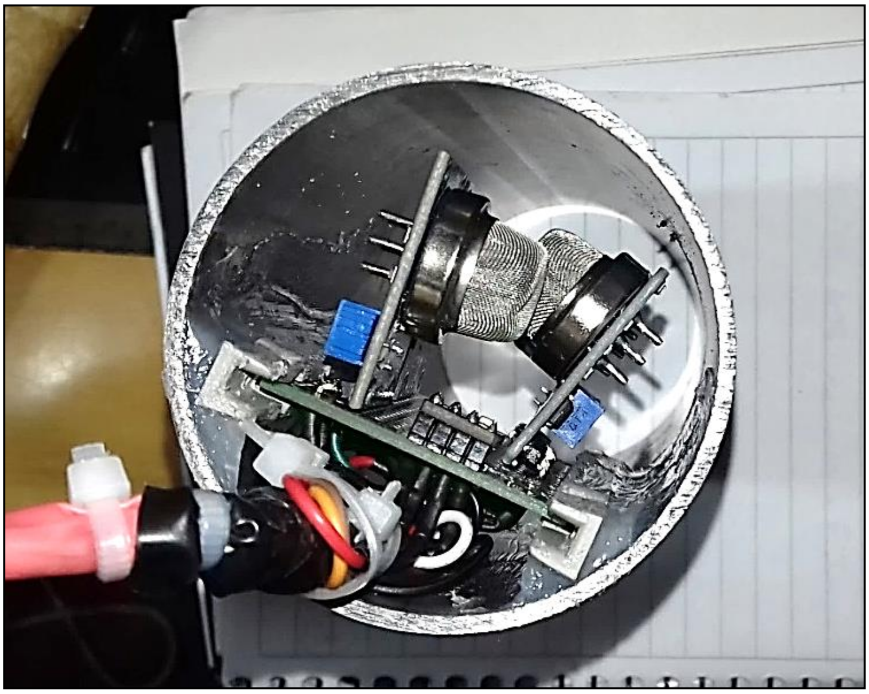


Figure 23 – Sensors mounted into the tube



Some principles are working in this design: the sample gas collected is cooled when passes through the sampling hose, enough to remove excessive moisture in the condensate separator, the dilution head mixes the gas sample with ambient air, so the pollutant concentration does not exceed the sensors measurement range, and the dilution ratio is made by the different areas from sample input tube and ambient air input.

The complete system weighs approximately 15 kg, considering the collector tube, dilution tube, blower, batteries, notebook, Raspberry, and Arduino. The blower is the main electric power consumption, requiring 4 A x 12 VCC, or ~50 W, and this is supplied by the vehicle's electric system. Although the RDE procedure determines that PEMS must be fully independent of the car's energy supply, this power consumption is approximately the same than one headlight, so it was considered negligible. Other devices, such as Raspberry, Arduino, and the notebook work autonomously, powered by their batteries.

3.2 Laboratory tests

The first experiments were done in November-December/2020, at the laboratory of vehicular emissions of CETESB in São Paulo. Initially, the sensors were tested only with standard gases, which are used in the calibration of the laboratory instruments bench, such as CO with concentrations of 1,000 and 3,000 ppm and propane (C_3H_8) with a concentration of 95 ppm. A gas divider is a device that makes the mixture of nitrogen with CO in proportions from 10% to 100% of CO, passing by the sensors and registering the results. The same is done with propane, diluted in synthetic air.

Another experiment was done in an evaporative chamber. This is the equipment to measure fugitive fuel emissions from vehicles, consisting of a sealed room where the vehicle is kept inside, heating the fuel tank, or just remaining there after a dynamometer test with the engine is still hot. Based on the known chamber volume and HC concentration change, measured with a FID, the fuel mass evaporated can be calculated. For the LCP test, the LCP hardware was kept inside the chamber, and portions of 2 g of ethanol were inserted into the chamber on a heated plate, which evaporate the fuel. After a stabilization time, the results from FID were compared with those from LCP sensors.

These first tests were finalized by running the car in the dynamometer, comparing the measurement from laboratory instruments with those from LCP. To avoid the influence of transients, such as accelerations and decelerations, these tests were done with the vehicle at constant speed. As the laboratory cycle ABNT NBR 6601 has three phases, in the first phase the car was running at 2,000 rpm, in the second phase at 3,000 rpm and the 3rd phase at 4,000 rpm, always in 3rd gear.

These experiments do not produce applicable results in terms of correlating laboratory and LCP. First, as electro-catalyst sensors are sensitive to humidity and standard gases have any water mixed, the response curves resulted far from what can result when sensors are in ambient air, or worse, when measuring exhaust gas with high relative humidity, and, as a consequence, it is not possible to do the calibration check with standard gases. Second, the evaporated ethanol produces different results than those from the exhaust gas, because it is composed of just a parcel of unburned fuel but plus a range of compounds from incomplete ethanol combustion, as sensors have strong cross-influence and different curves for each group of substances, both response curves of evaporated ethanol and exhaust gas are not correlated. Third, the noise from unplugged channels in Arduino compromised the measurements, because it was greater than the values measured in almost all experiments. Fourth, the test in dynamometer with constant speed produced close to zero pollutant concentrations in the exhaust gas, thus these values were practically out of the sensors ranges or produced large dispersion. Therefore, it was not possible to determine practical response curves for THC and CO.

The project was reviewed, grounding the Arduino unplugged channels to eliminate noise, second, the CO sensor was changed for a ZE-07 electrochemical sensor, which has lower sensitiveness to other substances, and, the THC sensor was changed for a MQ-6, that embraces more hydrocarbons compounds than the first sensors tested. Since some problems in the electric connections were detected, all cabling was replaced by new, reinforced ones. Due to the low-cost sensors sensitiveness to changes in temperature and humidity, it was abandoned the zero-span check with standard gases and adopted as a zero-value criterion the lower value registered by the sensor during each test measuring exhaust gas diluted in ambient air.

The second round of tests was performed in April/2021, in the laboratory dynamometer and running the test cycle FTP-74. This cycle is the same as FTP-75 and ABNT NBR 6601, but running only the two first phases and starting the vehicle hot, with engine coolant above 50 °C. This short cycle saves time and produces more regular results than type-approval cycles, because skips the cold phase, where the cold catalyst cannot control the pollutants, resulting in higher values that could distort the measurements.

The system produced coherent data, the condensate separator avoided moisture from enter in the dilution tube and, according to the data from the BME-280 sensor, the relative humidity raised only 5-10% more than ambient and the temperature was about 5-10 °C above than ambient, in the sensors' board. A minor issue was the internal volume of the condensate separator, which shows to be insufficient for longer tests. During the FTP-74 cycle, with only about 20 minutes, it was collected about 20 ml of water and the reservoir was almost 30% full. So, the change for a bigger separator was necessary, enough to lead on with a RDE test lasting one and a half to two hours long.

The comparison between LCP and CETESB laboratory allowed developing equations to transform the values from sensors in pollutant concentrations, in ppm. The LCP generates a text file with all data gathered from sensors, GPS, OBD, and sensors data must be aligned and recalculated to be transformed in ppm, after this the data can be post-processed by EMROAD. These equations, test data, and more are discussed in Chapter 5, Results.

3.3 Field tests according to RDE Brazilian procedure

The LCP development was completed with field tests, with the vehicle following the Brazilian RDE procedure. As these tests are longer than that in the laboratory, some specific problems must be fixed. The first was the battery capacity that went off after one hour of test, so to power the set Raspberry-Arduino it was necessary to change to a 10,000-mA power bank, which proved to be able to feed the LCP for two tests in the same day without recharge.

The second problem was a communication loss between Raspberry and Arduino. Both devices run their programs independently: Arduino reads the sensors, writes the text sentence, and waits for the Raspberry's request. On the other hand, Raspberry is reading the OBD and GPS data, calculates exhaust flow mass and CO_2 concentration, and, together, asking Arduino for sensors values. It worked well in the laboratory tests because they were relatively short, but as in-field runs demand more time, this problem began to happen, sometimes about 30 to 60 minutes after the start. The solution passed by the Arduino program rewriting: the original program was reading one sensor and writing a part of the text, a second sensor and writing the second value, and so on, while the modified program first reads all sensors, after writes the sentence in one step and pauses, waiting for Raspberry request. After this modification, the system worked perfectly and without failures.

There were some concerns for tests on the roads, related to, first, if vibrations from irregularities in the asphalt can affect the LCP, second, if the condensate separator has enough internal capacity to retain the moisture during all trip, and third, if all data collected will be useful and coherent, with few or no gaps or missing values. After all tests, it was noticed that the system is not sensitive to vibrations, even running in no-so well-conserved streets. Condensate water retained in the separator did not overpass 75% of the reservoir and any moisture reached the sensors; finally, all data collected were coherent and able to be processed, exception for few points in the exhaust mass flow, when OBD returned some noise and the data resulted in values about 10 times or more above the actual. The RDE procedure sets a limit for data interruption of 1% and for no more than a consecutive period of 30 seconds (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a). However, the LCP presented an averaged error of 5.6% from OBD readings in the field tests, although these loses happened in periods of just one second, in rare occasions for 2 or 3 seconds. This problem occurred only in the field tests, the data interruption in laboratory was on average less than 0.4%. The root cause was not identified, it is supposed that could be some bad connection in the OBD reader, and to fix it, during the preparation of the *.csv file for being post-processed, was included a step of identifying these outlier points and replacing them by an average of the previous and posterior points. The complete process for preparing and post-processing the LCP log file is described in Appendix 3.

The routes used in RDE tests were previously established during the first steps of the LCP research and applied in the research of USP colleagues, as well as in practical studies for developing the Brazilian RDE procedure, therefore for this research they were already mature, being used without big concerns, although some care must be taken yet in all runs, for example, to avoid rush hours due to heavy traffic congestion. Figure 24 has an example of the urban trip in Sao Bernardo do Campo, starting in CETESB vehicular laboratory and finishing close to Via Anchieta roadway, Figure 25 is the rural trip in the Via Anchieta, both with their respective topographic profiles, and all routes used in the tests are shown in Appendix 5.

After these steps, the LCP was considered able to work, which was done in many RDE tests covering diverse ambients, driving behaviors, and traffic conditions, and these results are discussed in Chapters 5 and 6.

Figure 24 – Sao Bernado do Campo urban trip – 3D view and topographic profile

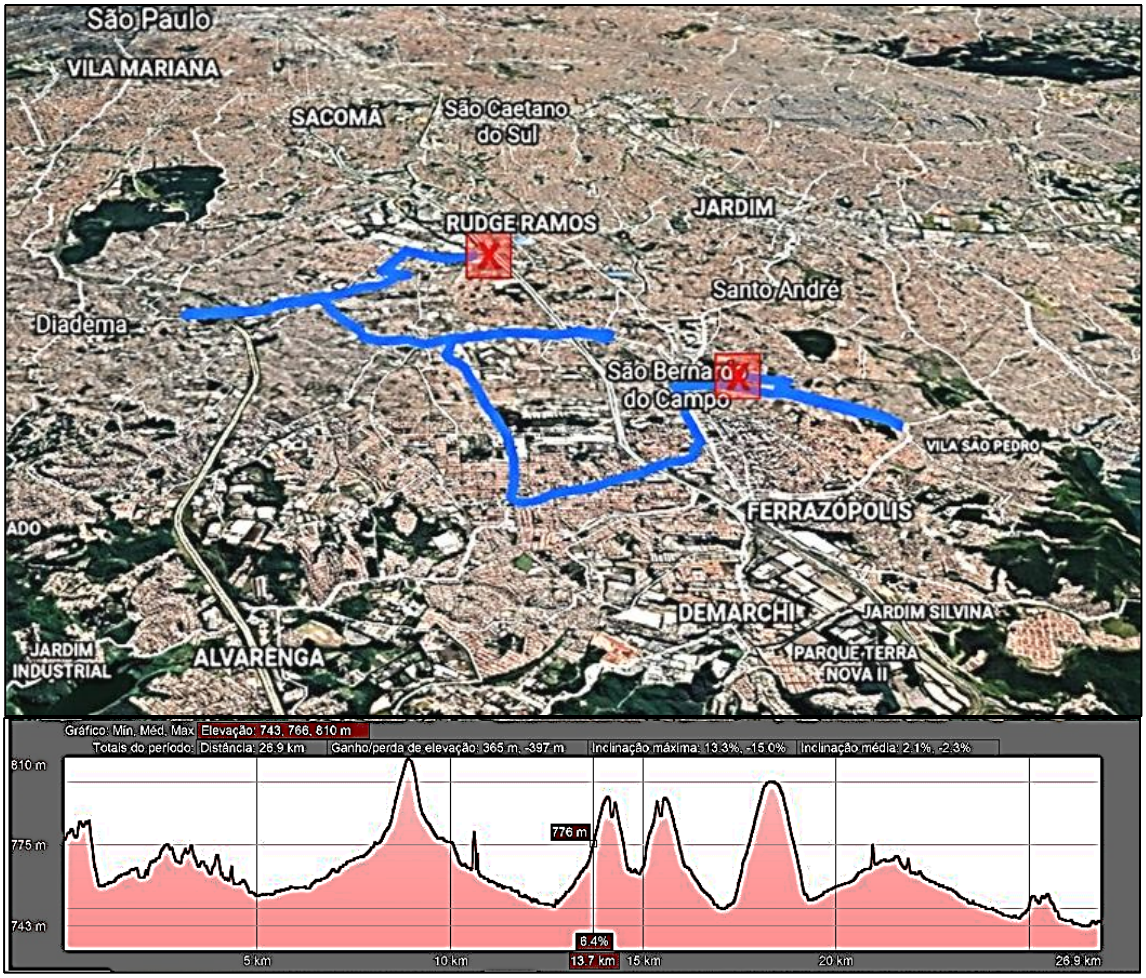
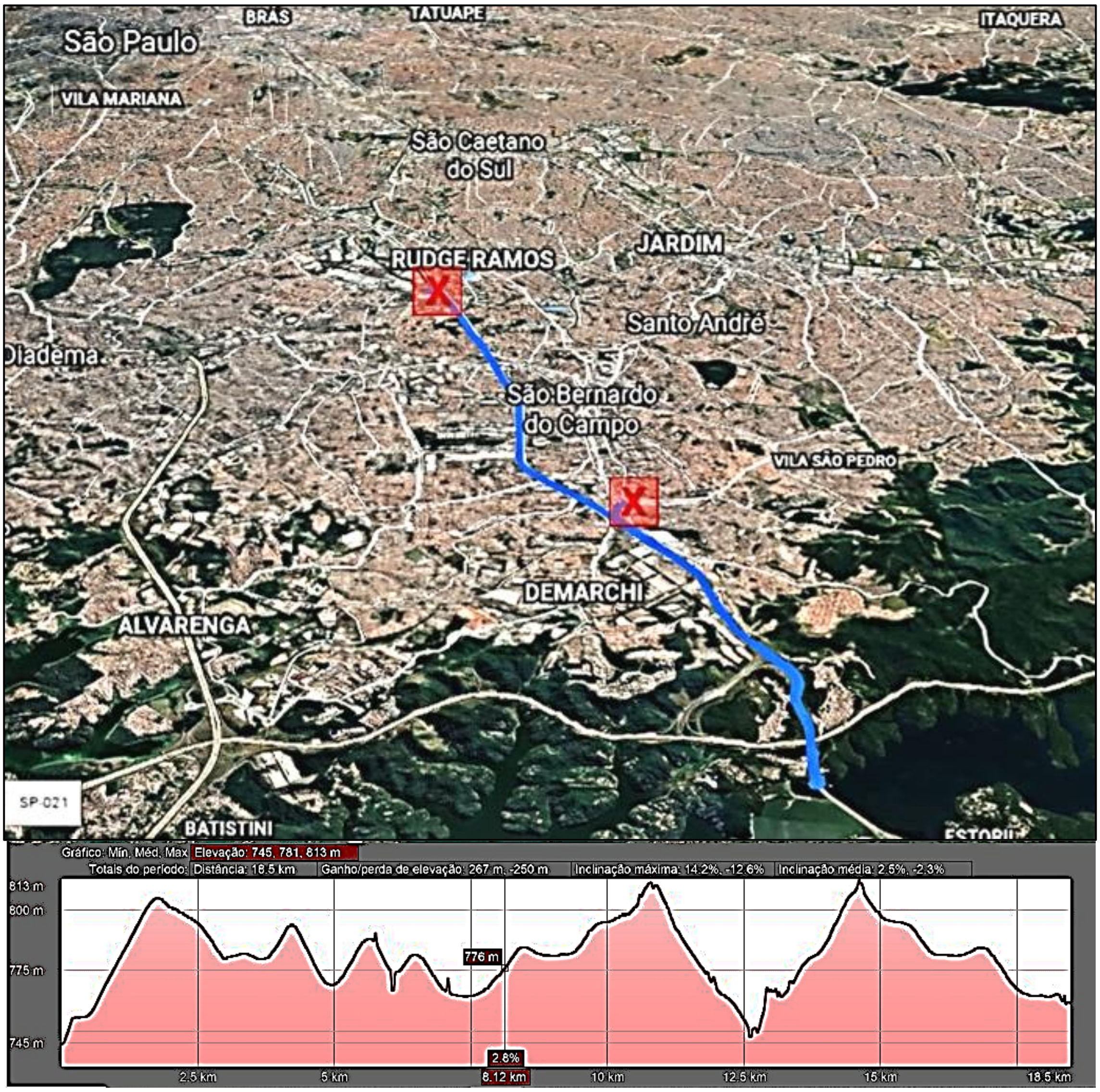


Figure 25 – Sao Bernardo do Campo rural trip – 3D view and topographic profile



4. VSP AS CRITERION FOR RDE DYNAMIC

This research resulted yet in a proposal of applying VSP as a complementary metric for evaluating the RDE dynamic. An article It was published in Environmental Science and Pollution Research, titled “Improving the assessment of RDE dynamics through Vehicle Specific Power Analysis”, with DOI 10.1007/s11356-022-19925-1 (FORCETTO et al., 2022). The first page of this paper is presented in Appendix 6, and here it is presented a summary of this article.

The RDE procedure has three parameters for evaluating the vehicle dynamic in the test: the comparison of CO_2 emission in g/km from RDE to that produced in the laboratory test, the Relative Positive Acceleration (RPA), and v*a_pos[95]. RPA is the mean of all positive acceleration in phases urban, rural, and, in Europe, motorway, and must be higher than a calculated value. In other turn, v*a_pos[95] represents the power required to move the vehicle, where the instantaneous speed is multiplied by the positive acceleration and the correspondent value to percentile 95% must be lower than a value obtained from an equation, for each RDE phase (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016b). These three regulatory parameters do not consider the road grade and it introduces a bias in the test because the power requirement is diverse when going up or down.

VSP is calculated by Equation 6 (JIMÉNEZ-PALACIOS, 1999), and it is based on average values for air density, rolling resistance, and aerodynamic drag of a regular LDV:

$$VSP = v * (1.1 * a + 9.81 * grade + 0.132) + \ 3.02 * 10 * E^{-4} * (v + vw)^2 * v \quad (6)$$

Where v is vehicle instant speed (m/s), a is vehicle instant acceleration (m/s^2), *grade* is the vertical rise by distance (%), v_w is wind speed (m/s), and the VSP result is expressed in W/kg.

As this study took in the calculations only positive acceleration points, this criterion was named VSP+. Two equations are used for defining curves for VSP+ max (Equation 7) and VSP+ min (Equation 8), which cover the area generated for test cycles WLTC and FTP-75, where each point represents the calculated VSP from each one-second measurement of speed and acceleration during the test cycle. These curves and the VSP+ distribution for both test cycles are shown in Figures 26 and 27.

$$VSP+_{max} = -0.0019 * x^2 + 0.472 * x + 0.6 \quad (7)$$

$$VSP+_{min} = 0.00128 * x^2 + 0.0028 * x + 0.57 \quad (8)$$

Figure 26 – Curves defining VSP+ max and min x VSP from WLTC cycle

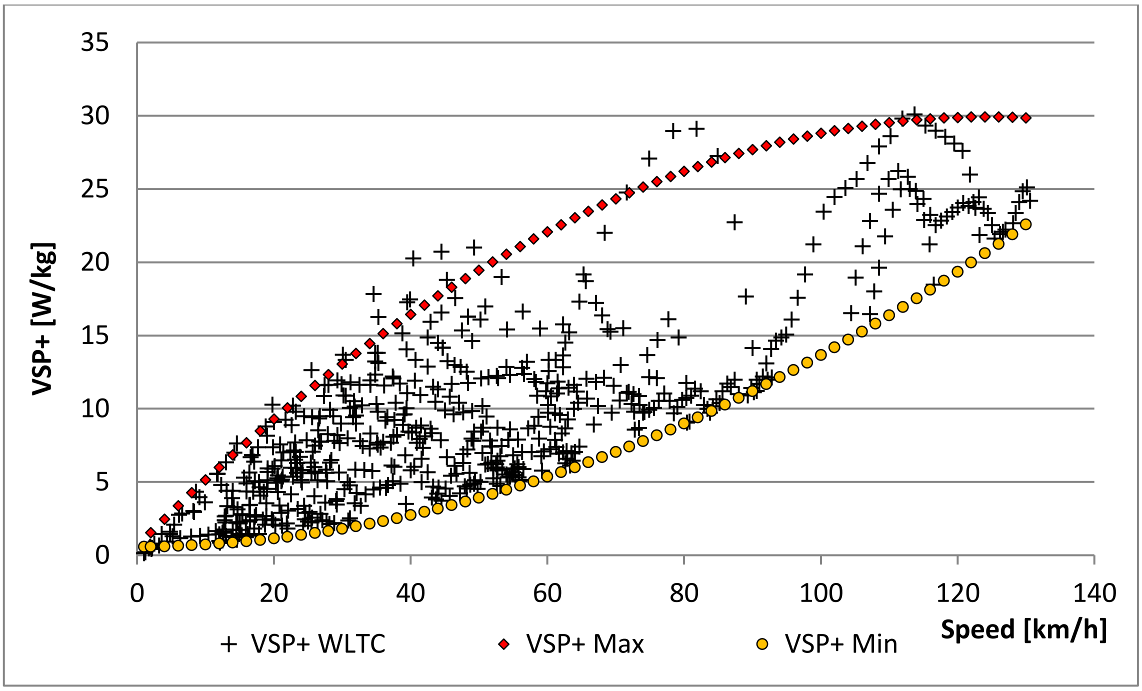
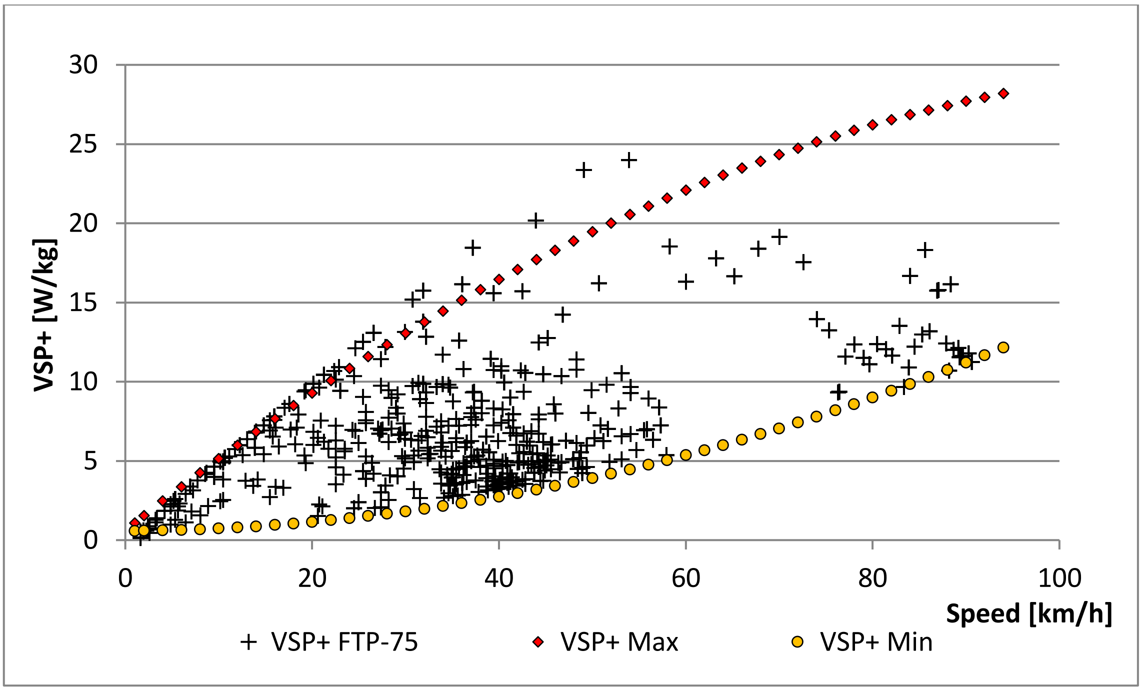


Figure 27 – Curves defining VSP+ max and min x VSP from FTP-75 cycle



The VSP becomes interesting for understanding the real-world dynamics of the vehicle because the curves represent the values from the regulatory test cycle, thus the points above the VSP+ Max curve from a RDE test are reflecting a more intensive power requirement in comparison to the laboratory cycle, request that can be caused by more driver aggressive driving and/or when it is accelerating the vehicle on a positive grade road. Similarly, the results below the VSP+ Min curve are able to represent speed gain in a negative slope, even without the use of energy from the engine.

In this way, VSP+ was included in Chapter 5, Results from RDE tests, being compared to the results of the regulatory metrics, to help the understanding of the tests dynamics. VSP is an important parameter in mathematic models for vehicle emissions, so in Chapter 6, RDE Emission Factors, its influence on vehicle emissions is deeper analyzed.

5. RESULTS FROM LABORATORY AND FIELD TESTS

According to the Plan of Action, tests in the laboratory were performed for determining the LCP accuracy, after this the system was tested in field and some adjustments and improvements were done. The results expressed in this section refer to the complete test or, when in the laboratory, they can be separated by the test phases and, in the field, according to the urban and rural trips, i.e., below or above 60 km/h.

5.1 Results from laboratory tests

The laboratory tests were executed from May/17th to May/25th/2021, with the vehicle fueled with E22 in 10 tests and with E100 in other 10 tests. Both E22 and E100 used in these tests are laboratory-grade fuels, or reference fuels, that must attend more restrictive quality parameters than the commercial ones. For example, the ethanol concentration in the reference E22 is 21 to 23%, while in the commercial blend goes up to 27% (BRAZIL, 2022). The Python program compensates this ethanol variation in the CO_2 calculation but the influence of the other parameters is not considered in the emission analysis.

The vehicle started in all tests with the engine temperature above the ambient, following the test cycle FTP-74, with duration of 11.9 km and approximately 1400 s, and Tables 8 and 9 have the main test conditions for E22 and E100, respectively. The tests with higher engine temperatures were executed after short intervals between runs, and those with lower temperatures usually after longer stops, for example after the lunch interval. As the laboratory is climatized, there is low variation in the ambient temperature, although the relative humidity is quite different in one week to another. As the zero-value criterion for the sensors is the lowest value recorded in each test, these variations did not impact the final results.

The sensors response delay in comparison to OBD data was determined by accelerating the vehicle from idle and measuring the required time to detect the change in the concentration of the pollutants. On average, they take about 8 to 15 seconds for changing the readings, thus all sensor’s data are shifted by a 10 s alignment in respect to the GPS and OBD signals.

Table 8 – General test conditions in the laboratory – E22

Test #	Ambient temperature (°C)	Relative humidity (%)	Engine temperature (°C)	Observations
1	23	60	85	
2	24	58	80	
3	24	54	87	
4	23	54	54	Catalyst lit on after 78 s
5	24	50	54	Catalyst lit on after 86 s
6	22	63	78	
7	23	59	69	Unexpected high THC emission
8	24	57	70	
9	23	58	45	Catalyst lit on after 72 s
10	25	52	82	

Table 9 – General test conditions in laboratory – E100

Test #	Ambient temperature (°C)	Relative humidity (%)	Engine temperature (°C)	Observations
1	23	35	85	
2	23	33	85	
3	23	32	51	Catalyst lit on after 147 s
4	23	32	78	
5	24	30	76	
6	24	38	61	Catalyst lit on after 132 s
7	24	38	76	
8	23	36	45	Catalyst lit on after 170 s
9	24	33	78	
10	25	31	78	

As refereed in Chapter 3, the sensors do not return directly the pollutant concentration but a signal that is proportional to the voltage or resistance variation, thus it was necessary to develop equations for transforming these values in pollutant concentration, in ppm.

At this point, a difficult occurred due to the different approaches that laboratory and PEMS have to calculate the results in g/km. In the laboratory, according to the normative ABNT NBR 6601 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2021), the emission in g/km is determined by multiplying the volume of exhaust gas plus the dilution air that had passed by the Constant Volume Sampling (CVS), times the pollutant density, and times the pollutant concentration in ppm measured in the bags that collected the exhaust gas sample from CVS, all divided by the traveled distance. In a general form, the emission calculation follows Equation 9:

$$Emission\left(\frac{g}{km}\right) = \frac{Vcvs * Density * Concentration}{Distance} \quad (9)$$

Where *Emission* is the pollutant produced in g/km, *Vcvs* is the volume of exhaust gas plus dilution air that passed by the CVS, *Density* is the pollutant density (g/m^3) and *Concentration* is the measured pollutant concentration (ppm) found in the bags where the diluted exhaust gas from the CVS is stored.

The CVS dilutes the exhaust gas with ambient air and this dilution can be calculated based on the proportion between the CO_2 concentration measured in the bags where the samples are collected, divided by the theoretical CO_2 concentration. This dilution ratio is applied to compensate for the pollutant background from ambient air, where its concentration is subtracted from that measured in the bags.

The PEMS works in a different way, where the raw exhaust gas is measured second by second and the pollutant concentration is multiplied by the exhaust mass flow, times the pollutant density. This pollutant mass emission second by second is integrated for the complete test duration to total mass emission, and it is divided by the traveled distance in the test to achieve the final result in g/km.

However, despite these methods seeing to have the same work principle, there is a conceptual error when it is compared the raw exhaust gas concentration average data measured by the PEMS, with the values resulting from laboratory bag concentration times its dilution ratio. First, in the laboratory procedure, this ratio is just for compensating the background concentration in ambient air and laboratory equations do not consider dilution for computing the emissions. Second, this proportion is calculated over a theoretical CO_2

concentration, 13.4%, and this value is far from the actual exhaust CO_2 averaged concentration because, first, this depends on what fuel is being burned, and second, due to the fact that in modern cars the fuel injection is cut-off in decelerations, thus anything is burned in this moments and CO_2 emission is zero, lowing its averaged ratio.

Therefore, the best way to compare laboratory and PEMS results is analyzing the results in g/km, so Equations 10 to 13 were developed for transforming LCP measurements in the respective concentration in ppm, able to be post-processed by EMROAD, that delivers the respective values in g/km.

$$HC_{E22} = 0.054 * X^2 - 2.33 * X \quad (10)$$

$$CO_{E22} = 8.06 * X \quad (11)$$

$$HC_{E100} = 0.0183 * X^2 - 0.65 * X \quad (12)$$

$$CO_{E100} = 12.1 * X - 33 \quad (13)$$

Where HC_{E22} is the THC concentration in ppm for E22 and HC_{E100} for E100, CO_{E22} is the CO concentration in ppm for E22 and CO_{E100} for E100, and X is the value read in the sensor for Arduino, minus the lowest value recorded in the test, following the method described in Appendix 3, LCP log file processing. The emission results in g/km, after this preparation and processing, are shown in Tables 10 for E22 and 11 for E100. The validation of the LCP according to the tolerances from the RDE normative are shown in Tables 12-13, and the system accuracy is determined, comparing its results to those from the laboratory.

Table 10 – Comparison between emissions measured in laboratory and Low-cost PEMS – E22

Test #	Phase	CO_2 (g/km)		CO (g/km)		HC (g/km)		Distance (km)	
		LAB	PEMS	LAB	PEMS	LAB	PEMS	LAB	PEMS
1	1	152.60	150.03	0.251	0.243	0.023	0.028	5.68	5.69
	2	181.70	182.38	0.004	0.018	0.003	0.001	6.30	6.26
2	1	156.20	151.75	0.272	0.228	0.012	0.057	5.79	5.79
	2	182.40	179.38	0.001	0.038	0.004	0.003	6.19	6.14
3	1	152.00	151.30	0.235	0.170	0.012	0.029	5.79	5.81
	2	180.50	182.36	0.066	0.063	0.004	0.010	6.21	6.16
4	1	161.70	157.62	0.444	0.448	0.061	0.068	5.78	5.82
	2	181.40	185.64	0.073	0.090	0.003	0.016	6.16	6.11
5	1	160.40	157.22	0.373	0.366	0.058	0.046	5.77	5.79
	2	181.70	185.11	0.089	0.110	0.000	0.028	6.18	6.14
6	1	155.70	155.74	0.148	0.101	0.011	0.016	5.78	5.77
	2	184.60	184.86	0.316	0.428	0.174	0.137	6.21	6.17
7	1	155.90	151.35	0.303	0.286	0.029	0.035	5.81	5.84
	2	180.30	184.04	0.015	0.012	0.002	0.001	6.20	6.14
8	1	153.10	152.75	0.358	0.359	0.033	0.037	5.79	5.91
	2	177.70	181.03	0.020	0.029	0.001	0.013	6.14	6.18
9	1	161.70	159.37	0.494	0.437	0.078	0.065	5.77	5.80
	2	182.50	188.44	0.015	0.019	0.002	0.001	6.21	6.19
10	1	155.60	151.88	0.356	0.310	0.011	0.039	5.76	5.77
	2	180.20	179.85	0.002	0.031	0.001	0.002	6.20	6.15

Table 11 – Comparison between emissions measured in laboratory and Low-cost PEMS – E100

Test #	Phase	CO_2 (g/km)		CO (g/km)		HC (g/km)		Distance (km)	
		LAB	PEMS	LAB	PEMS	LAB	PEMS	LAB	PEMS
1	1	148.70	138.36	0.017	0.012	0.018	0.070	5.66	5.82
	2	171.60	165.95	0.020	0.006	0.003	0.004	6.18	6.11
2	1	144.70	135.24	0.027	0.052	0.016	0.041	5.77	5.82
	2	173.90	166.90	0.029	0.016	0.003	0.006	6.17	6.16
3	1	152.70	144.99	0.031	0.068	0.123	0.143	5.78	5.77
	2	174.20	168.16	0.032	0.033	0.004	0.006	6.13	6.16
4	1	146.10	136.69	0.036	0.033	0.023	0.035	5.78	5.81
	2	174.00	166.90	0.050	0.041	0.004	0.006	6.13	6.11
5	1	145.90	136.00	0.054	0.074	0.043	0.058	5.72	5.77
	2	172.70	167.18	0.057	0.031	0.003	0.018	6.21	6.17
6	1	153.90	144.08	0.252	0.304	0.068	0.120	5.78	5.81
	2	177.10	166.32	0.266	0.439	0.023	0.005	6.17	6.16
7	1	148.20	138.42	0.319	0.359	0.004	0.056	5.76	5.80
	2	174.40	165.75	0.346	0.304	0.009	0.006	6.17	6.14
8	1	155.80	147.14	0.473	0.460	0.215	0.150	5.78	5.83
	2	173.00	168.02	0.589	0.798	0.013	0.014	6.15	6.13
9	1	143.20	136.01	0.670	0.805	0.035	0.015	5.76	5.76
	2	169.40	164.74	1.257	1.322	0.009	0.001	6.14	6.11
10	1	**103.80**	135.89	1.392	1.568	0.022	0.011	5.79	5.80
	2	170.00	159.63	2.030	1.700	0.004	0.003	6.21	6.18

The value in Table 11, test #10 phase 1, for CO_2, is highlighted in bold font because this point showed to be an outlier. The mean value for CO_2 in phase 1, E100, is 148.8 g/km with a standard deviation of 4.4, and test #10 phase 1 is 45.0 g/km above the mean, or 10.2 times greater than the standard deviation, thus it was excluded of the calculations.

Table 12 – Low-cost PEMS validation in comparison to laboratory, according to RDE normative (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a) – E22

	CO2 (g/km)	**CO (mg/km)**	**THC (mg/km)**	**Distance (m)**
PEMS average	168.61	189.3	31.6	5982
Laboratory average	168.90	191.8	26.1	5986
Absolute difference	0.29	2.5	5.5	4
Relative difference	0.2%	1.3%	21.1%	-
Normative tolerances	+/-10 g/km or 10%	+/- 150 mg/km or 15%	+/- 15 mg/km or 15%	+/- 250 m
Approved?	*Yes*	*Yes*	*Yes*	*Yes*

Table 13 – Low-cost PEMS validation in comparison to laboratory, according to RDE normative (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022; EUROPEAN COMMISSION, 2016a) – E100

	CO2 (g/km)	**CO (mg/km)**	**THC (mg/km)**	**Distance (m)**
PEMS average	153.50	421.3	38.3	5971
Laboratory average	161.55	397.4	32.1	5962
Absolute difference	8.05	23.9	6.2	9
Relative difference	5.0%	6.0%	19.3%	-
Normative tolerances	+/-10 g/km or 10%	+/- 150 mg/km or 15%	+/- 15 mg/km or 15%	+/- 250 m
Approved?	*Yes*	*Yes*	*Yes*	*Yes*

The statistical results from Pearson analysis and the correlated Coefficient of Determination R^2 are presented in Table 14, and Figures 28 to 35 display graphically the results from Tables 10-11 and 14-15.

Table 14 – LCP accuracy: coefficient of determination R^2

	CO_2	CO	HC	Distance
E22				
Coefficient of determination (R^2)	0.9761	0.9434	0.8521	0.9724
Number of elements	20	20	20	20
E100				
Coefficient of determination (R^2)	0.9839	0.9601	0.7285	0.9662
Number of elements	19	20	20	20

Figure 28 – Comparison of CO_2 results (g/km): laboratory instruments x Low-cost PEMS – E22

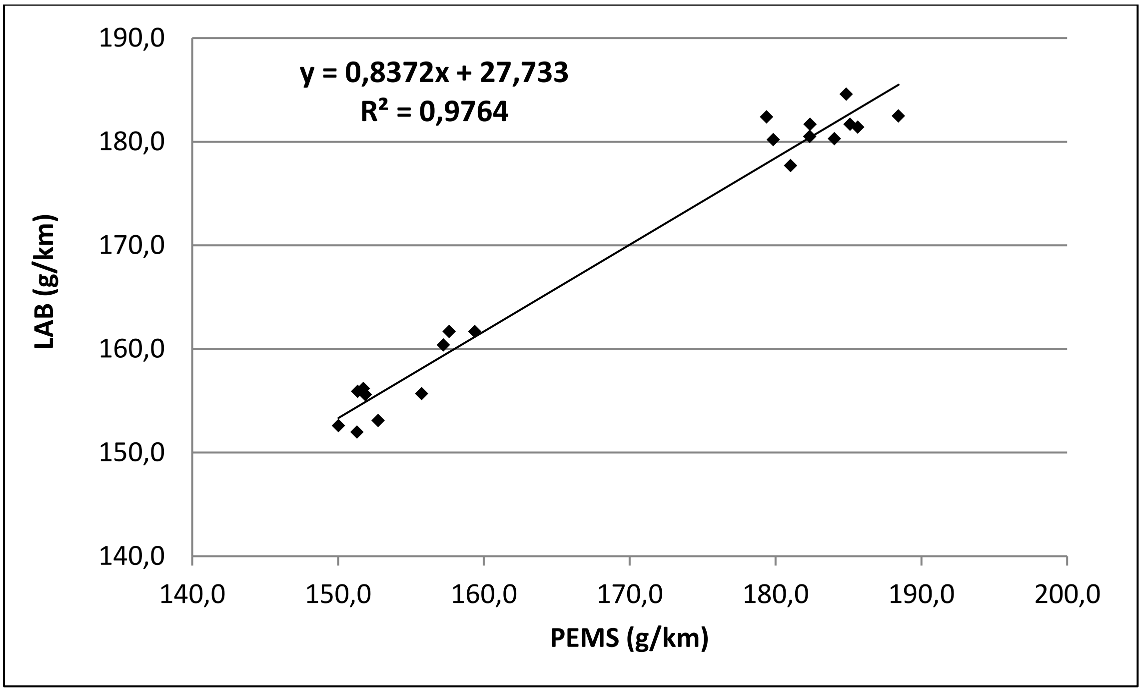


Figure 29 – Comparison of CO results (g/km): laboratory instruments x Low-cost PEMS – E22

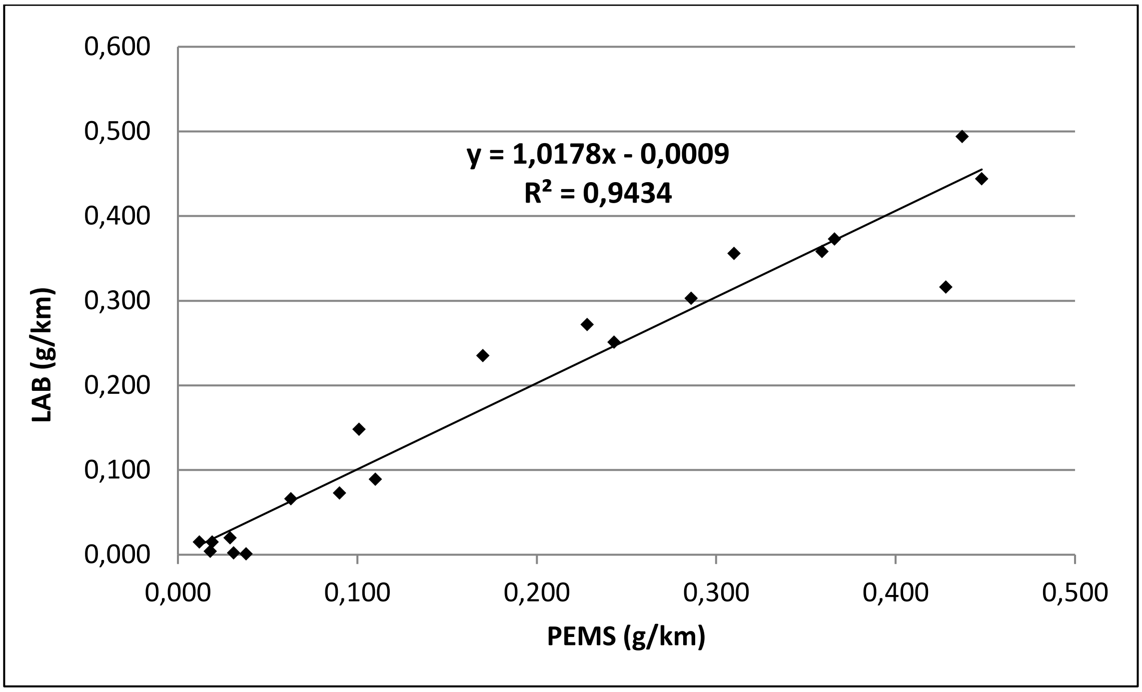


Figure 30 – Comparison of THC results (g/km): laboratory instruments x Low-cost PEMS – E22

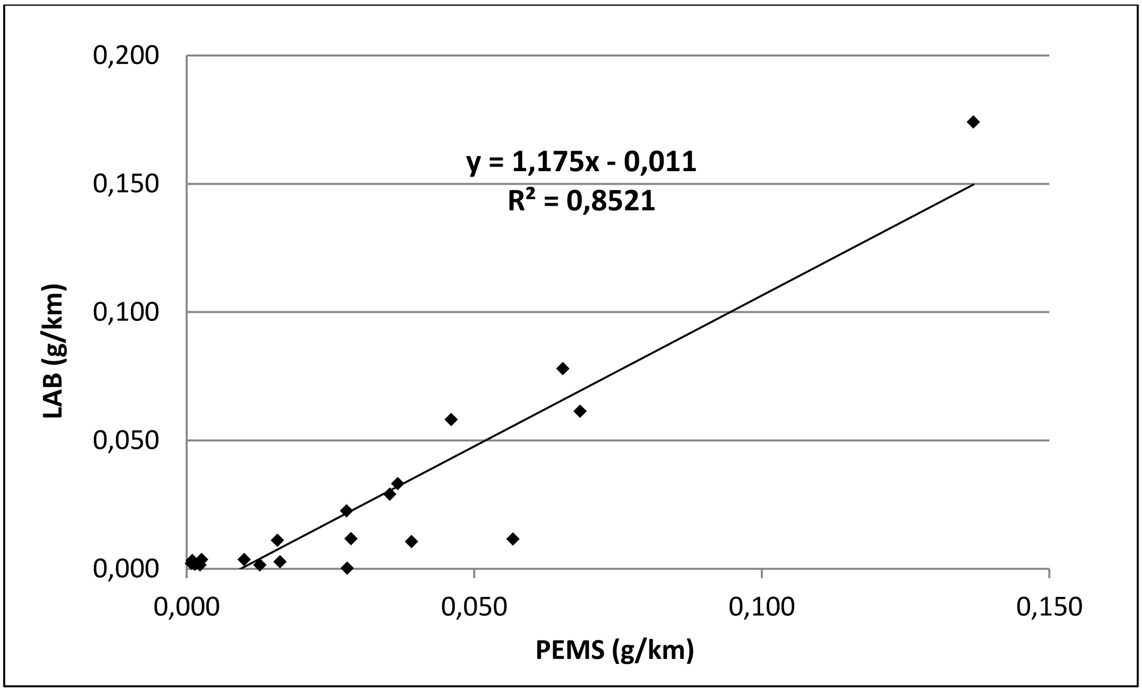


Figure 31 – Comparison of distance traveled (km): laboratory x Low-cost PEMS – E22

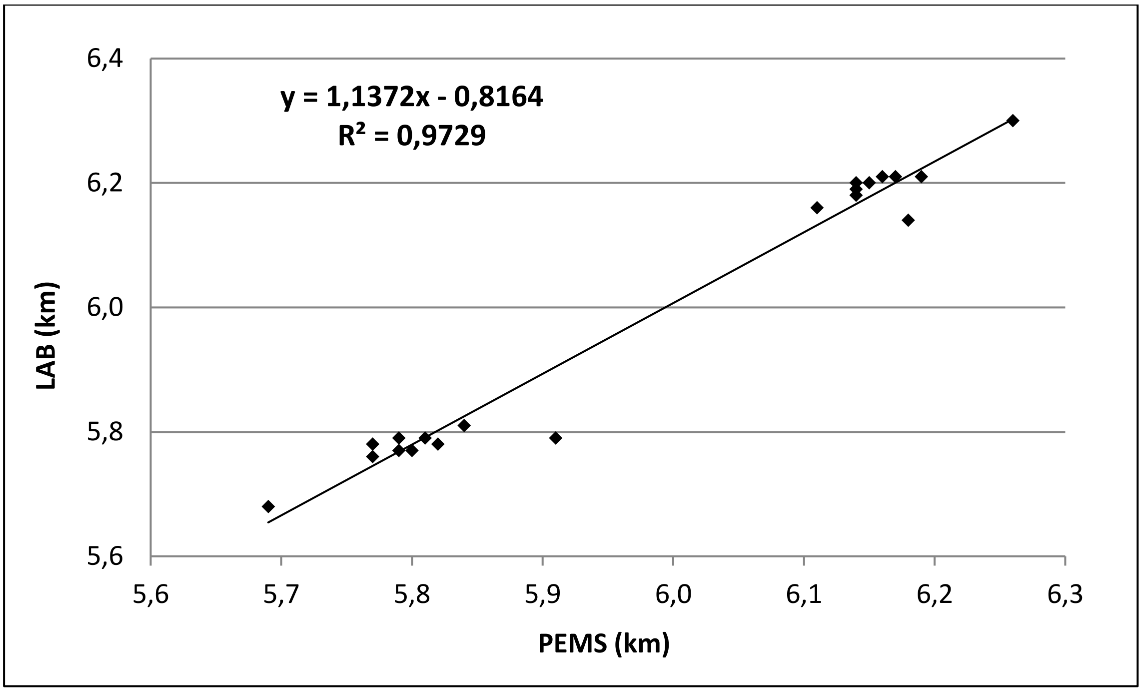


Figure 32 – Comparison of CO_2 results (g/km): laboratory instruments x Low-cost PEMS – E100

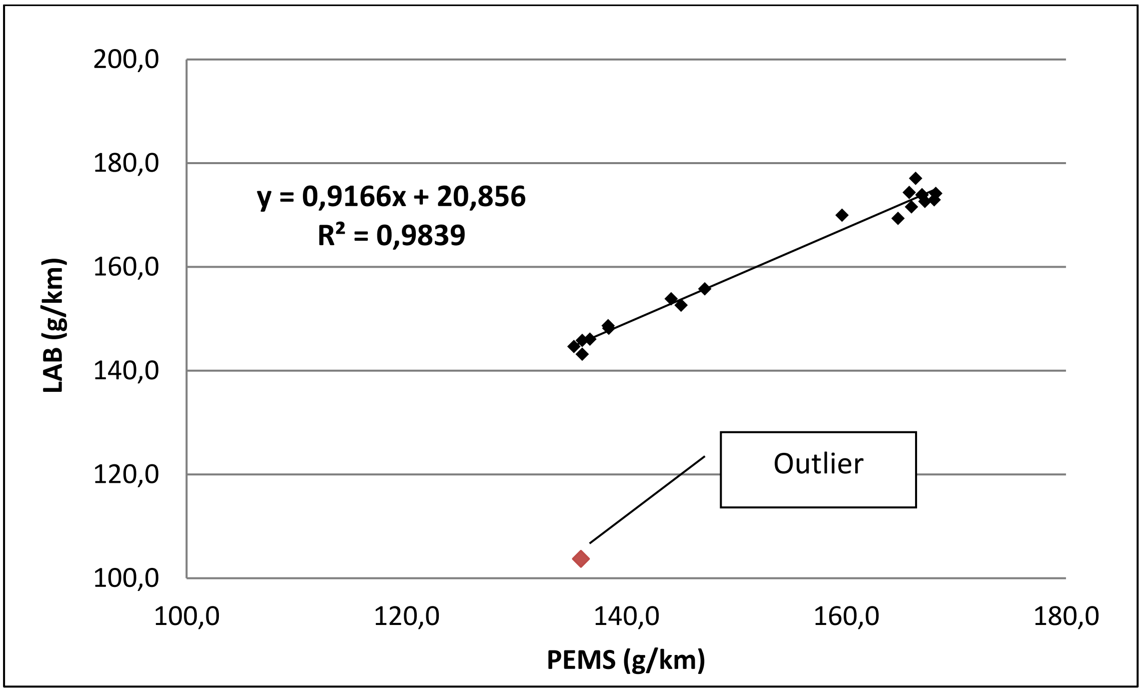


Figure 33 – Comparison of CO results (g/km): laboratory instruments x Low-cost PEMS – E100

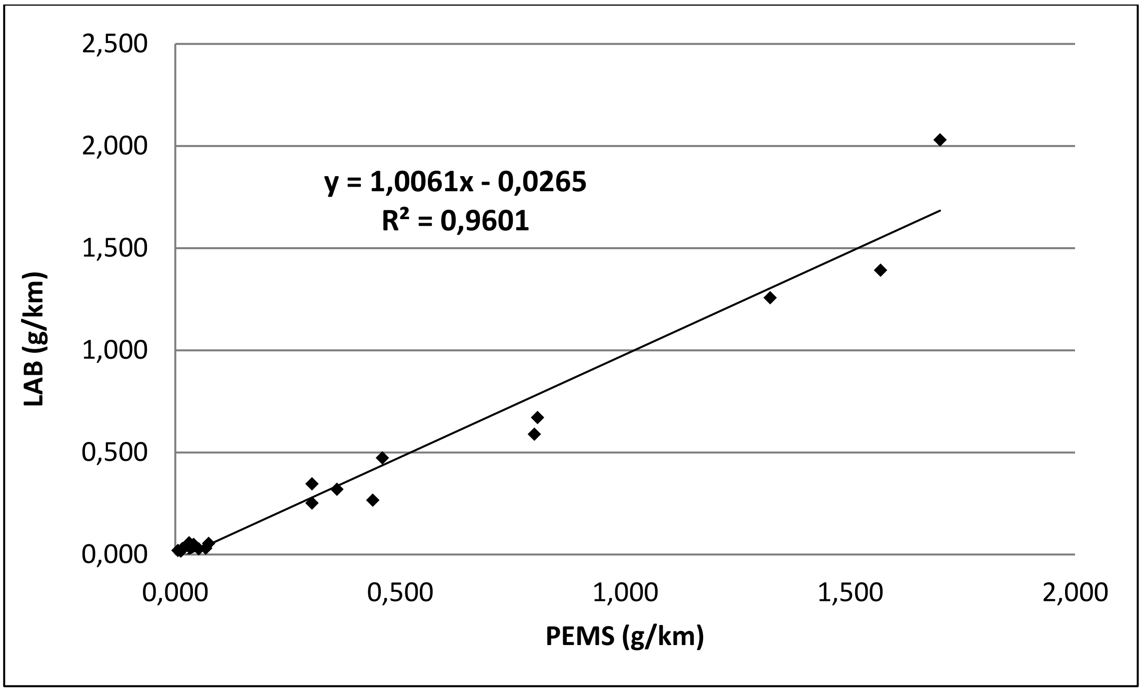


Figure 34 – Comparison of THC results (g/km): laboratory instruments x Low-cost PEMS – E100

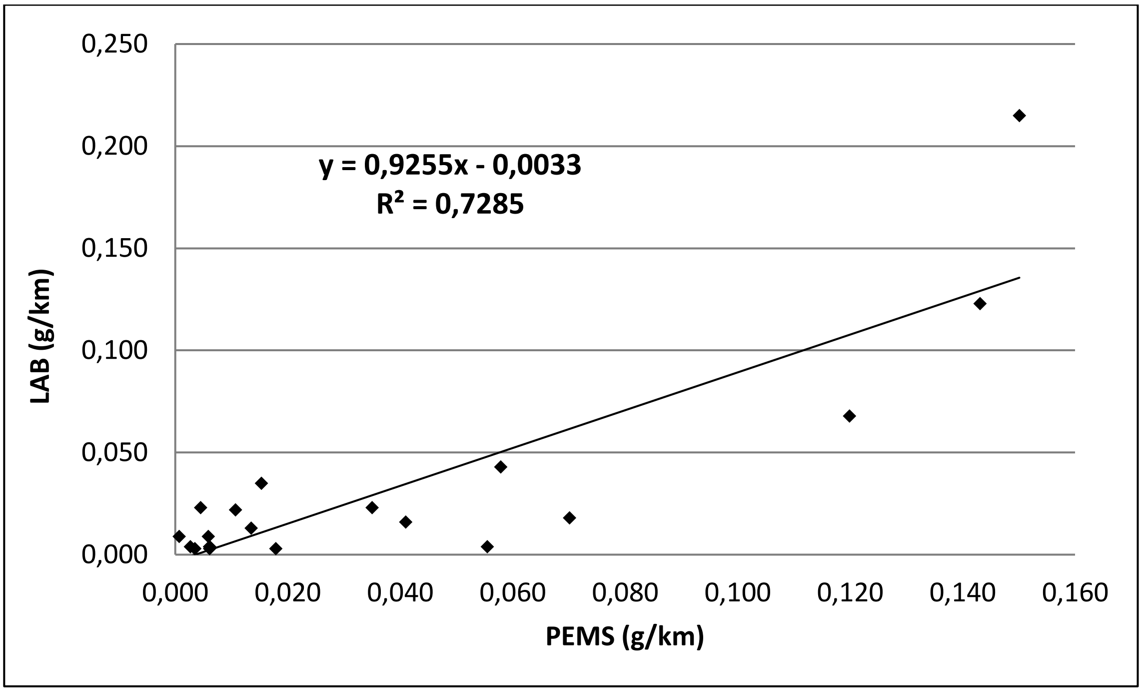
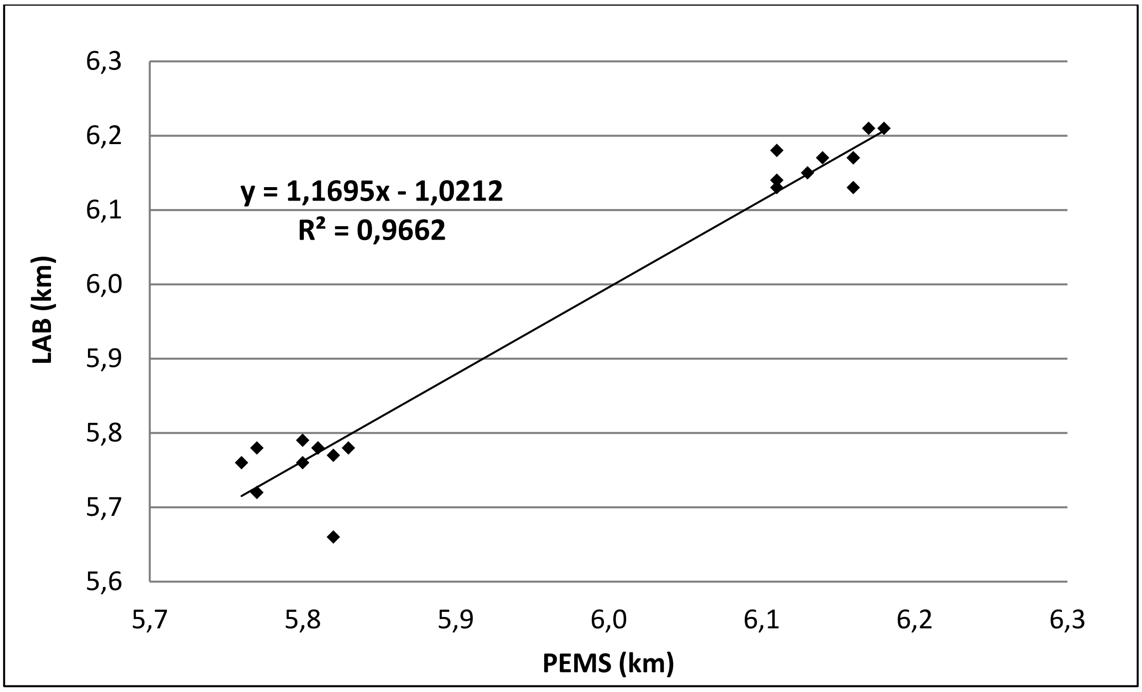


Figure 35 – Comparison of distance traveled (km): laboratory x Low-cost PEMS – E100



The study of Cross et al. about electrochemical sensors indicates a R^2 of 0.94 for an Alphasense CO device (CROSS et al., 2017). As the LCP reaches a coefficient of determination R^2 higher than 0.9 for CO, CO_2 and distance, their accuracy was considered enough for the proposals of this research. The result for THC, R^2 of 0.85 for E22 and 0.73 for E100, was considered acceptable.

At least, the CO_2 concentration in the exit of the LCP was measured. The vehicle was fueled with E22, and the LCP air and sample gas intakes were open, so the concentration found was 0.7%. With the ambient air closed, thus only passing by the LCP raw exhaust gas, the CO_2 raises to 15.3%, resulting in a dilution ratio of 1:22.

5.2 Results from field tests

5.2.1 Ambient, routes, traffic, dynamics

Twenty-six RDE tests were done, performing about 1,500 km traveled. Of these, 8 trips were not considered in the results, because the firsts #1 to #6 were used for finishing the LCP development, and two more were just for verifying the LCP behavior in motorways (#24) and at sea level (#25). The 18 valid runs were executed from June/28th/2021 to

August/30th/2021, the vehicle was fueled with commercial E22 in 7 of them and with commercial E100 in the others.

They were performed in diverse ambient and traffic conditions, sometimes with the engine starting cold, sometimes warm, driving according to a regular behavior, i.e. just following the traffic flow, or with a style for saving fuel. The urban routes were located in Sao Bernardo do Campo and Santo Andre, Sao Paulo State, and the rural trip runs every time in Sao Bernardo, these test conditions are summarized in Tables 15 to 19.

The classification of the traffic volume in the tests was subjective, but because it is important to have some criteria in the observations, it was adopted that a traffic *free* meaning streets with few vehicles, easily reaching the speed limits, and stops only at traffic lights and crossroads, *regular* means the streets with the constant presence of other vehicles, usual flow, running into the speed limits and stops at traffic lights, crossroads and, occasionally, due to excess of vehicles, *intense* means a high volume of vehicles, frequent stops due to traffic congestion, and more time required to reached constant speed after traffic lights and crossroads.

Table 15 – Results from RDE tests: engine temperature, ambient, and traffic conditions – E22

Test #	**Date**	**Time (start)**	**Engine Temp. (°C)**	**Ambient Temp. (°C)**	**Humidity (%)**	**Traffic Volume**
7	28/Jun	14:20	75	23	55	Regular-intense
8	30/Jun	14:40	64	13	50	Intense
9	01/Jul	10:00	44	13	65	Regular
10	02/Jul	11:46	39	12	36	Regular
11	06/Jul	10:40	45	16	69	Free w/some intense parts
12	06/Jul	14:10	50	17	51	Free w/some intense parts
26	30/Ago	09:25	17	17	63	Regular

Table 16 – Results of RDE tests: engine temperature, ambient, and traffic conditions – E100

Test #	**Date**	**Time (start)**	**Engine Temp. (°C)**	**Ambient Temp. (°C)**	**Humidity (%)**	**Traffic Volume**
13	07/Jul	11:00	48	16	70	Regular-intense
14	07/Jul	14:40	50	17	53	Intense
15	08/Jul	10:10	47	15	69	Free
16	08/Jul	13:40	55	19	40	Free w/some intense parts
17	09/Jul	10:25	67	15	73	Free w/some intense parts
18	09/Jul	13:20	66	19	44	Free w/some intense parts
19	21/Jul	09:20	10	12	65	Regular-intense
20	26/Jul	12:30	21	23	38	Free w/some intense parts
21	26/Jul	15:00	67	28	26	Free w/some intense parts
22	27/Jul	12:20	22	25	32	Intense
23	27/Jul	15:00	67	29	27	Intense

About the routes, Tables 17 and 18, four options were used for the urban trips and 1 for rural. The urban routes were named *SBC regular*, *S. Andre*, *SBC high alt gain,* and *SBC low alt gain,* and the rural was the *SBC*. All urban trips finish at the same place, near Via Anchieta motorway, thus it was possible to alternate between different urban trips and to do the same rural route. About the positive cumulative altitude gain, or altitude gain for short, *low alt gain* means that this parameter is close to the inferior limit of the Brazilian RDE normative 17011 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022), 600 m/100km, and *high alt gain* means that is close to the upper limit, 1,200 m/100km.

Two parameters to take into account are the averaged urban speed and urban stop percentage, where low speed and high stop values denote higher traffic volume. In these circumstances, stop-and-go driving tends to raise consumption and affect emissions.

Table 17 – Results from RDE tests and routes data: duration, speed, altitude gain – E22

Test #	Urban route	Rural route	Total trip (km)	Total time (min)	Share Urban x Rural (%)	Avg speed Urban (km/h)	Avg speed Rural (km/h)	Urban stop (%)	Altitude gain Total (m/ 100km)	Altitude gain URBAN (m/ 100km)
7	S.ANDRÉ	SBC	45.6	75.6	62/38	27.4	76.7	23.8	862.1	807.2
8	S.ANDRÉ	SBC	44.9	84.2	64/36	24.0	76.2	24.0	878.3	836.2
9	SBC regular	SBC	45.7	86.9	61/39	23.0	77.3	20.6	868.7	805.9
10	SBC regular	SBC	45.2	83.8	62/38	23.8	77.7	23.8	857.3	773.7
11	SBC low alt gain	SBC	47.9	96.5	63/37	21.9	78.5	28.1	700.3	552.9
12	SBC high alt gain	SBC	45.5	93.0	62/38	21.2	78.3	23.5	1095.3	1175.1
26	SBC regular	SBC	45.6	81.8	60/40	24.4	77.4	24.3	854.9	782.2

Table 18 – Results from RDE tests and routes data: duration, speed, altitude gain – E100

Test #	Urban route	Rural route	Total trip (km)	Total time (min)	Share Urban x Rural (%)	Avg speed Urban (km/h)	Avg speed Rural (km/h)	Urban stop (%)	Altitude gain Total (m/ 100km)	Altitude gain URBAN (m/ 100km)
13	S.ANDRÉ	SBC	46.1	76.0	63/37	27.8	78.8	19.0	856.1	805.8
14	S.ANDRÉ	SBC	46.1	83.4	62/38	24.5	77.9	20.8	868.5	811.4
15	SBC regular	SBC	45.5	84.4	62/38	23.6	79.8	23.5	864.7	822.3
16	SBC regular	SBC	45.5	92.7	62/38	21.4	77.8	23.4	856.4	800.9
17	SBC low alt gain	SBC	48.1	92.0	63/37	23.4	77.8	22.8	671.6	502.2
18	SBC high alt gain	SBC	45.8	82.0	61/39	24.6	79.1	19.4	1090.6	1177.6
19	SBC regular	SBC	45.6	85.7	61/39	23.2	79.4	24.5	884.4	833.2
20	SBC regular	SBC	45.6	80.0	61/39	25.1	78.7	24.5	857.6	800.4
21	SBC regular	SBC	45.4	86.6	61/39	22.8	79.3	25.7	919.0	893.9
22	S.ANDRÉ	SBC	46.4	76.3	62/38	27.3	80.8	19.8	857.8	779.5
23	S.ANDRÉ	SBC	46.5	75.4	62/38	27.7	80.1	19.7	844.1	772.9

The VSP+ results are compared in Table 19 with the RDE regulatory parameter v*a_pos. They are sorted according to the following criteria: for VSP+, *low* is when VSP+ above Max curve is lower than 5%, *medium* is between 5-8%, and *high* is above 8%. The driving behavior is divided into *eco* and *regular, eco* is when it is followed the gear shift indicator, a vehicle device that recommends the ideal moment to change the gear for saving fuel, usually at low engine speeds and, as a consequence, accelerations are reduced, and *regular* driving is when the driver just follow his own practice, changing gears in higher revolutions where more acceleration is needed. The average engine speed in the RDE tests was 1,700 rpm for eco and 2,000 rpm for regular driving. For altitude gain, it is used the same reference as in Tables 17-18.

Table 19 – Results from RDE tests: comparison of RDE regulatory dynamic parameters and VSP+

	RDE dynamic			**VSP+**				**Classifications**		
Test #	**v*a pos Urban (m^2/s^3)**	**v*a pos Rural (m^2/s^3)**		**VSP+ between curves**	**VSP+ above MAX**	**VSP+ below MIN**		**VSP+ severity H/M/L**	**Eco or Regular drive?**	**Altitude gain H/M/L**
					E22					
7	13.2	15.7		75.0%	9.5%	15.5%		H	R	M
8	8.7	12.2		79.5%	3.9%	16.6%		L	E	M
9	8.4	12.8		81.9%	3.3%	14.8%		L	E	M
10	11.2	13.3		78.9%	6.8%	14.3%		M	R	M
11	13.0	15.6		79.9%	9.0%	11.1%		H	R	L
12	10.9	13.9		74.0%	7.8%	18.2%		M	R	H
26	12.1	14.6		77.0%	8.2%	14.9%		H	R	M
					E100					
13	12.0	14.6		76.3%	7.3%	16.4%		M	R	M
14	7.4	11.2		78.4%	2.2%	19.4%		L	E	M
15	12.2	16.2		79.3%	7.6%	13.1%		M	R	M
16	7.5	12.8		84.2%	2.2%	13.6%		L	E	M
17	11.3	14.4		80.0%	6.9%	13.1%		M	R	L
18	10.3	16.9		73.5%	8.2%	18.3%		H	R	H
19	11.2	13.9		77.6%	8.0%	14.4%		M	R	M
20	12.7	13.4		76.2%	8.8%	15.0%		H	R	M
21	11.8	13.8		77.1%	7.0%	15.9%		M	R	M
22	10.9	13.7		77.1%	5.4%	17.5%		M	R	M
23	11.6	15.7		76.1%	5.9%	18.0%		M	R	M

Note: H: high, M: medium, L: low, E: economic drive, R: regular drive

All tests were approved for v*a_pos[95], which barely reflects the driver's behavior or power requirement when compared to results from similar altitude gain. On the other hand, the VSP+ percentage above the VSP+ maximum curve shows to be more sensitive to these two factors, driver style, and altitude gain. For example, the lowest values for VSP+ happened in the tests conducted with an economic driving style. Furthermore, there is a tendency for lower results for v*a_pos in high altitude gains, even when needed more power to surpass the topography.

5.2.2 RDE emissions

The basis for understanding RDE emissions is the laboratory tests. CETESB, while representative of the Brazilian Ministry of Environment for homologation of auto motor vehicles, has a database that was started in the 1980s with reports from type-approval processes. Two tests were identified for E22 and two more for E100 for the model of this research in the CETESB files. In the same way, the vehicle used in the LCP development was evaluated in CETESB laboratory according to the regulatory procedure, and all results are summarized in Table 20 for E22 and Table 21 for E100. The values are close to each other, despite the vehicle used in the research has about 90,000 km mileage. The results from the complete RDE tests, Tables 22 and 23, are considering the complete route, so urban and rural trips, as defined in the Brazilian normative ABNT 17011 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2022).

Table 20 – Emissions in the laboratory for VW Gol City 1.0 flexfuel – E22

Results from	THC (mg/km)	CO (mg/km)	CO_2 (g/km)
Homologation	35.0	357.0	156.9
	24.0	72.0	158.8
CETESB laboratory	24.0	111.0	163.1
	25.0	108.0	162.1
Average	**27.0**	**162.0**	**160.2**
Average in g/l	**0.37**	**2.21**	**2.17**

Table 21 – Emissions in the laboratory for VW Gol City 1.0 flexfuel – E100

Results from	THC (mg/km)	CO (mg/km)	CO_2 (g/km)
Homologation	75.0	293.0	155.0
	98.0	706.0	148.3
CETESB laboratory	132.0	592.0	157.0
	128.0	572.0	157.7
Average	**108.3**	**540.8**	**154.5**
Average in g/l	**0.99**	**4.99**	**1.43**

Table 22 – Total of emissions in RDE and difference from laboratory results – E22

Test #	CO_2 (g/km)	Diff Lab x RDE	CO (mg/km)	Diff Lab x RDE	THC (mg/km)	Diff Lab x RDE
7	161.1	1%	300.6	86%	58.3	116%
8	150.5	-6%	159.8	-1%	48.3	79%
9	156.7	-2%	102.3	-37%	55.8	107%
10	165.8	3%	219.0	35%	30.3	12%
11	168.6	5%	212.4	31%	72.8	170%
12	173.0	8%	153.6	-5%	48.6	80%
26	166.1	4%	229.9	42%	29.1	8%

Table 23 – Total of emissions in RDE and difference from laboratory results – E100

Test #	CO_2 (g/km)	Diff Lab x RDE	CO (mg/km)	Diff Lab x RDE	THC (mg/km)	Diff Lab x RDE
13	141.2	-9%	784.1	45%	50.0	-54%
14	141.6	-8%	527.2	-3%	63.2	-42%
15	150.9	-2%	743.8	37%	39.3	-64%
16	151.1	-2%	618.9	14%	59.1	-45%
17	149.5	-3%	320.7	-41%	34.1	-68%
18	151.3	-2%	472.4	-13%	35.8	-67%
19	151.9	-2%	580.0	7%	40.0	-63%
20	147.5	-5%	622.4	15%	103.7	-4%
21	154.2	0%	447.5	-17%	40.2	-63%
22	142.2	-8%	591.0	9%	54.1	-50%
23	144.6	-6%	546.3	1%	40.7	-62%

The CO_2 emissions are close to those from the laboratory, but some divergences are found in THC and CO, which must be considered:

- THC emissions for E22 are significantly higher than in the laboratory, but the overall amount is low.
- THC emissions for E100 are significantly lower than in the laboratory, although the vehicle has been tested many times at low ambient temperature, when the fuel mixture is enriched to avoid failures in the combustion.
- CO seems to be more sensitive to driving behavior and ambient conditions. CO and THC emissions follow almost the same patterns, showing peaks at the same time, but in this vehicle, the second-by-second correlation for them with an R^2 average of only 0.36.

Therefore, it is not possible to stand a rule to THC emissions, just based on the total result of the RDE tests. In sequence, the values for urban and rural routes are shown separately, in

Tables 24 and 25, and Figures 36-37 have an example of typical graphic results from a RDE test, in this case, the test number #8.

Table 24 – RDE: Comparison between urban and rural emissions – E22

	CO_2 (g/km)		CO (mg/km)		HC (mg/km)	
Test #	**URBAN**	**RURAL**	**URBAN**	**RURAL**	**URBAN**	**RURAL**
7	188.2	116.4	222.3	430.2	21.6	119.1
8	173.8	109.9	157.2	164.5	50.8	43.8
9	184.7	112.2	104.1	99.4	65.5	40.4
10	199.2	112.0	226.1	207.5	26.5	36.4
11	201.2	112.9	239.9	165.3	86.9	48.8
12	210.4	112.3	171.7	124.2	48.3	49.1
26	199.0	115.9	242.2	211.1	39.4	13.3
Difference from lab:	**+21%**	**-29%**	**+20%**	**+24%**	**+79%**	**+86%**

Table 25 – RDE: Comparison between urban and rural emissions – E100

	CO_2 (g/km)		CO (mg/km)		HC (mg/km)	
Test #	**URBAN**	**RURAL**	**URBAN**	**RURAL**	**URBAN**	**RURAL**
13	163.0	103.8	795.4	764.9	67.4	20.0
14	164.5	104.2	614.7	384.5	93.5	13.6
15	179.6	104.9	680.8	844.9	53.4	16.7
16	180.8	102.3	613.9	627.2	81.5	22.1
17	175.5	104.2	228.5	480.8	42.2	20.0
18	179.1	106.8	381.4	617.6	35.3	36.5
19	182.7	103.3	840.1	169.3	64.4	1.5
20	177.3	100.8	756.6	412.0	133.5	57.1
21	187.4	101.6	365.0	578.2	45.7	31.5
22	167.2	101.8	671.8	459.7	74.3	21.2
23	170.2	103.4	578.0	495.3	49.8	26.1
Difference from lab:	**+13%**	**-33%**	**+10%**	**-2%**	**-38%**	**-78%**

Figure 36 – Typical results from the RDE test #8 – CO and THC

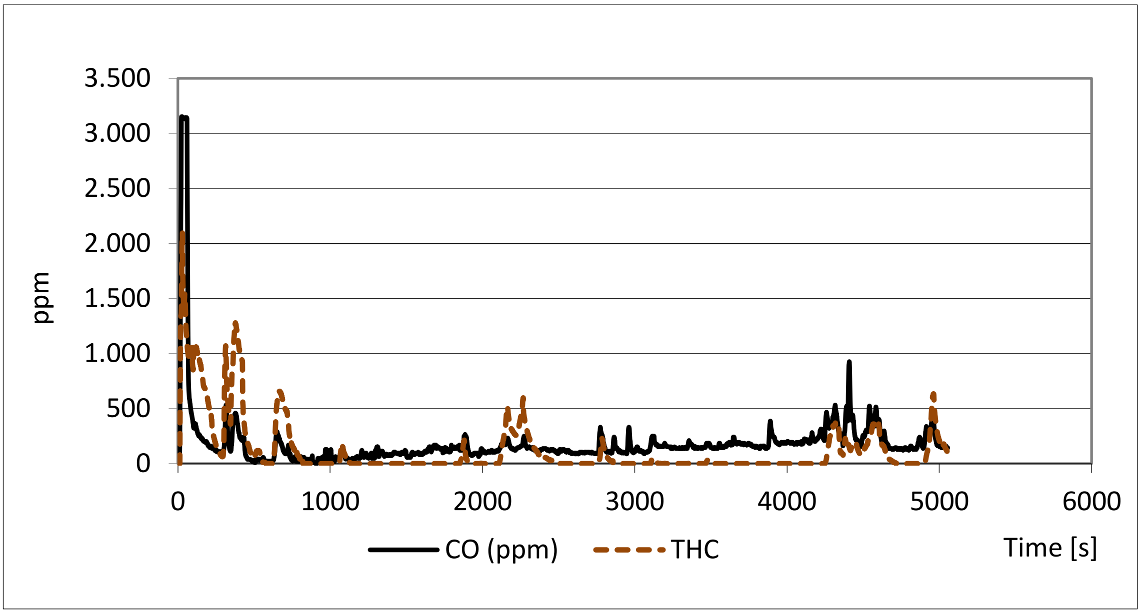
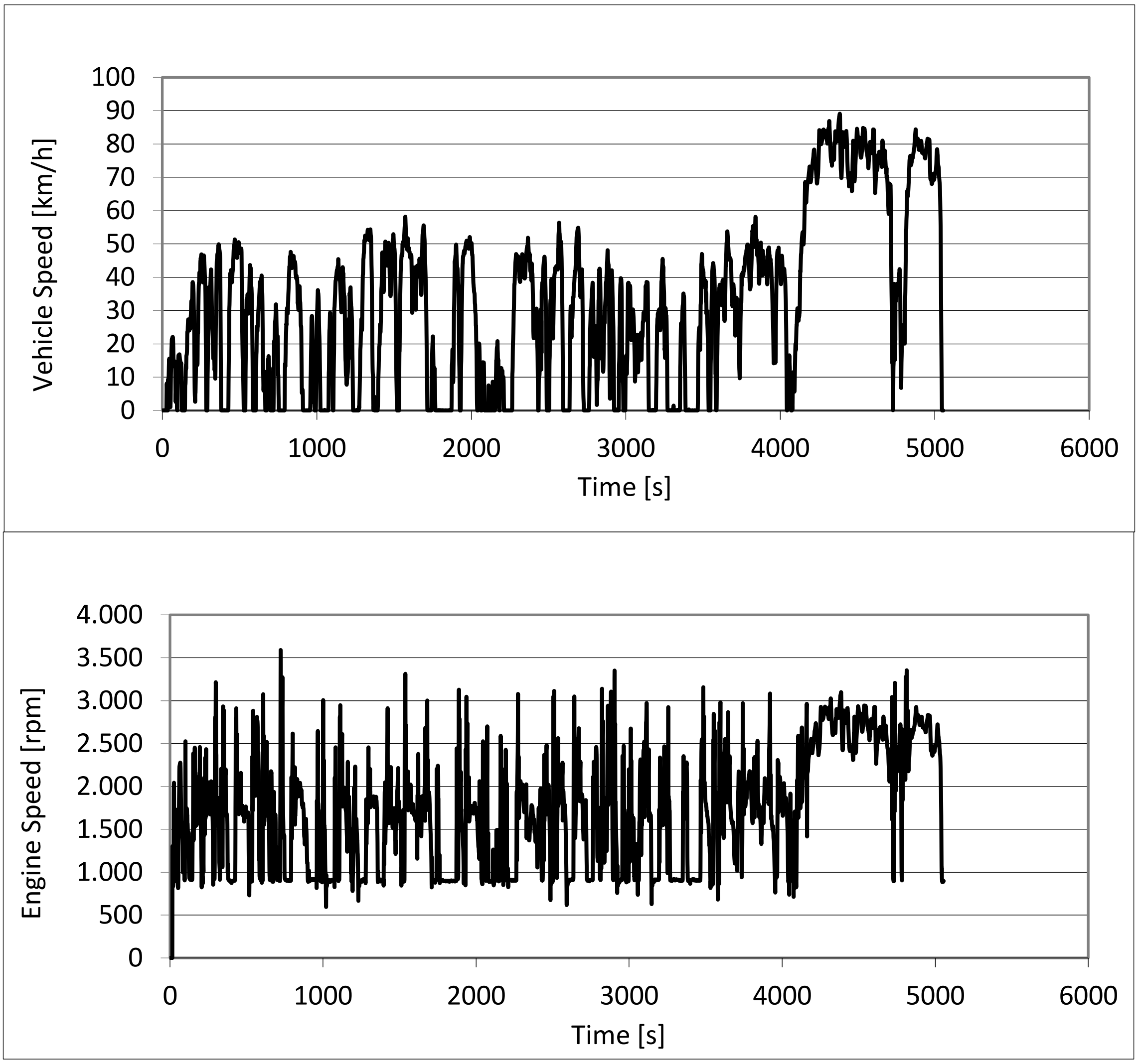


Figure 37 – Typical results from the RDE test #8 – Vehicle and Engine speed



In all tests, CO_2 emissions in urban routes are 40% higher than in rural, however, the CO and THC do not follow the same behavior, whatever running in the city or on the road. It is relevant to observe that THC urban emission for E100 is all the time higher than in the rural part. This tendency could be associated with the enrichment of the fuel mixture in accelerations, more frequent in the city, and to better combustion or better catalyst efficiency for ethanol in constant engine speeds, typical conditions found in the motorways. Another point that must be considered is that there are no specific reasons for the high THC emission in test #7 in the rural trip, anything abnormal was recorded, neither in traffic nor in the driver behavior, only that the vehicle had an emission peak when leave the urban street to enter in the road, due to the high acceleration required at this moment. A possible explanation is that this event could be caused by some temporary engine malfunction.

Mainly, the tests were done with the engine starting hot (above 70°C) or, at least, warm (below 70°C, above temperature ambient) but in some of them it was cold (at ambient temperature), thus the increase of CO and THC emissions in the city cannot be clear. As the CO_2 is not so much influenced by engine's temperature, the difference between laboratory tests and urban RDE signalizes a point that must be considered: due to the stop-and-go city traffic, the vehicle will every time produce more pollutants and CO_2 in the urban trips than what was measured in the laboratory and this difference can impact as well as emissions inventories and mathematic models for vehicular pollution. These differences are deeper studied in Chapter 6, when the results are sorted and the influence of diverse parameters are individually analyzed, e.g., ambient temperature and cold/hot engine.

6. RDE Emission Factors

While the analysis of the RDE tests in Chapter 5 takes care of the overall results from the complete tests or, at least, of discrete parts, such as the urban/rural classification, the study of the Emission Factors (EF) is done considering specific parameters, for example, ambient temperature or vehicle acceleration.

All data from in-field tests were gathered in two files, one for E22 and another for E100, with the CO_2, CO, and THC emissions and vehicle dynamic data being sorted according to these parameters under analysis, giving a better understanding of their influence on the EF. The results are expressed in emissions of CO_2, CO, and THC in g/km and g/l, and their relative EF, that is the ratio between the specific emission in comparison to the historical values from Chapter 5, Tables 20 and 21, thus every EF in this Chapter is dimensionless.

The seven RDE tests done with E22 correspond to 35,933 seconds and the eleven tests with E100 another 54,600 s. Each second means one measurement from LCP or calculated data from EMROAD of vehicle speed, instantaneous pollutants emission in g/s, distance traveled, and specific pollutant emissions in g/km and g/l, among other parameters.

Only four tests started with the engine cold, so the EF analysis focused on when the engine is hot and, separately, it is discussed the cold/hot emission. Hence, remains for the vehicle engine running above 70°C 34,435 s for E22 and 52,214 s for E100, which is more than 95% of the original data. Thus, the EF can produce different results than those from complete tests, exactly because the cold start has been analyzed separately.

6.1 Emission Factors for ambient temperature

Studies about the influence of the ambient temperature in vehicular emissions (DARDIOTIS; MARTINI; MANFREDI, 2012; MARTIN; WOODS; THOMAS, 2017), as well simulations in COPERT by Laskowski (LASKOWSKI et al., 2021) indicate a tendency for raising CO_2, CO and HC emissions at low temperatures. However, Abdullah et al. and Giechaskiel et al. report some CO reduction and HC increase in similar circumstances (ABDULLAH et al., 2015; GIECHASKIEL et al., 2021). According to Abdullah et al. (ABDULLAH et al., 2015), this CO behavior is related to the higher air density when at colder temperatures, allowing the engine to breath more oxygen and improving the combustion.

The results sorted by ambient temperature with results in g/km for CO_2 and mg/km for THC and CO, and their respective EF are summarized in Tables 26 and 27 and in Figures 38 to 41. The missing lines in tables and empty columns in figures, e.g., 16 and 17°C for E22, are due to the fact that there is no test performed at these temperatures, thus any data is available for these ranges.

Table 26 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km according to ambient temperature – E22

Ambient Temp.	**THC**		**CO**		**CO_2**	
°C	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
14	25.7	0.95	74.1	0.46	147.9	0.92
15	21.2	0.78	28.0	0.17	163.1	1.02
18	9.0	0.33	99.1	0.61	159.8	1.00
20	46.6	1.73	100.6	0.62	173.4	1.08
21	36.1	1.34	117.1	0.72	159.0	0.99
23	38.9	1.44	282.9	1.75	158.1	0.99
Lab reference	**27.0**	**-**	**162.0**	**-**	**160.2**	**-**

Table 27 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km according to ambient temperature – E100

Ambient Temp.	**THC**		**CO**		**CO_2**	
°C	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
13	14.5	0.13	108.2	0.20	145.5	0.94
16	38.0	0.35	416.4	0.77	153.5	0.99
17	39.7	0.37	327.9	0.61	149.3	0.97
20	70.4	0.65	304.4	0.56	151.0	0.98
22	31.8	0.29	355.4	0.66	162.9	1.05
23	75.0	0.69	372.3	0.69	153.1	0.99
25	38.7	0.36	300.4	0.56	140.9	0.91
27	35.8	0.33	381.1	0.70	156.1	1.01
29	43.8	0.41	581.8	1.08	159.4	1.03
Lab reference	**108.3**	**-**	**540.8**	**-**	**154.5**	**-**

Figure 38 – THC, CO, and CO_2 emissions in mg/km and g/km according to ambient temperature – E22

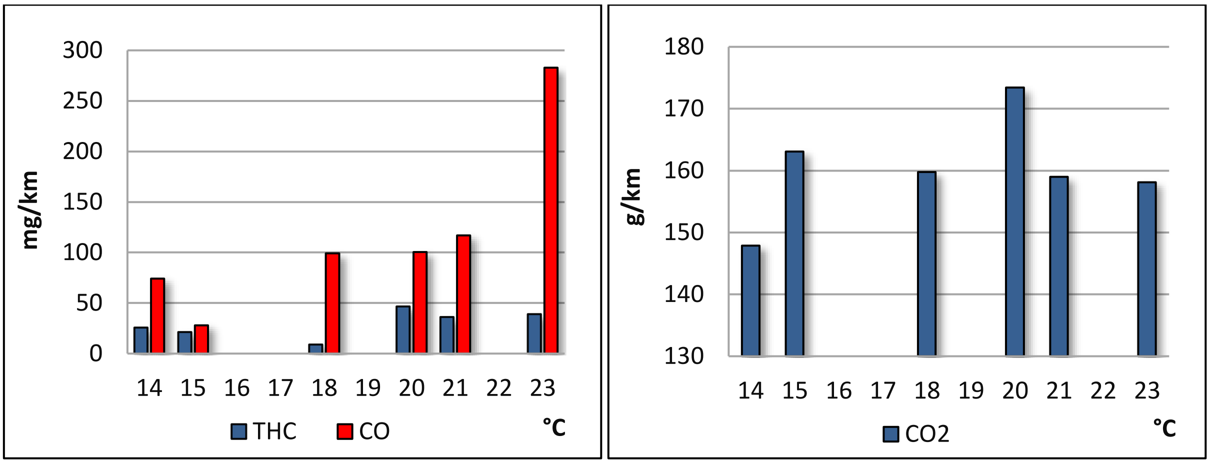


Figure 39 – EF for THC, CO, and CO_2 in g/km according to ambient temperature – E22

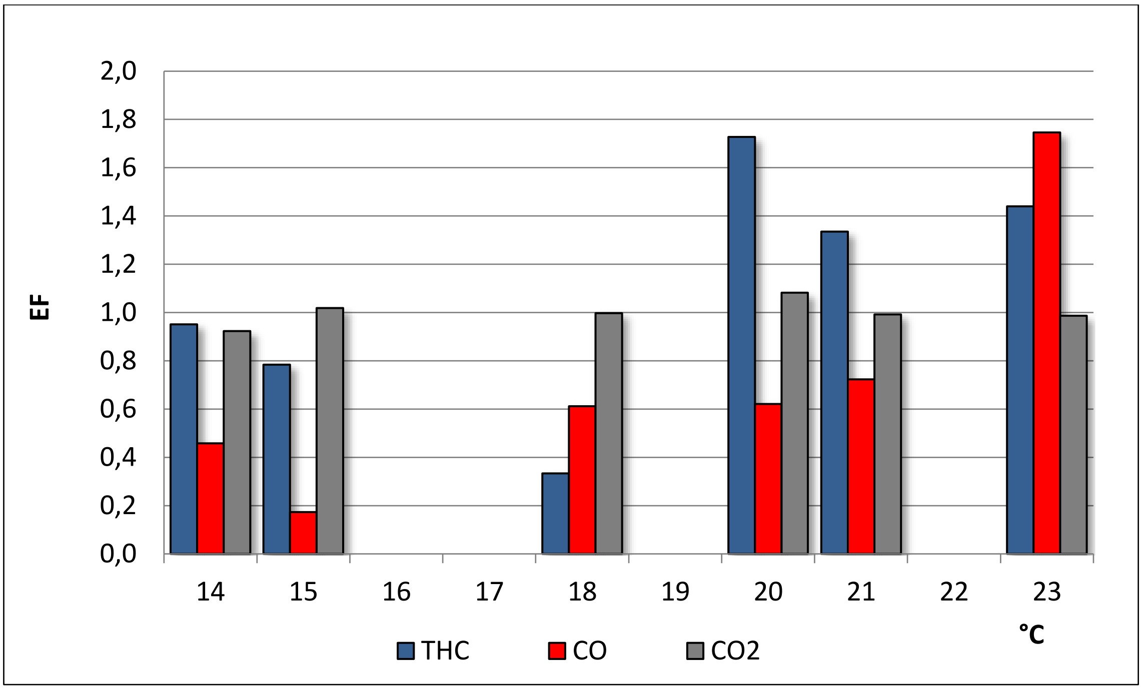


Figure 40 – THC, CO, and CO_2 emissions in mg/km and g/km according to ambient temperature – E100

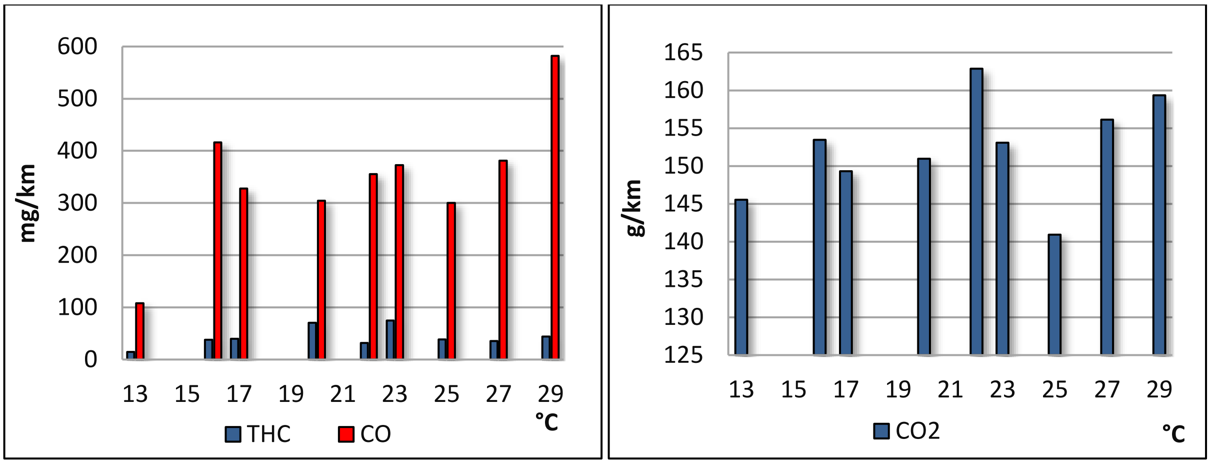
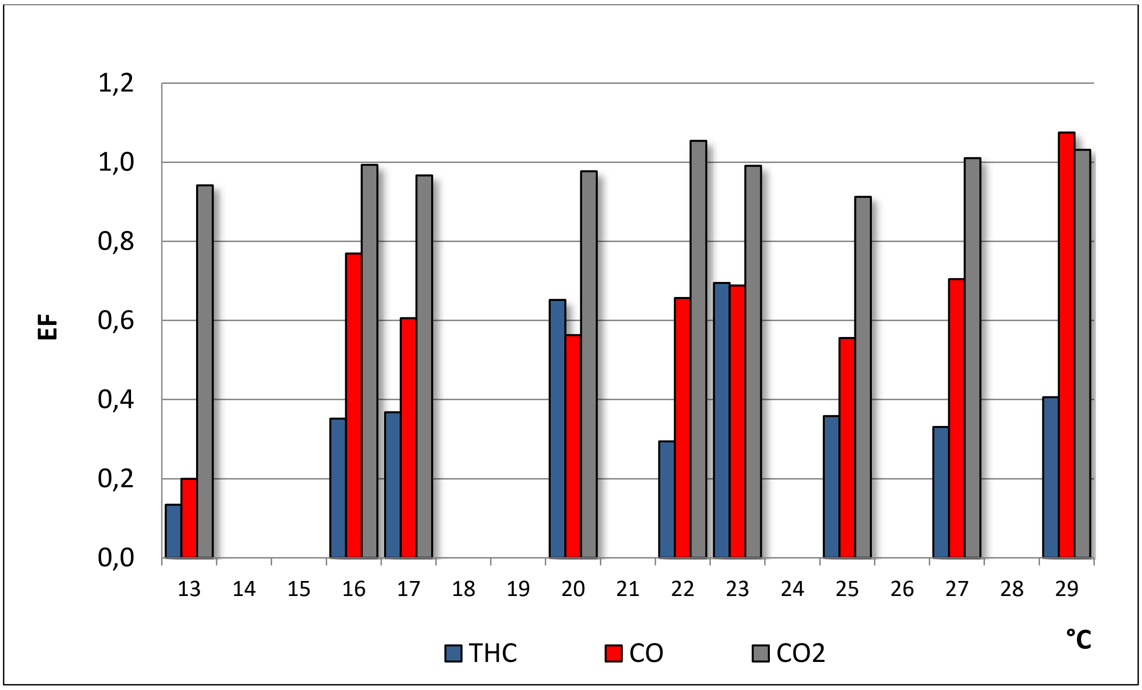


Figure 41 – EF for THC, CO, and CO_2 in g/km according to ambient temperature – E100



The results of EF in g/km for ambient temperature presented some dispersion, indicating that other variables beyond the environment are influencing emissions. For E22, the EF in g/km presents some tendency for reduction in CO_2 at lower temperatures. THC and CO emissions have an irregular behavior, but it is still possible to identify some rising at low temperatures, as expected, and CO showed also an increase at high temperatures.

For E100 in g/km, THC has abnormal values at temperatures below 18°C, when a rise was expected due to the fuel mixture enrichment for avoiding misfire. The inherent conception of the LCP can explain this result because the low-cost sensors must be preserved from water condensation, so the sample hose is designed to cool the exhaust gas and retain the humidity in the condensate separator, far from the sensors. As ethanol and some derivates are water-soluble, these compounds may be retained in the condensate at ambient temperatures below 20°C. It happens as like it is measured unburned ethanol in the laboratory test, where the sample hose must be kept warm to not form condensation, to avoid trapping HC into the line and introducing a bias in the results. For example, US regulation 40 CFR86.109-94 recommends maintaining the sample line above the exhaust gas dew point when measuring methanol, to avoid this problem (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2016b).

As a consequence, this behavior should be understood as a limitation of the low-cost PEMS for E100, thus the analysis of EF regarding vehicle speed, acceleration, and VSP shall avoid using THC data for E100 when below 18°C, remaining valid 64% of the general THC data, or 33,232 s. Despite this limitation, for E100, THC emissions in g/km tend to reduce and CO increases when the temperature rises, as well as CO_2 has an increase at hot temperatures, like as to E22.

The results in g/l for CO and THC are summarized in Tables 28 and 29 and Figures 42 to 45. CO_2 emission in g/l is not analyzed here because its values are every time constant due to the gasoline/ethanol stoichiometric burn.

Table 28 – EF and emissions of THC and CO in g/l according to ambient temperature - E22

Ambient Temp.	**THC**		**CO**	
°C	**g/l**	**EF**	**g/l**	**EF**
14	0.90	2.43	1.70	0.77
15	0.95	2.56	1.48	0.67
18	0.73	1.96	4.29	1.94
20	0.68	1.83	2.81	1.27
21	1.09	2.94	4.20	1.90
23	0.32	0.86	3.95	1.79
Lab reference	**0.37**	**-**	**2.21**	**-**

Table 29 – EF and emissions of THC and CO in g/l according to ambient temperature – E100

Ambient Temp.	THC		CO	
°C	**g/l**	**EF**	**g/l**	**EF**
13	0.58	0.58	7.43	1.49
16	0.63	0.63	8.98	1.80
17	0.81	0.81	7.87	1.57
20	1.18	1.18	9.81	1.96
22	0.34	0.34	5.72	1.14
23	1.24	1.24	10.12	2.03
25	1.09	1.10	10.20	2.04
27	0.42	0.42	5.66	1.13
29	0.61	0.61	9.16	1.83
Lab reference	**0.99**	**-**	**4.99**	**-**

Figure 42 – THC and CO emissions in g/l according to ambient temperature – E22

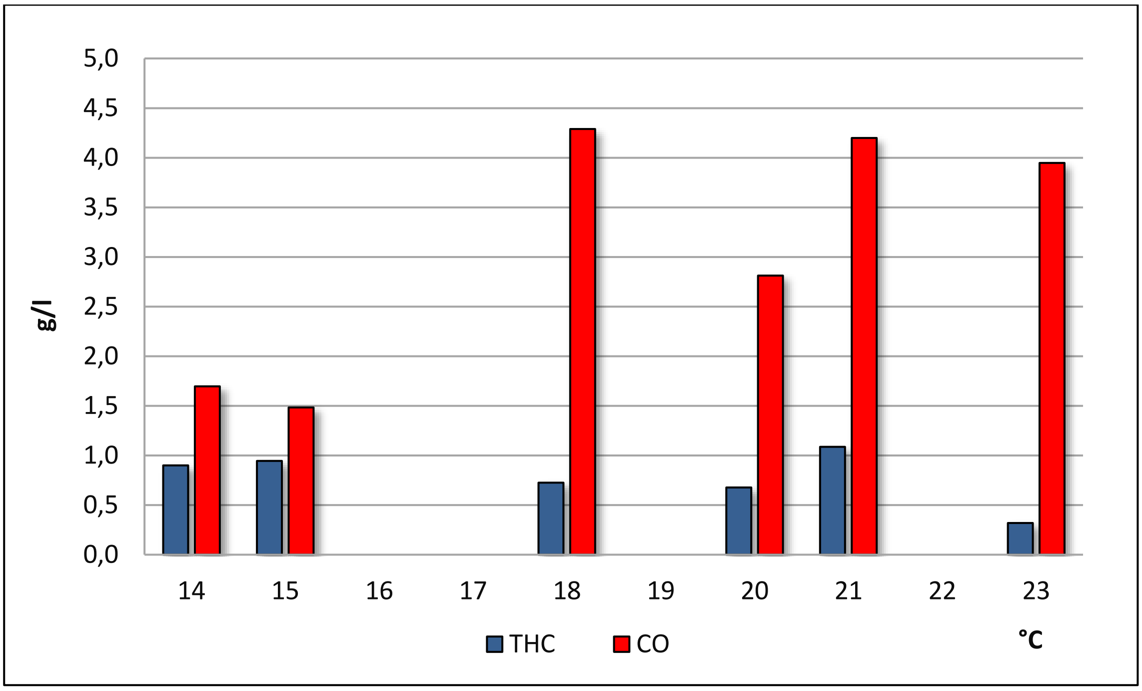


Figure 43 – EF for THC and CO in g/l according to ambient temperature – E22

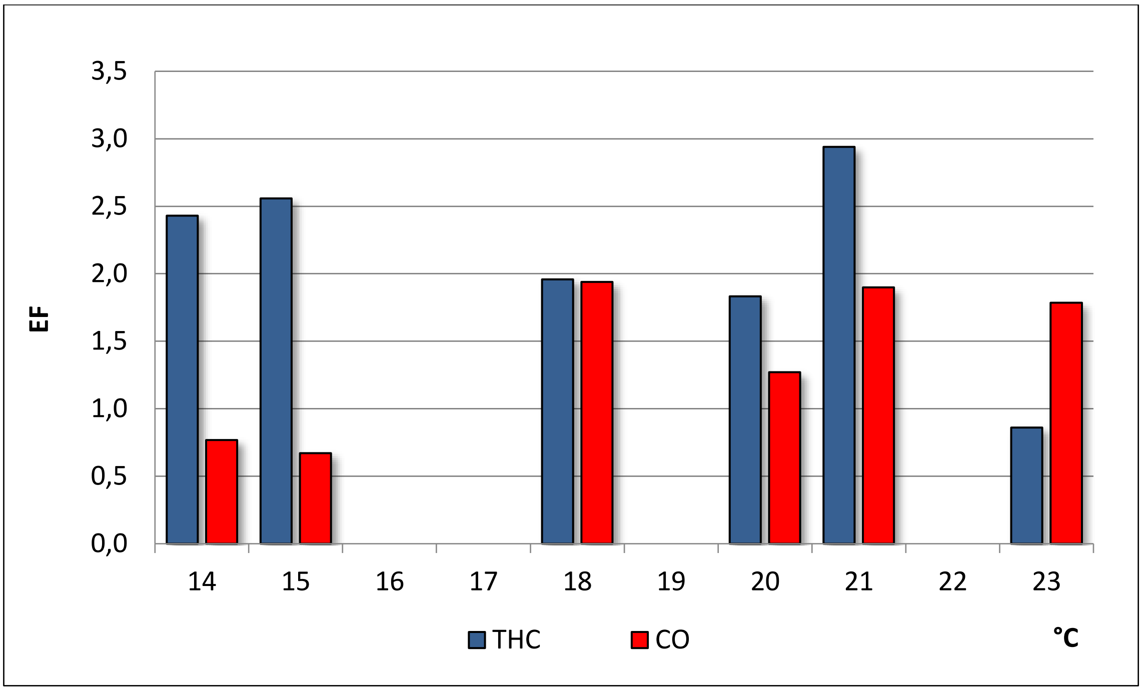


Figure 44 – THC and CO emissions in g/l according to ambient temperature – E100

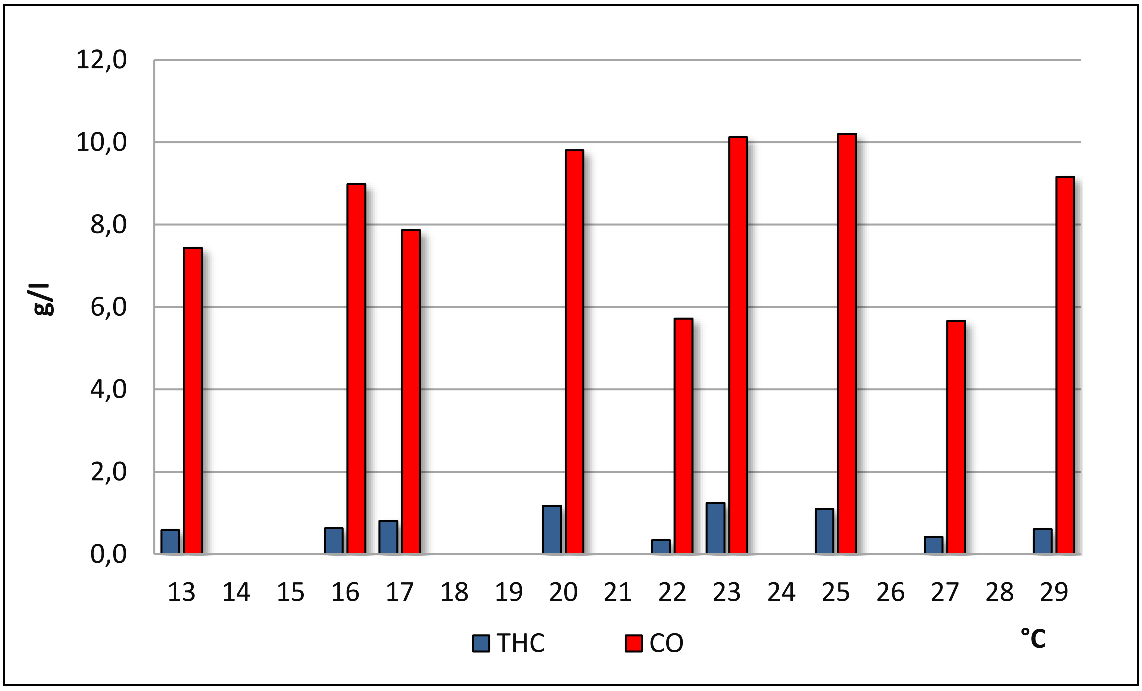
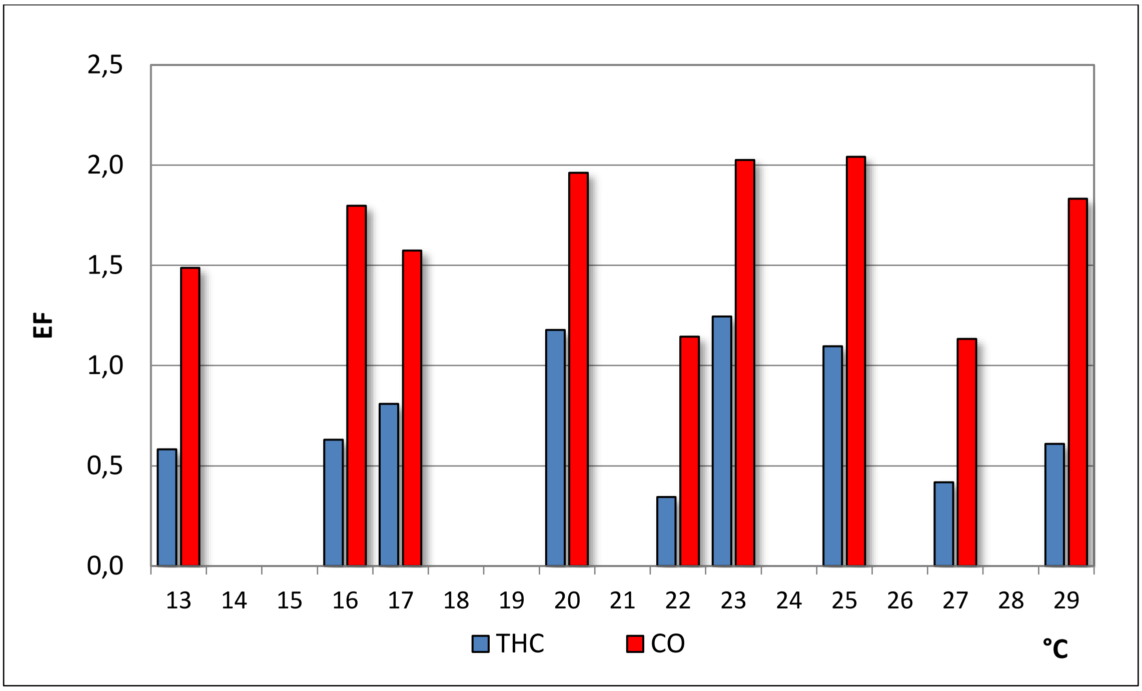


Figure 45 – EF for THC and CO in g/l according to ambient temperature – E100



For E22, THC in g/l increases, and CO decreases at lower temperatures, as expected (ABDULLAH et al., 2015). The emissions behavior for E100 repeats the issue at lower temperatures, with THC reducing below 18°C, but CO seems not to have been significantly affected, presenting a profile similar to that in E22. Despite the EF for THC and CO in g/l having a more coherent behavior than in g/km, they still have a dispersion in the results that reinforces the possibility of other variables beyond the environment conditions influencing emissions.

6.2 Emission Factors for vehicle speed

As some models for vehicle emissions have vehicle speed as a criterion in their calculations, for example, the European COPERT and the Brazilian VEIN (IBARRA-ESPINOSA, 2017; NTZIACHRISTOS et al., 2009), it is relevant to analyze its influence in the RDE results. For this and the next parameters, all EF for THC with E100 are calculated for ambient temperature above 18°C, due to the LCP limitation. The EF in g/km for speed intervals, for E22 and E100, are shown in Tables 30-31 and Figures 46 to 49.

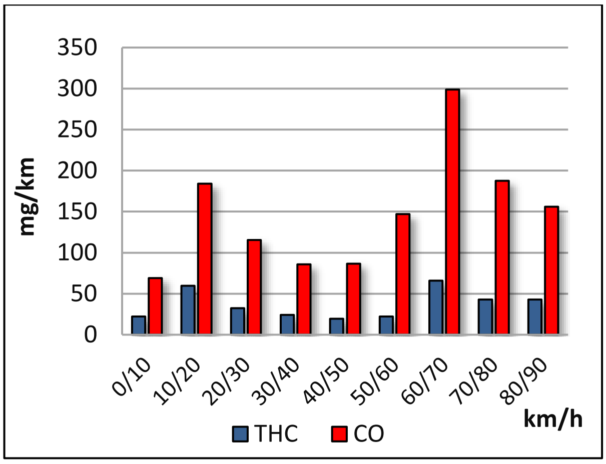
Table 30 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km for vehicle speed – E22

Speed	**THC**		**CO**		**CO_2**	
km/h	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
0 / 10	22.2	0.82	69.0	0.43	142.8	0.89
10 / 20	59.5	2.20	183.9	1.14	319.1	1.99
20 / 30	32.5	1.20	115.3	0.71	206.2	1.29
30 / 40	24.0	0.89	85.7	0.53	151.1	0.94
40 / 50	19.4	0.72	86.4	0.53	125.4	0.78
50 / 60	22.4	0.83	147.0	0.91	109.8	0.69
60 / 70	66.0	2.44	298.6	1.84	125.0	0.78
70 / 80	43.1	1.60	187.7	1.16	109.9	0.69
80 / 90	42.8	1.59	156.1	0.96	113.6	0.71
Lab reference	**27.0**	**-**	**162.0**	**-**	**160.2**	**-**

Table 31 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km for vehicle speed – E100

Speed	**THC**		**CO**		**CO_2**	
km/h	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
0 / 10	47.1	0.44	239.5	0.44	151.8	0.98
10 / 20	93.6	0.87	492.5	0.91	303.6	1.96
20 / 30	65.8	0.61	335.2	0.62	192.0	1.24
30 / 40	65.2	0.60	325.2	0.60	144.3	0.93
40 / 50	50.1	0.46	297.0	0.55	112.2	0.73
50 / 60	33.1	0.31	297.6	0.55	95.3	0.62
60 / 70	43.9	0.41	846.9	1.57	114.1	0.74
70 / 80	29.4	0.27	508.5	0.94	100.9	0.65
80 / 90	27.2	0.25	490.3	0.91	104.1	0.67
Lab reference	**108.3**	**-**	**540.9**	**-**	**154.5**	**-**

Figure 46 – THC, CO, and CO_2 emissions in mg/km and g/km for vehicle speed – E22



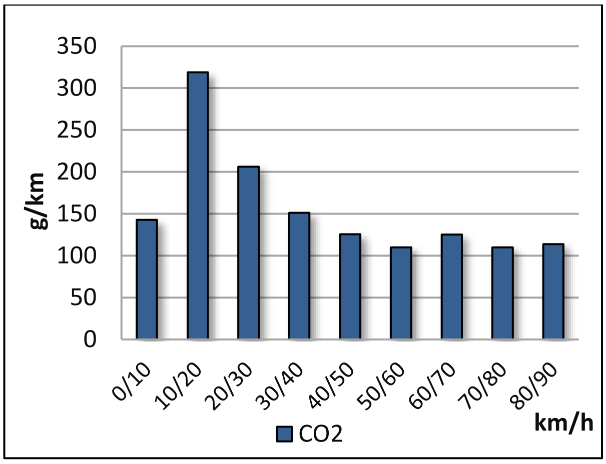


Figure 47 – EF for THC, CO, and CO_2 in g/km for vehicle speed – E22

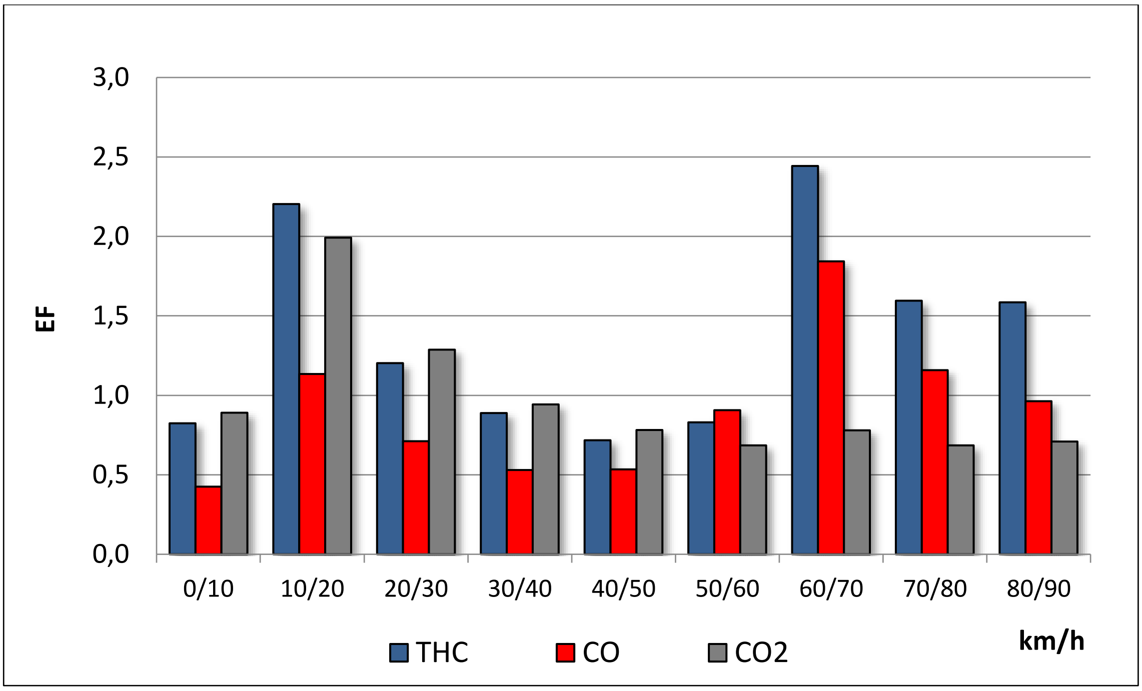
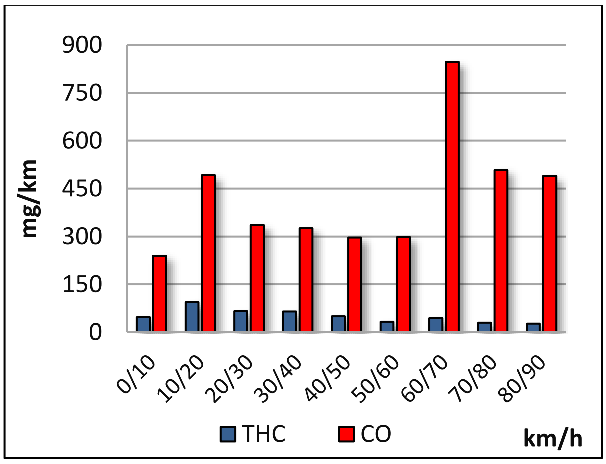


Figure 48 – THC, CO, and CO_2 emissions in mg/km and g/km for vehicle speed – E100



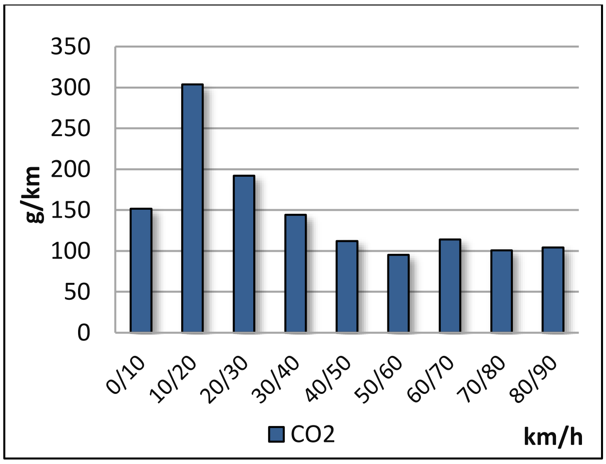
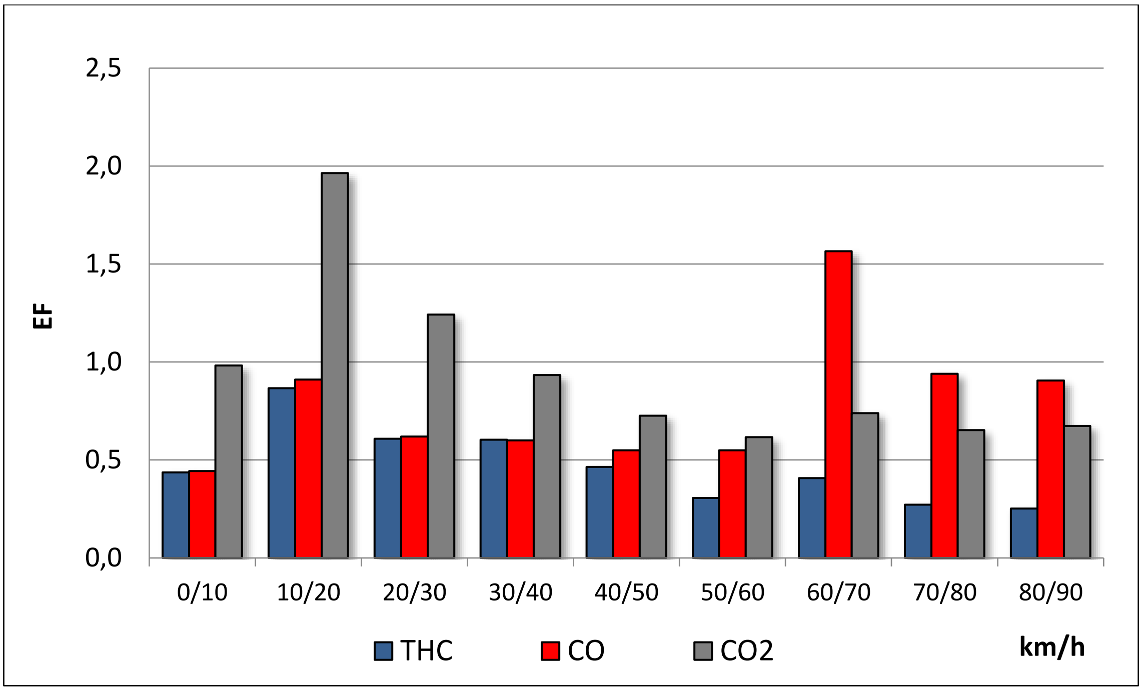


Figure 49 – EF for THC, CO, and CO_2 in g/km for vehicle speed – E100



There is a bias at the bin 60-70 km/h, for the EF in g/km for both fuels, because this speed range is the transition from urban to rural in the RDE test, so usually the driver tends to accelerate harder for not remaining too much time in this interval and/or oscillating between urban/rural speeds. This bias resulted in an abnormal increase in this range of fuel consumption and, consequently, in the THC, CO, and CO_2 emissions, therefore the EF for speed must not consider this bin for better representativeness. This issue does not happen in the EF in g/l, because the pollutants emissions are proportional to the fuel consumption.

Apart from the issue at the 60-70 km/h bin, the EF for vehicle speed in g/km resulted, as expected, in higher values in the urban bins, reflecting the stop-and-go when driving in the city, and getting lower in the rural part due to the more constant speeds, with a discrete increase for the upper speeds, that is in line with the rise in the aerodynamic resistance that occurs above 60 km/h. In sequence, the EF in g/l are reported in Tables 32-33 and Figures 50 to 53.

Table 32 – EF and emissions of THC and CO in g/l for vehicle speed – E22

Speed	THC		CO	
km/h	g/l	EF	g/l	EF
0 / 10	0.88	2.37	3.31	1.50
10 / 20	0.94	2.55	3.68	1.67
20 / 30	0.94	2.53	3.59	1.62
30 / 40	0.97	2.61	3.59	1.62
40 / 50	0.84	2.27	3.27	1.48
50 / 60	0.65	1.75	2.85	1.29
60 / 70	0.51	1.38	2.20	1.00
70 / 80	0.50	1.36	2.31	1.05
80 / 90	0.51	1.38	2.20	0.99
Urban	0.90	2.41	3.40	1.54
Rural	0.50	1.37	2.30	1.02
Lab reference	**0.37**	**-**	**2.21**	**-**

Table 33 – EF and emissions of THC and CO in g/l for vehicle speed – E100

Speed	THC		CO	
km/h	g/l	EF	g/l	EF
0 / 10	0.93	0.93	9.03	1.81
10 / 20	0.86	0.86	9.31	1.86
20 / 30	0.86	0.87	8.61	1.72
30 / 40	1.01	1.01	9.64	1.93
40 / 50	0.96	0.96	8.85	1.77
50 / 60	0.86	0.86	8.22	1.64
60 / 70	0.62	0.62	5.28	1.06
70 / 80	0.61	0.61	5.51	1.10
80 / 90	0.59	0.59	5.46	1.09
Urban	0.93	0.93	9.01	1.80
Rural	0.60	0.60	5.46	1.09
Lab reference	**0.99**	**-**	**4.99**	**-**

Figure 50 – THC and CO emissions in g/l for vehicle speed – E22

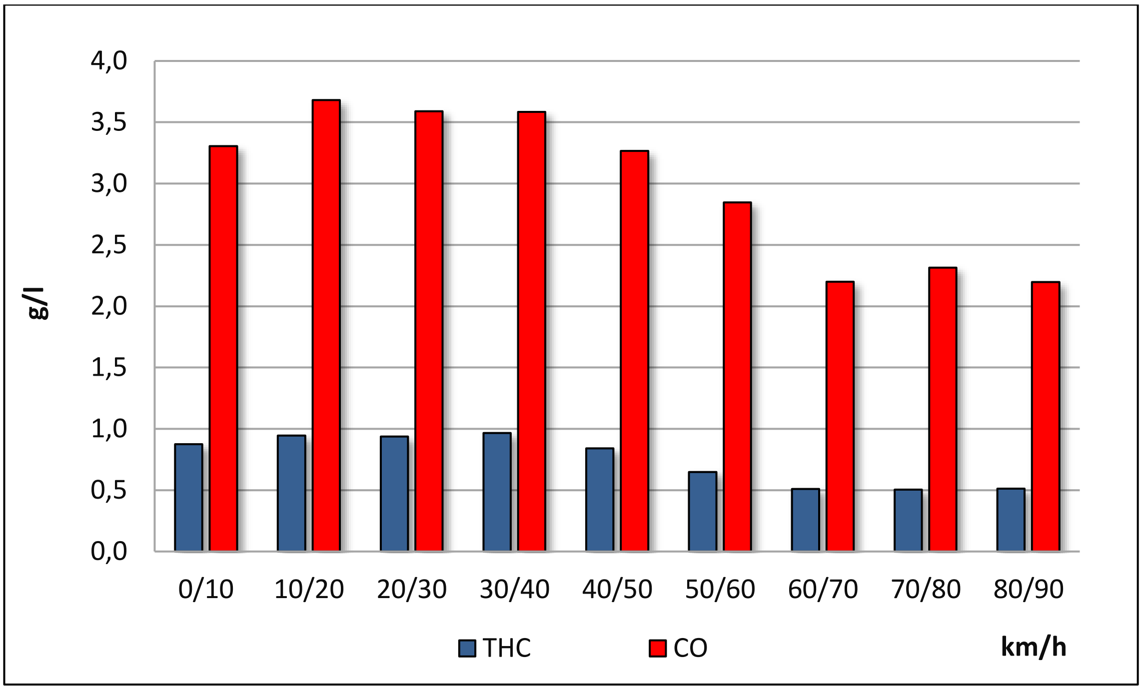


Figure 51 – EF for THC and CO in g/l for vehicle speed – E22

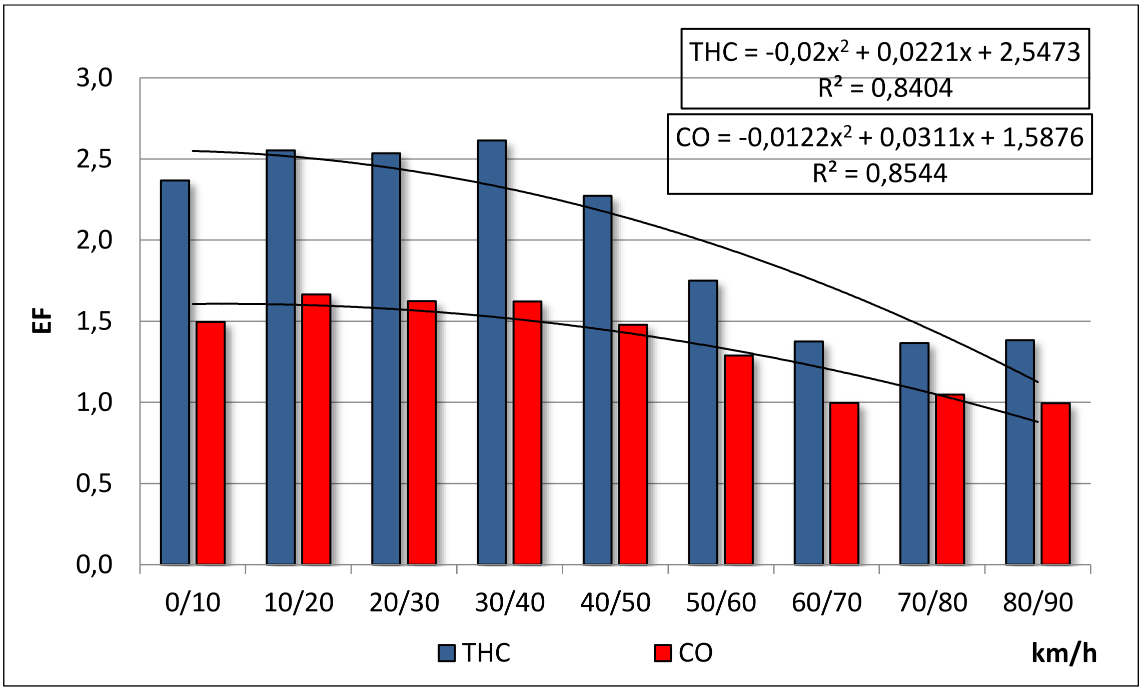


Figure 52 – THC and CO emissions in g/l for vehicle speed – E100

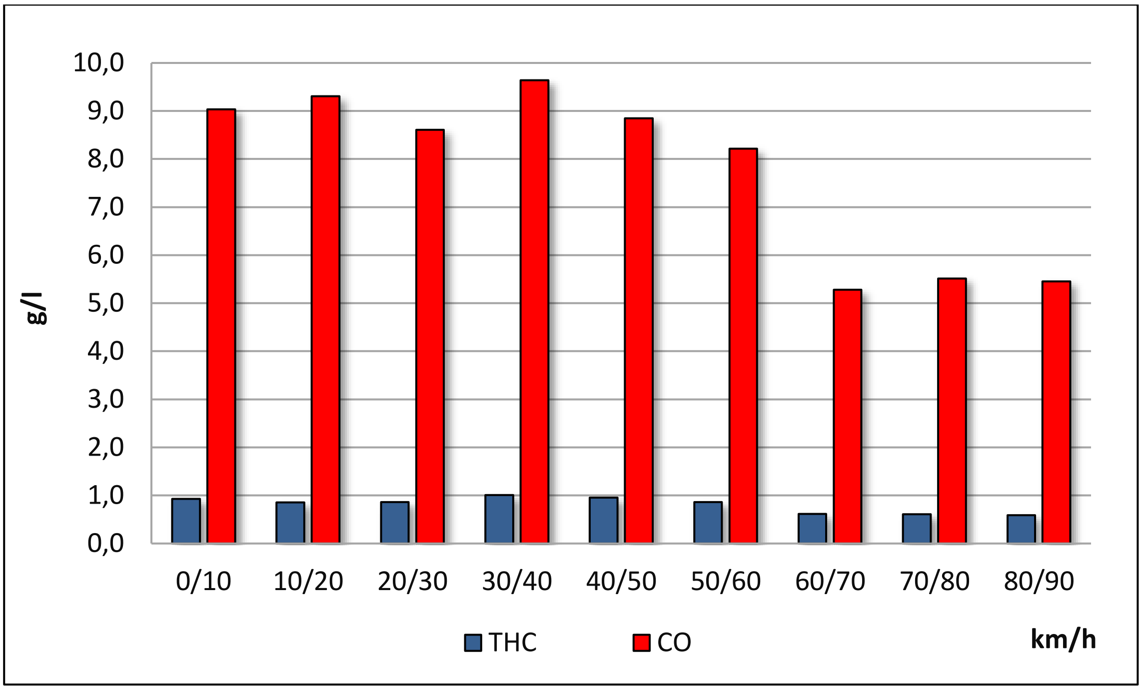
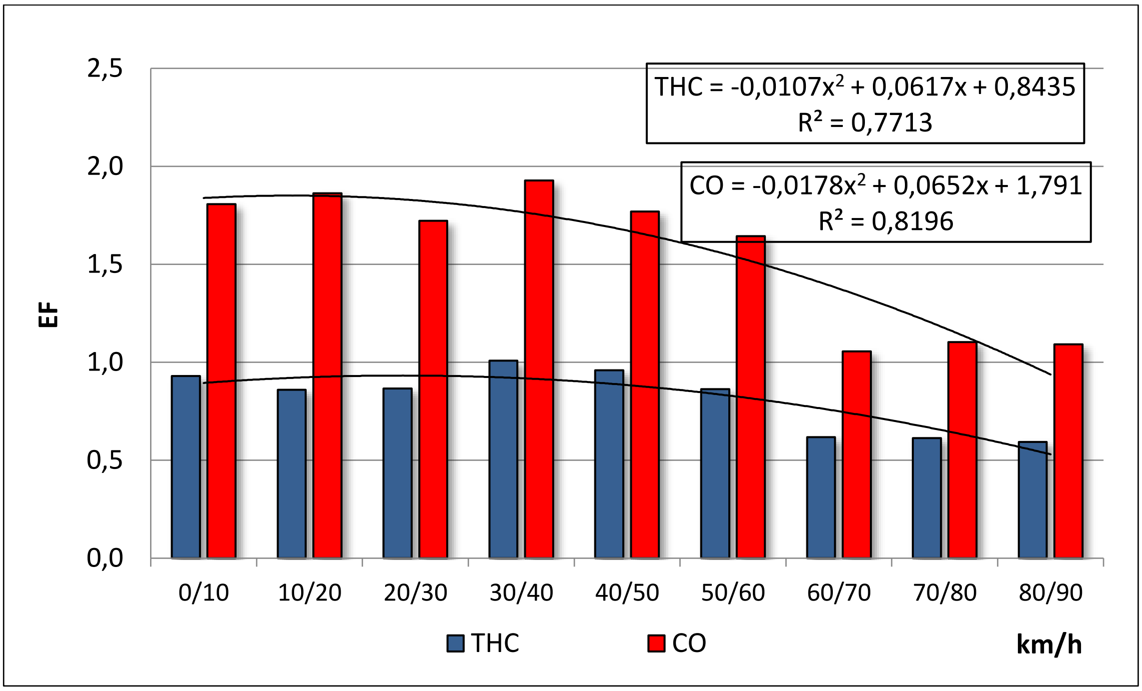


Figure 53 – EF for THC and CO in g/l for vehicle speed – E100



The EF for vehicle speed in g/l has a close behavior than in g/km, higher in the urban bins and in lower for the rural part, but with a small increase due to the aerodynamic resistance when above 60 km/h. The EF decrease in the rural interval reflects that, when the vehicle is running in more constant velocities, the catalyst can work more efficiently. The EF for vehicle speed in g/l resulted in adjust curves with coefficients of determination R^2 of 0.77 or above, indicating that this parameter is representative for analyzing emissions.

A relevant issue must be considered here when mathematic models for vehicle emissions make use of EF that are based on the results from homologation tests. The laboratory test cycles FTP-75 and WLTC are composed of urban, rural, and, for WLTC, motorway trips, and the reports combine these parts to achieve the homologation values. However, if considering only the urban emission, the EF is significantly higher and this difference can distort the calculations of the models.

6.3 Emission Factors for vehicle acceleration

Vehicle acceleration is another parameter used in the COPERT model, although its influence is composed in this model with the vehicle speed (NTZIACHRISTOS et al., 2009). It is important to have in mind that the ECU of the vehicle cuts off the fuel injection in decelerations when the engine is above 1,500-2,000 rpm for saving fuel, but when the accelerator is partially open or the engine is below 2,000 rpm the fuel remains being injected, thus producing CO_2 and pollutants. So, in order to not introduce a bias in the results, EF for negative acceleration must be disregarded, remaining still 51% of the overall RDE data that are positive values. Emissions and EF for g/km are summarized here in Tables 34-35 and Figures 54 to 57 and, for g/l, in Tables 36-37 and Figures 58 to 61.

Table 34 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km for vehicle acceleration – E22

Acceleration	THC		CO		CO_2	
m/s²	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
< 0	20.6	0.76	73.1	0.45	100.7	0.63
0 / 0.5	27.7	1.02	101.9	0.63	137.7	0.86
0.5 / 1	66.4	2.46	268.7	1.66	370.8	2.31
1 / 1.5	113.9	4.22	433.2	2.67	644.6	4.02
1.5 / 2	124.2	4.60	460.4	2.84	727.1	4.54
2 / 2.5	48.3	1.79	436.5	2.69	687.8	4.29
> 2.5	158.3	5.86	482.6	2.98	794.9	4.96
Lab reference	**27.0**	**-**	**162.0**	**-**	**160.2**	**-**

Table 35 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km for vehicle acceleration – E100

Acceleration	THC		CO		CO_2	
m/s²	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
< 0	37.5	0.35	247.0	0.46	102.2	0.66
0 / 0.5	47.5	0.44	333.4	0.62	133.9	0.87
0.5 / 1	112.4	1.04	684.2	1.26	335.7	2.17
1 / 1.5	196.9	1.82	1085.0	2.01	594.5	3.85
1.5 / 2	236.6	2.19	1346.5	2.49	628.6	4.07
2 / 2.5	236.6	2.19	1367.6	2.53	676.9	4.38
> 2.5	509.5	4.72	2287.0	4.23	575.7	3.73
Lab reference	**108.3**	-	**540.8**	-	**154.5**	-

Figure 54 – THC, CO, and CO_2 emissions in mg/km and g/km for vehicle acceleration – E22

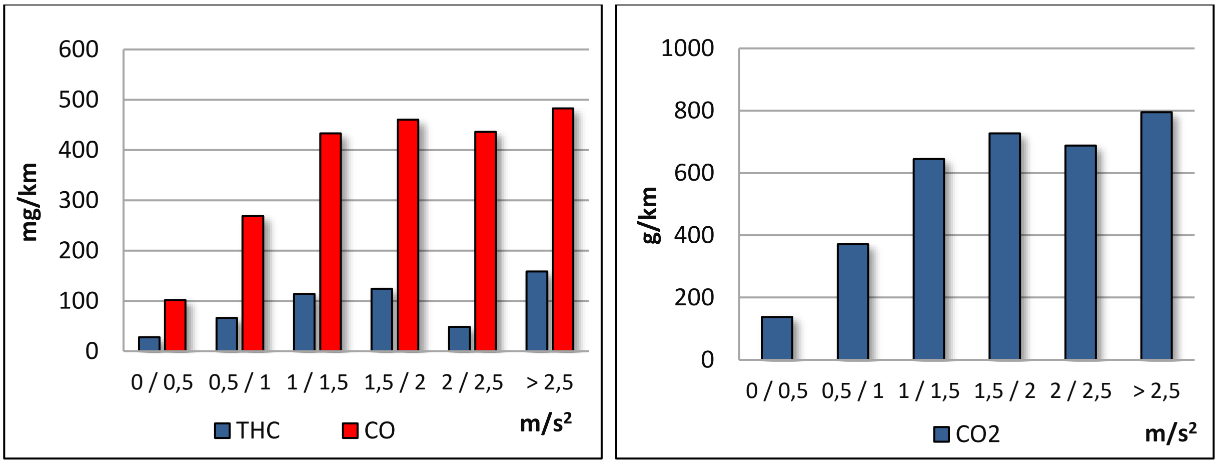


Figure 55 – EF for THC, CO, and CO_2 in g/km for vehicle acceleration – E22

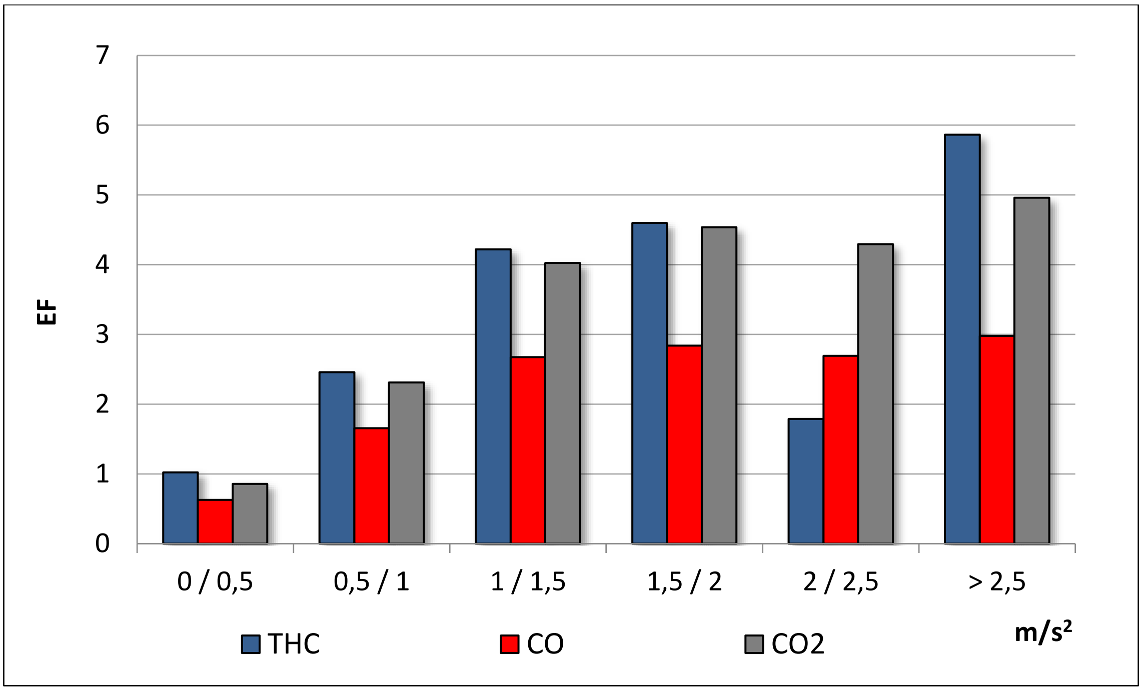


Figure 56 – THC, CO, and CO_2 emissions in mg/km and g/km for vehicle acceleration – E100

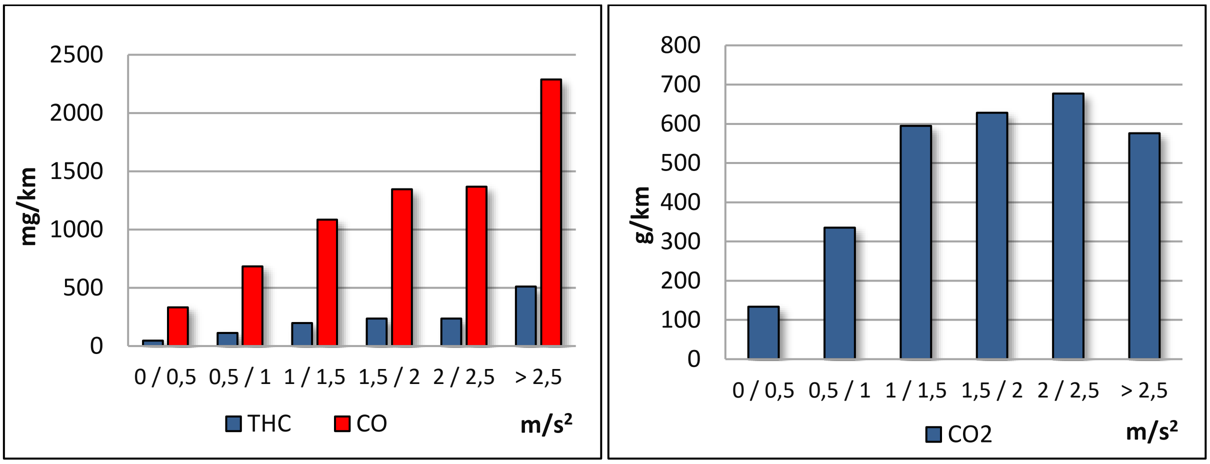


Figure 57 – EF for THC, CO, and CO_2 in g/km for vehicle acceleration – E100

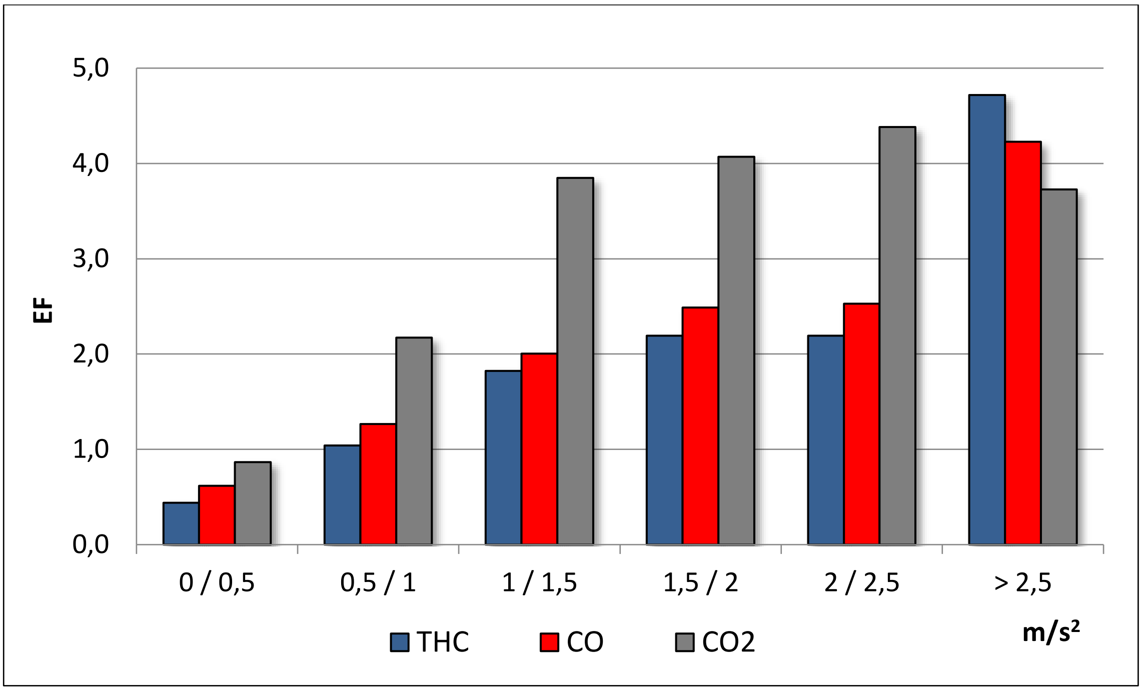


Table 36 – EF and emissions of THC and CO in g/l for vehicle acceleration – E22

Acceleration	THC		CO	
m/s²	**g/l**	**EF**	**g/l**	**EF**
< 0	0.83	2.26	3.26	1.48
0 / 0.5	0.80	2.17	3.06	1.38
0.5 / 1	0.84	2.28	3.41	1.54
1 / 1.5	0.92	2.50	3.82	1.73
1.5 / 2	1.00	2.71	4.25	1.92
2 / 2.5	0.87	2.36	3.82	1.73
> 2.5	1.12	3.03	3.13	1.42
Lab reference	**0.37**	**-**	**2.21**	**-**

Table 37 – EF and emissions of THC and CO in g/l for vehicle acceleration – E100

Acceleration	THC		CO	
m/s^2	g/l	EF	g/l	EF
< 0	0.87	0.87	8.44	1.69
0 / 0.5	0.88	0.88	8.29	1.66
0.5 / 1	0.86	0.86	8.50	1.70
1 / 1.5	0.90	0.90	9.07	1.82
1.5 / 2	0.90	0.90	9.57	1.91
2 / 2.5	1.00	1.01	10.36	2.07
> 2.5	0.77	0.77	11.19	2.24
Lab reference	**0.99**	-	**4.99**	-

Figure 58 – THC and CO emissions in g/l for vehicle acceleration – E22

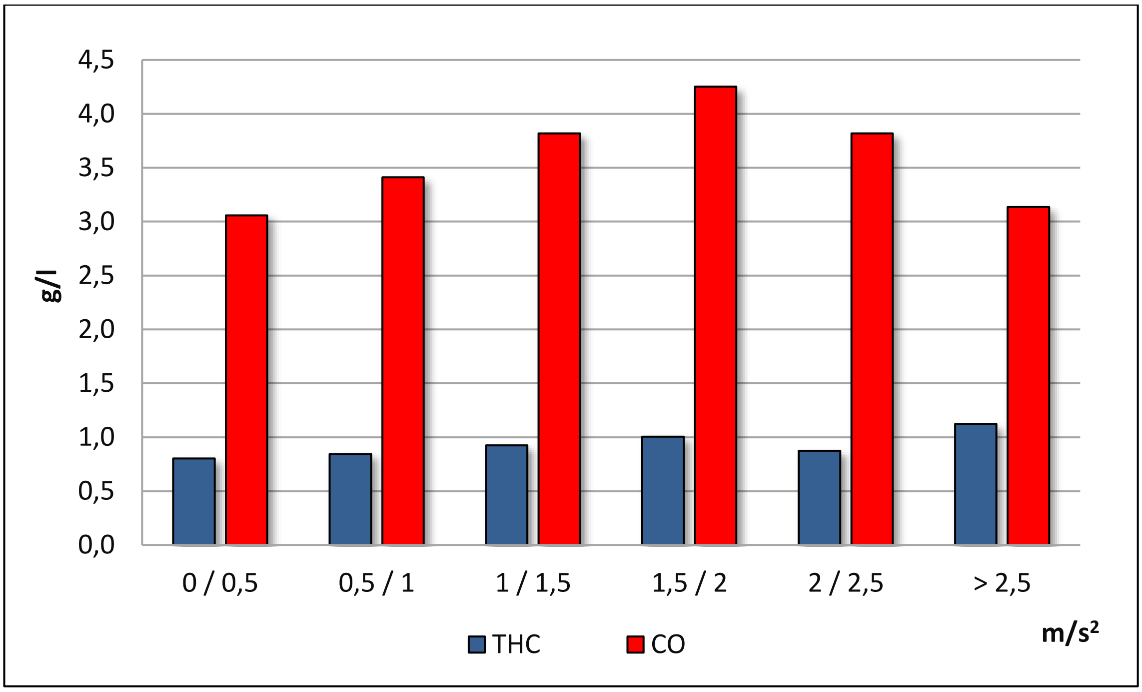


Figure 59 – EF for THC and CO in g/l for vehicle acceleration – E22

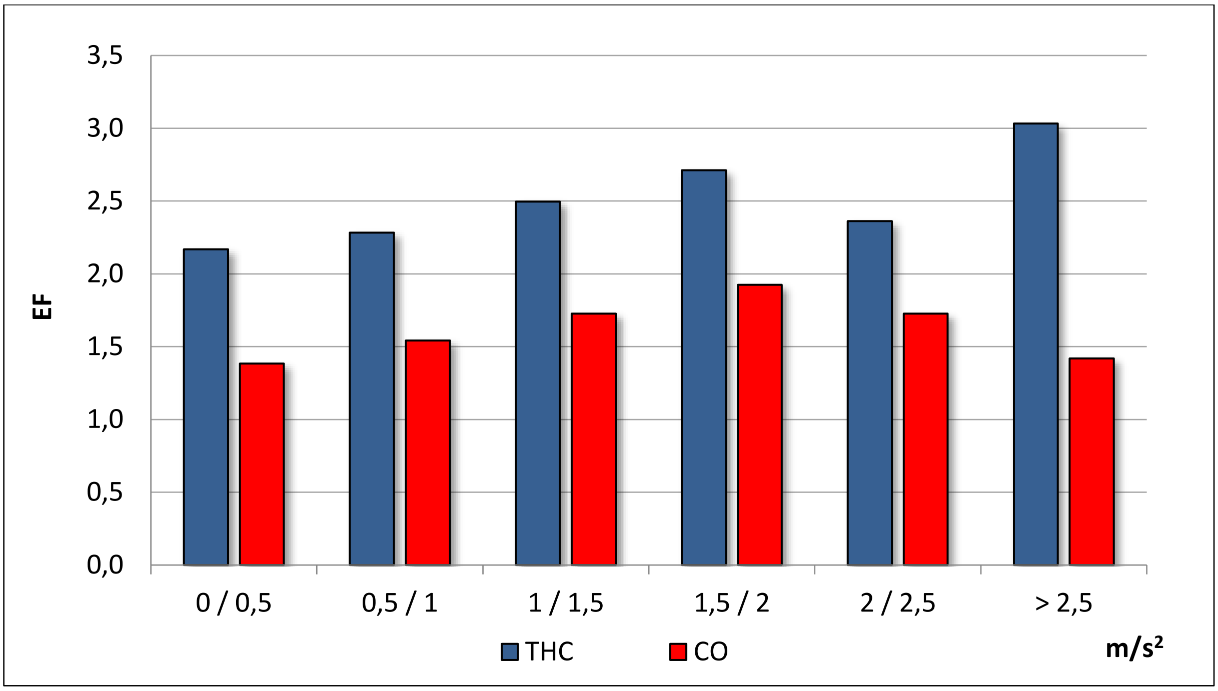


Figure 60 – THC and CO emissions in g/l for vehicle acceleration – E100

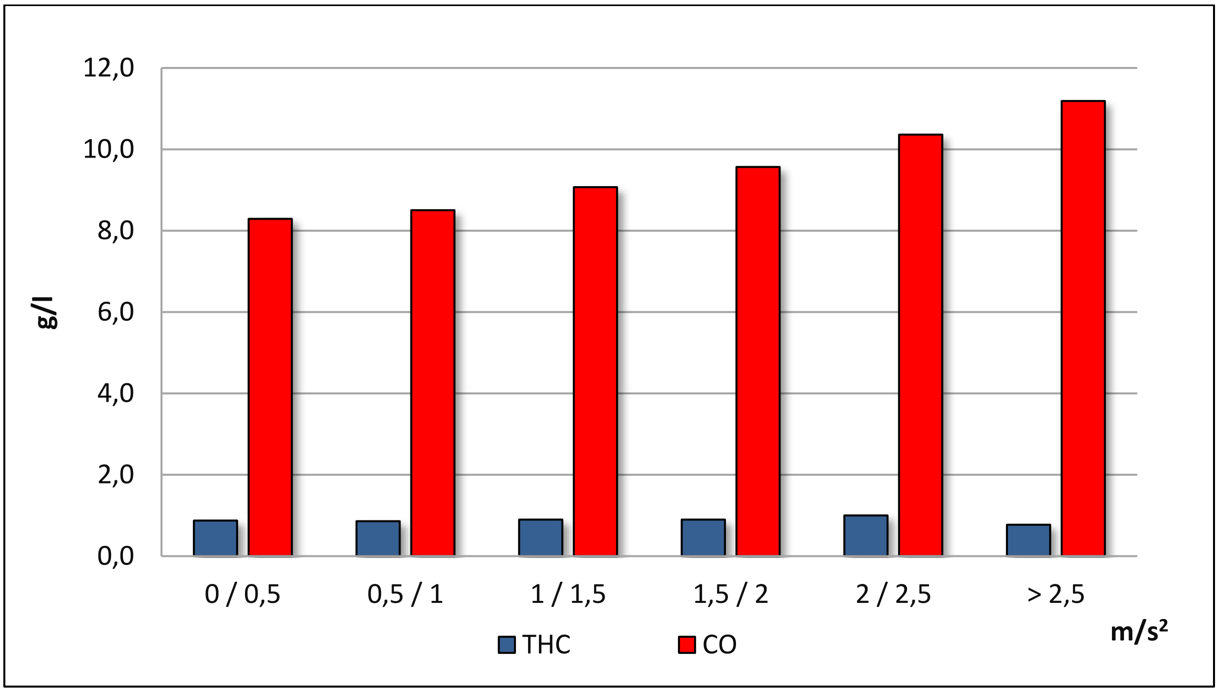
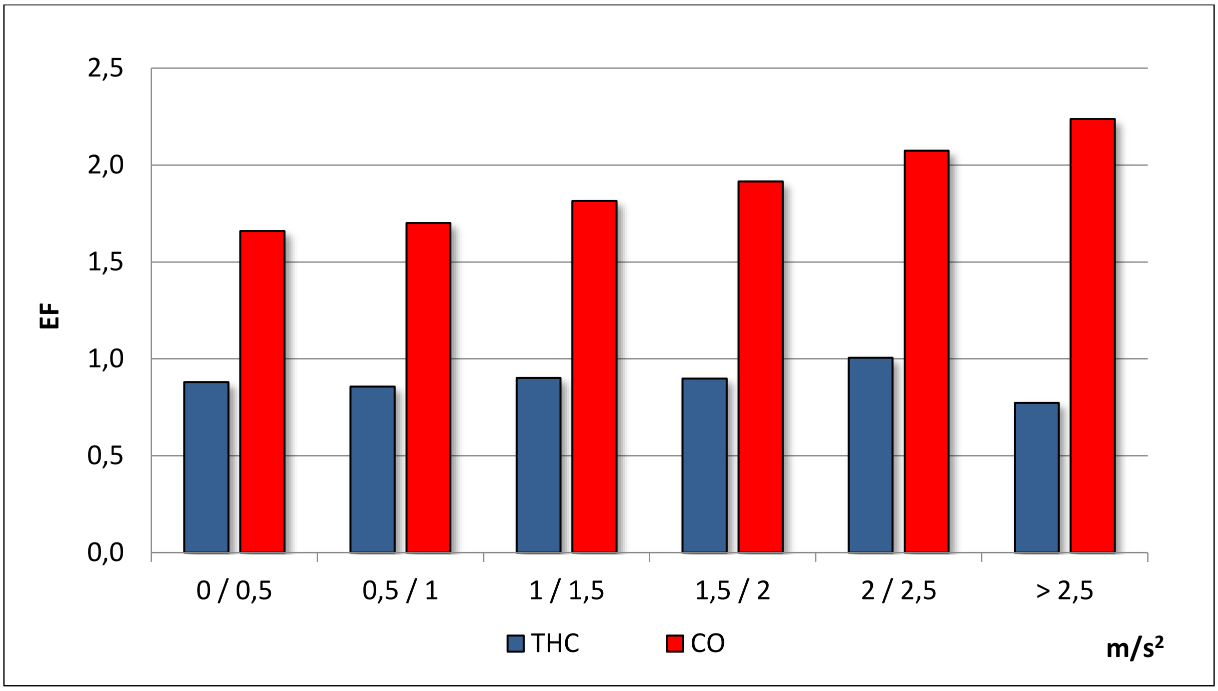


Figure 61 – EF for THC and CO in g/l for vehicle acceleration – E100



Acceleration from the RDE tests did not exceed 3 m/s^2 and from all positive values, which represent 51% of all data, about 80% happened up to only 0.5 m/s^2. This limited range is a consequence of the traffic congestion, road conditions, and speed limits in the urban part, and restricted engine power of the vehicle in the rural driving. Due to this, the analysis of EF for acceleration is difficult, so this parameter should be more useful when taking into account further data, such as vehicle speed, as it is done in the COPERT model (NTZIACHRISTOS et al., 2009).

When considering only the lower bins, up to 1.5 m/s^2, the EF in g/km for CO_2, THC, and CO tends to increase in upper ranges, for both fuels, and the EF in g/l playing in the same way, as it is expected.

6.4 Emission Factors for Vehicle-Specific Power

VSP is applied in the U.S. EPA MOVES mathematic model for vehicular emissions, and considers jointly the influence of vehicle speed, acceleration, and road grade, being more comprehensive for analyzing vehicle dynamics in real-world (FREY; ZHANG; ROUPHAIL, 2010; KHAN; FREY, 2016). Tables 38-39 and Figures 62 to 67 have the emissions for VSP in g/km, remembering that the VSP mode definition follows the ranges as used in the EPA MOVES model (KOUPAL et al., 2003; U.S. ENVIRONMENTAL PROTECTION AGENCY, 2002).

Table 38 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km according to VSP modes – E22

VSP mode	VSP range	THC		CO		CO_2	
	W/kg	mg/km	EF	mg/km	EF	g/km	EF
1	**< -2**	12.6	0.47	43.4	0.27	58.4	0.36
2	**-2 / 0**	32.5	1.20	104.8	0.65	185.9	1.16
3	**0 / 1**	11.4	0.42	37.0	0.23	64.4	0.40
4	**1 / 4**	40.0	1.48	128.8	0.80	244.9	1.53
5	**4 / 7**	39.2	1.45	138.6	0.86	245.9	1.53
6	**7 / 10**	48.0	1.78	169.1	1.04	248.7	1.55
7	**10 / 13**	62.5	2.31	270.0	1.67	266.7	1.67
8	**13 / 16**	63.6	2.36	339.3	2.09	274.4	1.71
9	**16 / 19**	81.5	3.02	367.7	2.27	292.3	1.82
10	**19 / 23**	141.2	5.23	737.2	4.55	296.7	1.85
11	**23 / 28**	288.3	10.68	1593.8	9.84	335.3	2.09
12	**> 28**	370.8	13.73	2065.5	12.75	367.5	2.29
	Lab reference	**27.0**	**-**	**162.0**	**-**	**160.2**	**-**

Table 39 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km according to VSP modes – E100

VSP mode	VSP range	THC		CO		CO_2	
	W/kg	mg/km	EF	mg/km	EF	g/km	EF
1	**< -2**	26.4	0.24	153.4	0.28	61.3	0.40
2	**-2 / 0**	59.4	0.55	347.4	0.64	183.6	1.19
3	**0 / 1**	22.4	0.21	112.8	0.21	70.6	0.46
4	**1 / 4**	75.9	0.70	400.5	0.74	220.3	1.43
5	**4 / 7**	79.1	0.73	437.7	0.81	215.5	1.39
6	**7 / 10**	78.9	0.73	540.0	1.00	224.7	1.45
7	**10 / 13**	77.1	0.71	699.4	1.29	227.0	1.47
8	**13 / 16**	71.9	0.67	882.7	1.63	228.8	1.48
9	**16 / 19**	68.7	0.64	1082.1	2.00	239.6	1.55
10	**19 / 23**	91.6	0.85	1524.1	2.82	250.1	1.62
11	**23 / 28**	160.3	1.48	3280.9	6.06	268.3	1.74
12	**> 28**	190.1	1.76	4405.7	8.14	330.5	2.14
	Lab reference	**108.3**	**-**	**540.8**	**-**	**154.5**	**-**

Figure 62 – THC and CO emissions in mg/km according to VSP modes – E22

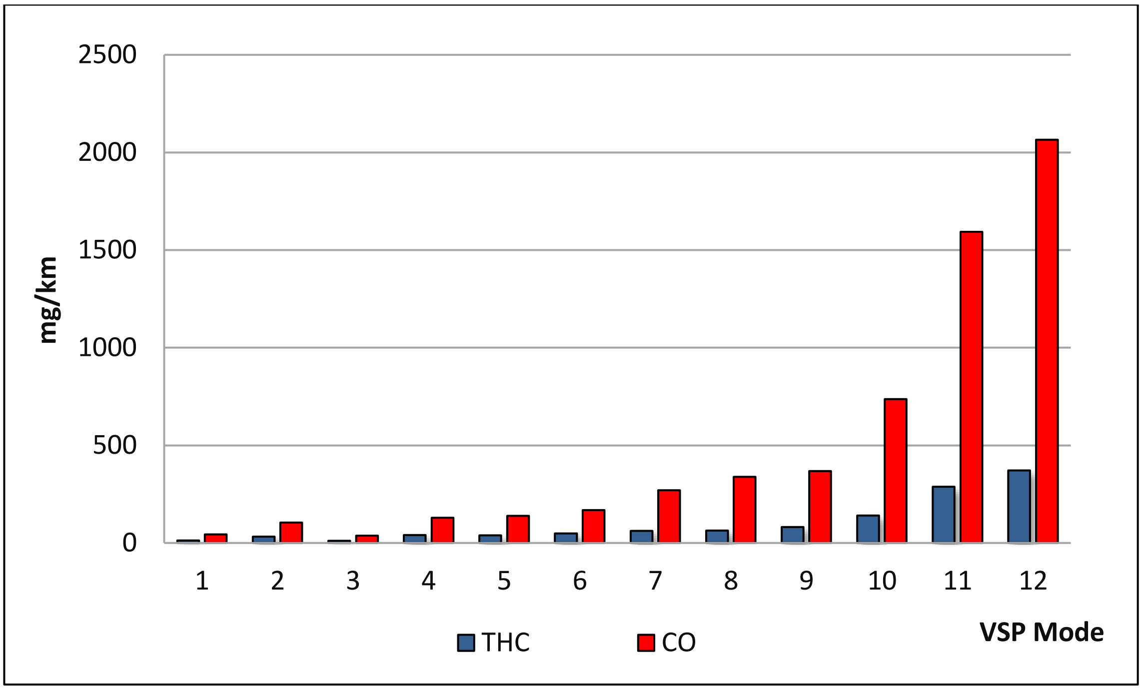


Figure 63 – CO_2 emissions in g/km according to VSP modes – E22

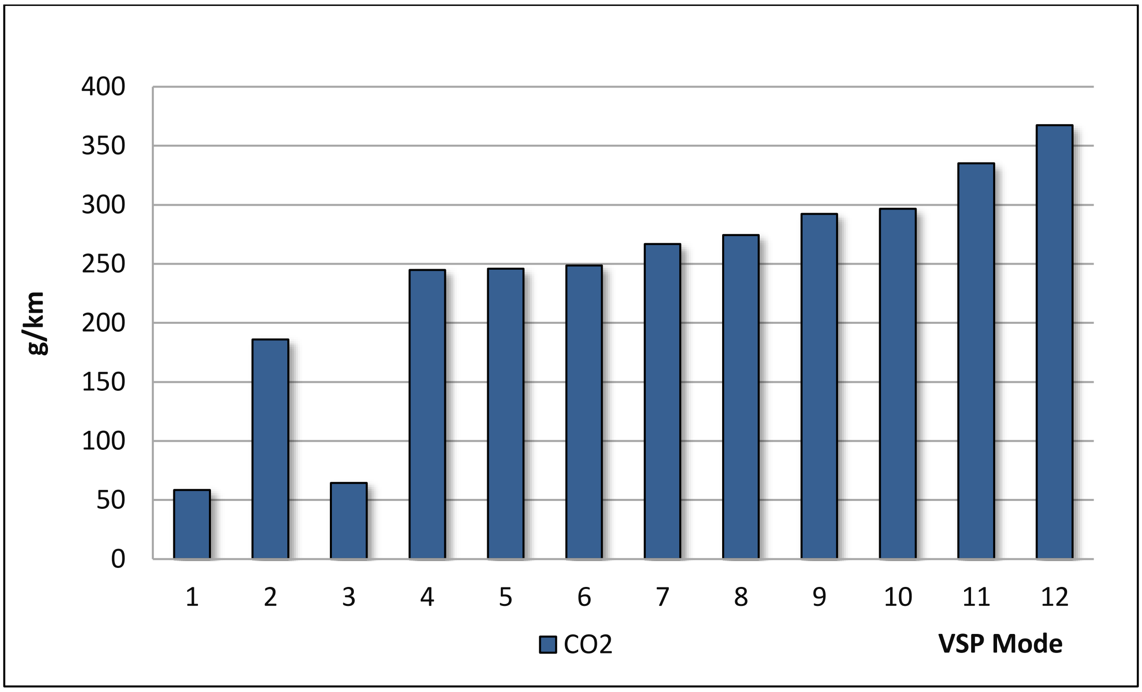


Figure 64 – EF for THC, CO, and CO_2 in g/km according to VSP modes – E22

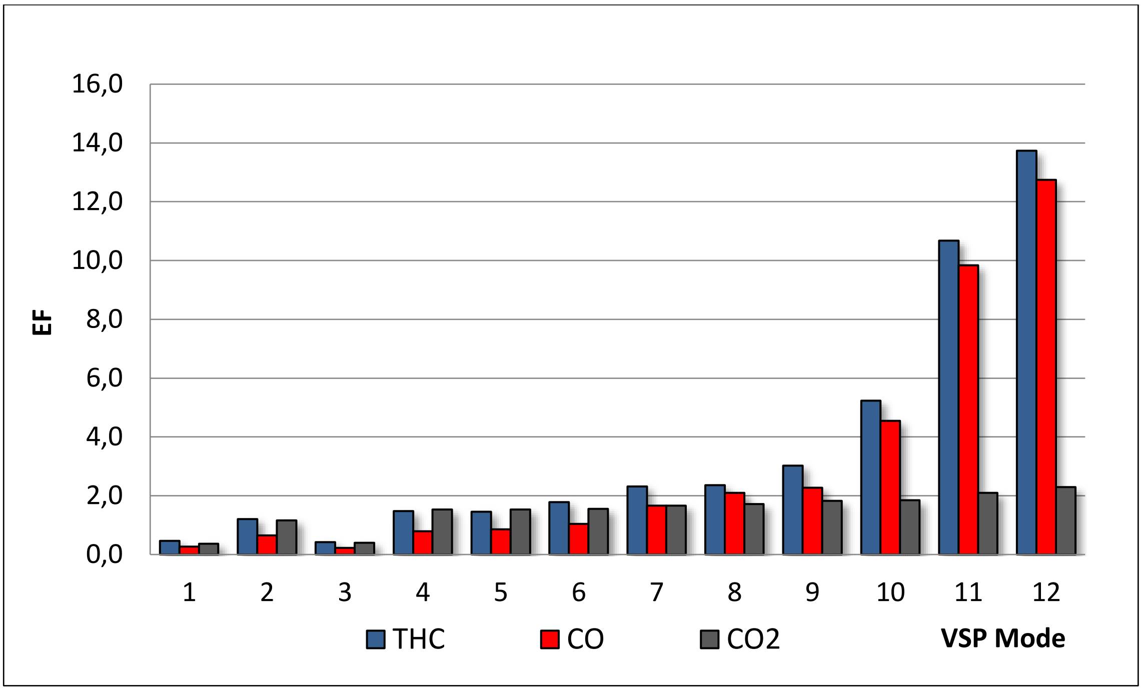


Figure 65 – THC and CO emissions in mg/km according to VSP modes – E100

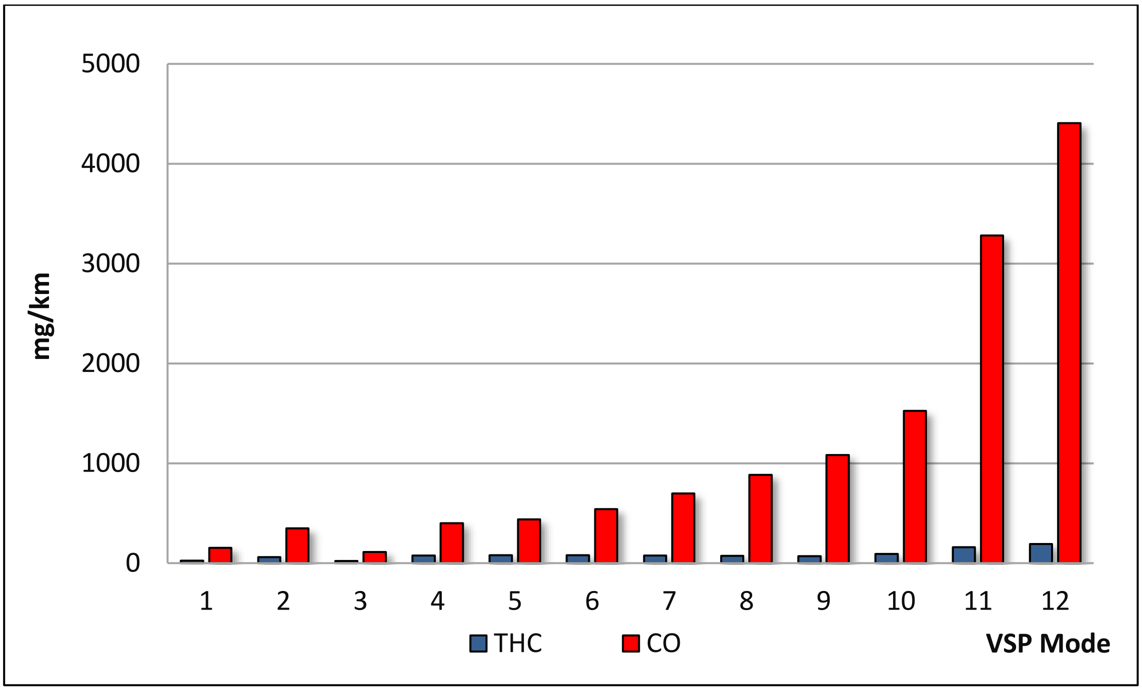


Figure 66 – CO_2 emissions in g/km according to VSP modes – E100

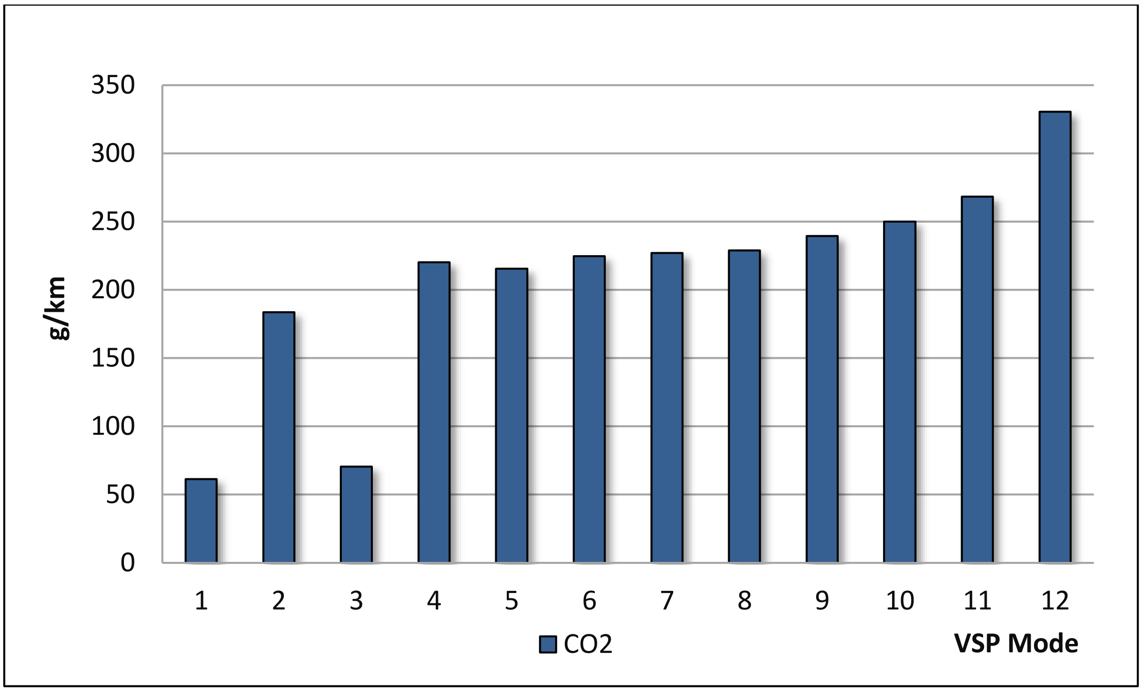
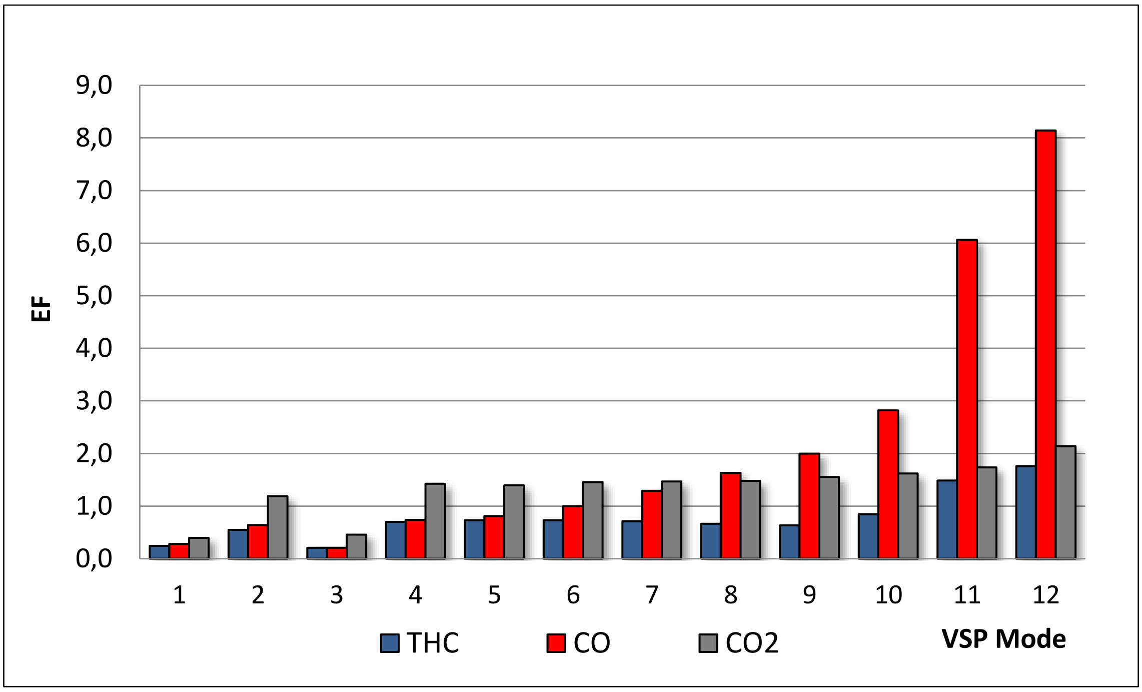


Figure 67 – EF for THC, CO, and CO_2 in g/km according to VSP modes – E100



The emission in g/km for VSP increases in upper modes for all compounds and both fuels, although for CO_2 in more discrete proportion; however, the EF for CO_2 in mode #4 to up are almost 50% above the laboratory reference. CO has a significant increment in the highest modes for E100, while for E22 it is closer to THC results. Another issue to be noticed is that up to mode #8, which represents more than 97% of all measurements, all EF increase are not as intense as in the highest modes. In sequence, Tables 40-41 and Figures 68 to 71 show the emissions and EF for VSP in g/l.

Table 40 – EF and emissions of THC and CO in g/l according to VSP modes – E22

VSP mode	VSP range	THC		CO	
	W/kg	**g/l**	**EF**	**g/l**	**EF**
1	**< -2**	0.82	2.23	3.34	1.51
2	**-2 / 0**	0.89	2.40	3.39	1.53
3	**0 / 1**	0.88	2.39	3.32	1.50
4	**1 / 4**	0.88	2.39	3.28	1.48
5	**4 / 7**	0.79	2.13	3.05	1.38
6	**7 / 10**	0.71	1.91	2.90	1.31
7	**10 / 13**	0.70	1.88	3.05	1.38
8	**13 / 16**	0.63	1.71	2.80	1.27
9	**16 / 19**	0.62	1.67	2.73	1.23
10	**19 / 23**	0.58	1.55	2.77	1.25
11	**23 / 28**	0.50	1.35	2.53	1.14
12	**> 28**	0.54	1.46	2.63	1.19
	Lab reference	**0.37**	**-**	**2.21**	**-**

Table 41 – EF and emissions of THC and CO in g/l according to VSP modes – E100

VSP mode	VSP range	THC		CO	
	W/kg	g/l	EF	g/l	EF
1	< -2	0.86	0.86	8.57	1.71
2	-2 / 0	0.87	0.87	8.90	1.78
3	0 / 1	0.93	0.93	8.82	1.76
4	1 / 4	0.91	0.92	8.66	1.73
5	4 / 7	0.88	0.88	8.24	1.65
6	7 / 10	0.79	0.79	7.66	1.53
7	10 / 13	0.73	0.73	7.24	1.45
8	13 / 16	0.70	0.71	6.91	1.38
9	16 / 19	0.65	0.65	6.34	1.27
10	19 / 23	0.70	0.70	6.21	1.24
11	23 / 28	0.55	0.55	5.24	1.05
12	> 28	0.53	0.53	5.17	1.03
	Lab reference	**0.99**	-	**4.99**	-

Figure 68 – THC and CO emissions in g/l according to VSP modes – E22

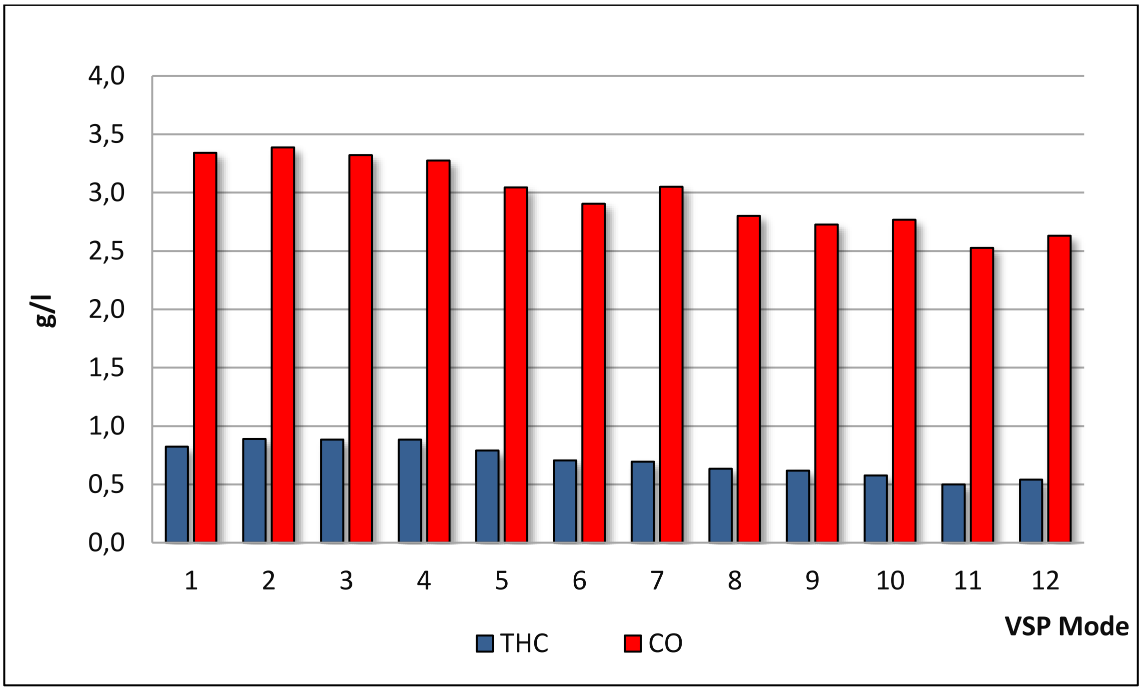


Figure 69 – EF for THC and CO in g/l according to VSP modes – E22

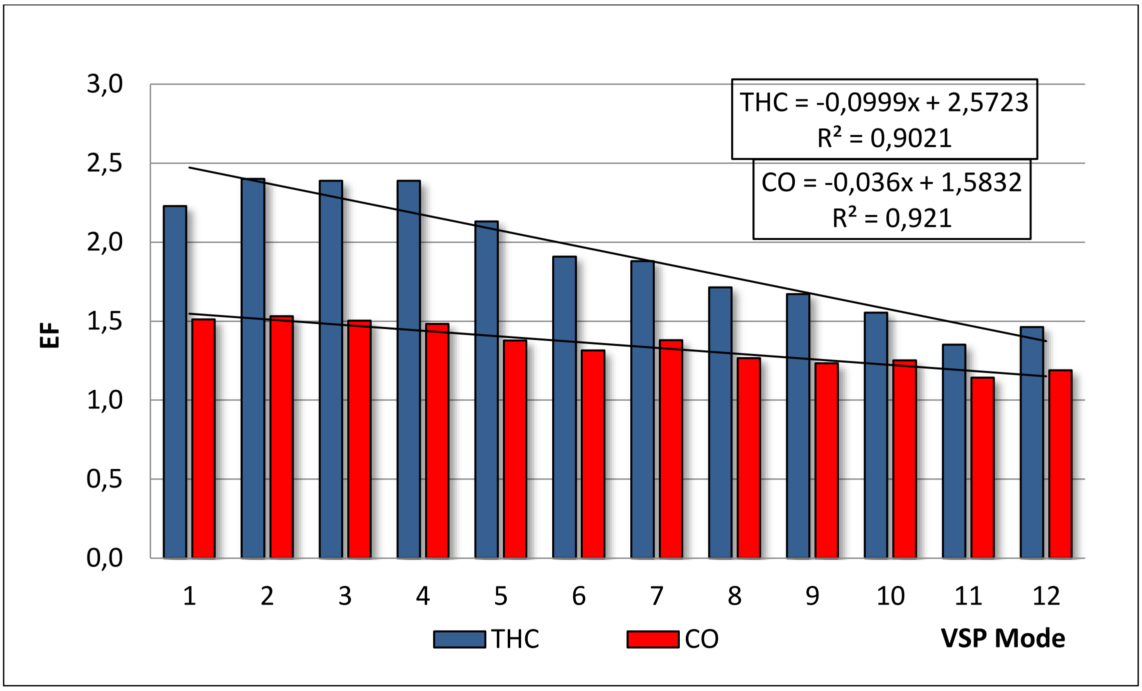


Figure 70 – THC and CO emissions in g/l according to VSP modes – E100

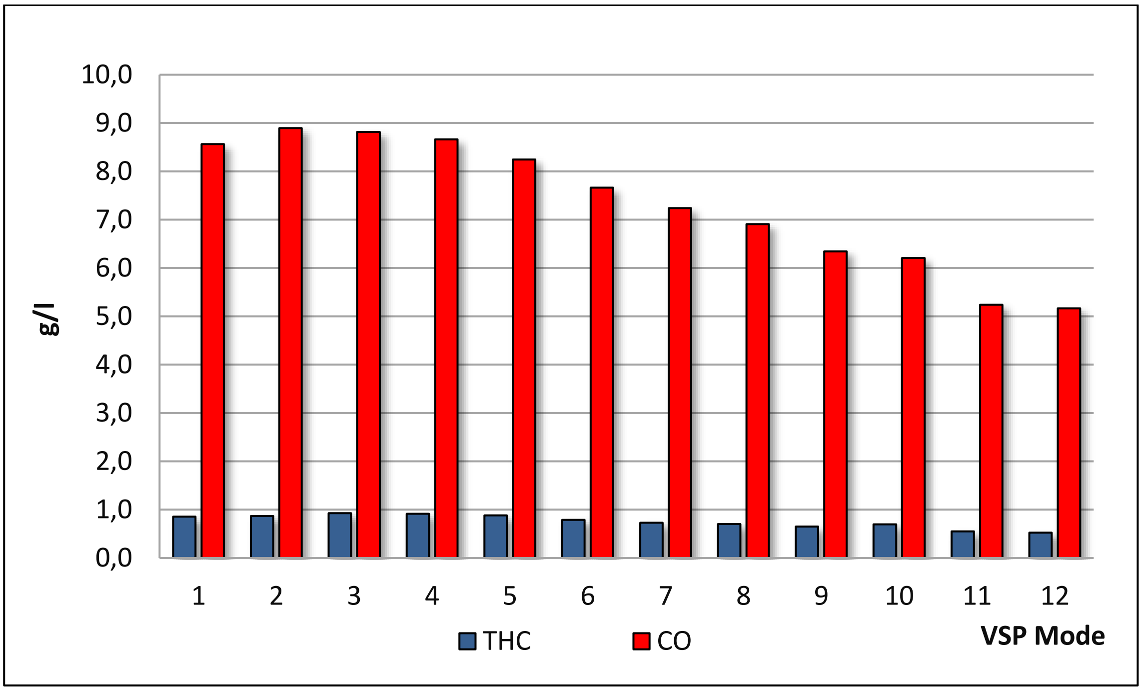
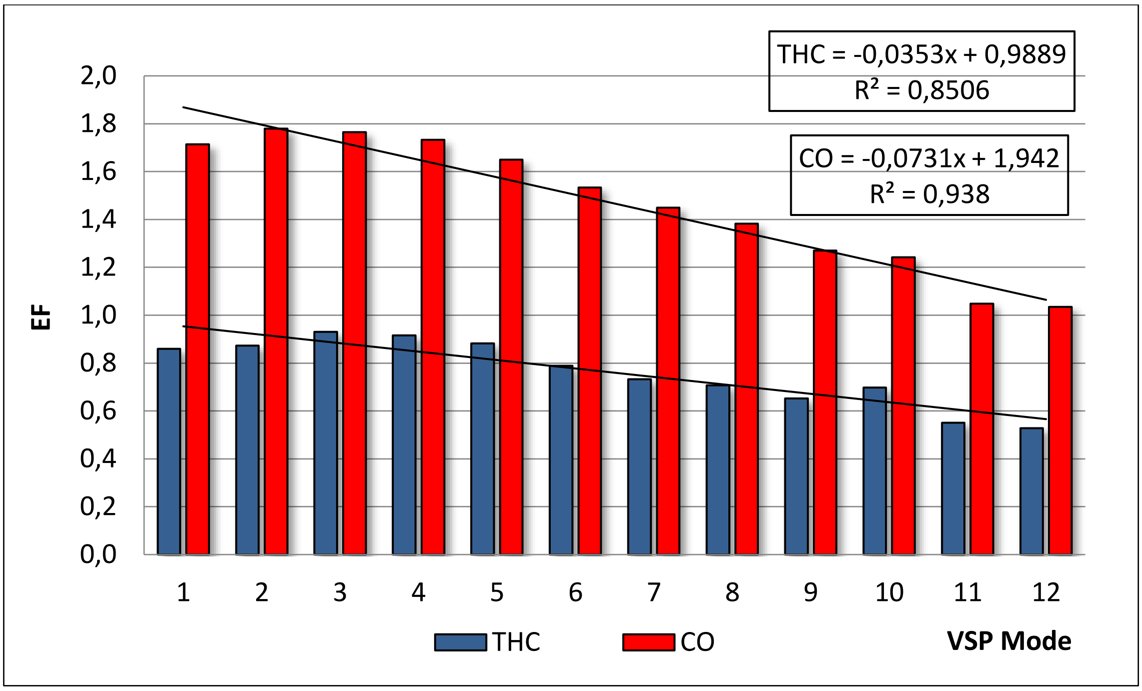


Figure 71 – EF for THC and CO in g/l according to VSP modes – E100



Diversely than for g/km, EF for VSP in g/l decreases in higher modes for all fuels and pollutants, because the specific emissions are been compensated by the rise in the fuel consumption.

The EF for VSP for g/l resulted in coefficients of determination R^2, close to or better than 0.90, even when the tendency lines are expressed in first-degree equations, an indication that VSP is representative of the vehicle emission behavior. However, VSP requires more effort for being effective, because it is not only necessary data from the traffic flow (speed and acceleration) but also from the local topography (road grade) and eventually they are not available at the same time.

6.5 Emission Factors for engine temperature

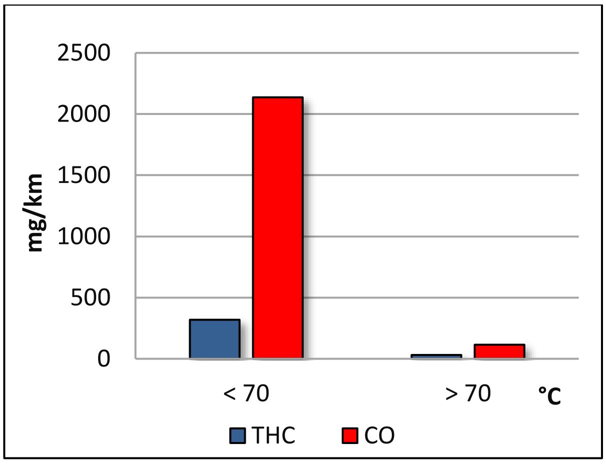
Engine temperature is relevant when considering that it is necessary the catalyst must get warm up enough to do the appropriate reactions and keep emissions under control. COPERT and VEIN models include this parameter in their calculations (IBARRA-ESPINOSA, 2017; LASKOWSKI et al., 2021). An useful application of this EF is that it can be extrapolated for emissions from tampered vehicles, which are running with no catalyst or with it in bad conditions because their emissions will be like that from a good one in cold start.

From all RDE tests, four of them started with the engine at ambient temperature, others with it warm but below 70°C. The cold start data happened in 1,498 s or 4.2% of all measurements for E22 and 2,386 s or 4.4% for E100, and the vehicle required approximately 346 s or 5.7 min to reach 70°C when starting completely cold. The EF in g/km is presented in Table 42 and Figures 72-75, and for g/l in Table 43 and Figures 76-79.

Table 42 – EF and emissions of THC, CO, and CO_2 in mg/km and g/km according to engine temperature

Engine temp	**THC**		**CO**		**CO_2**	
E22						
°C	**mg/km**	**EF**	**mg/km**	**EF**	**g/km**	**EF**
< 70	319.4	11.83	2136.1	13.19	290.7	1.81
> 70	30.9	1.15	115.2	0.71	160.2	1.00
Lab reference	**27.0**	**-**	**162.0**	**-**	**160.2**	**-**
E100						
< 70	298.5	2.76	5993.3	11.08	264.7	1.71
> 70	53.2	0.49	350.1	0.65	152.3	0.99
Lab reference	**108.0**	**-**	**541.0**	**-**	**154.5**	**-**

Figure 72 – THC, CO, and CO_2 emissions in mg/km and g/km according to engine temperature – E22



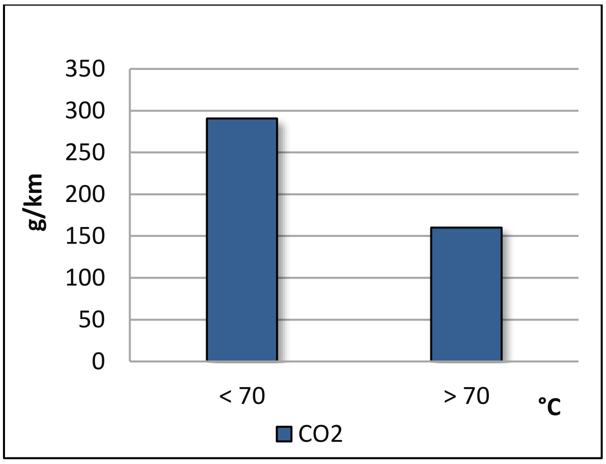


Figure 73 – EF for THC, CO, and CO_2 in g/km according to engine temperature – E22

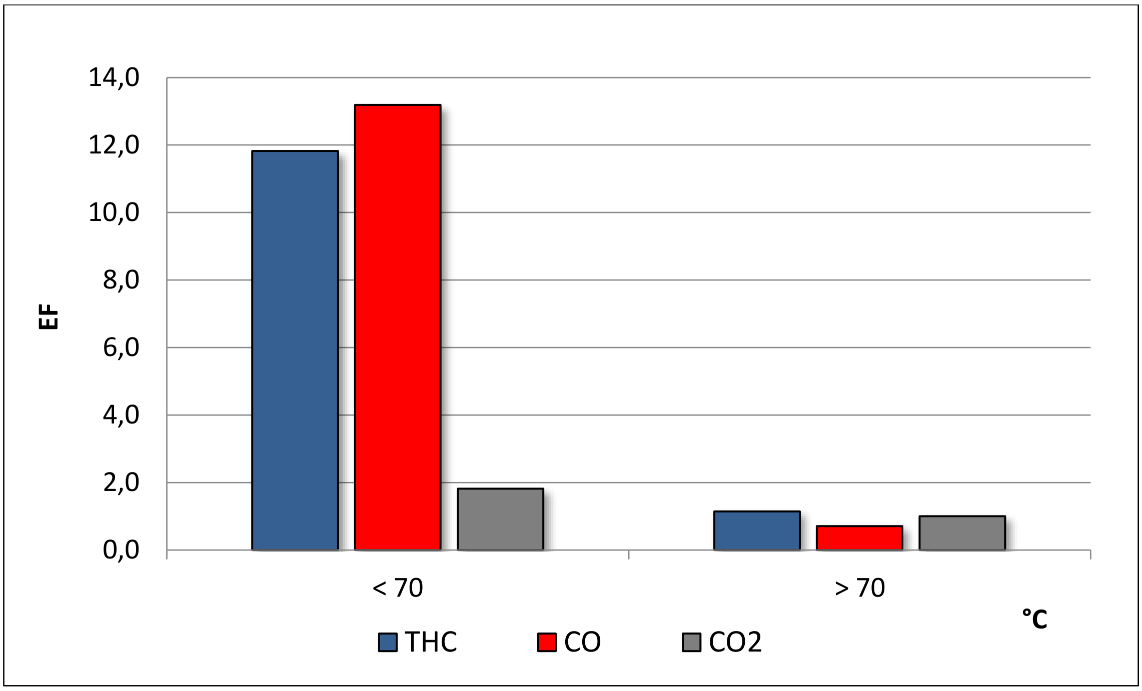


Figure 74 – THC, CO, and CO_2 emissions in mg/km and g/km according to engine temperature – E100

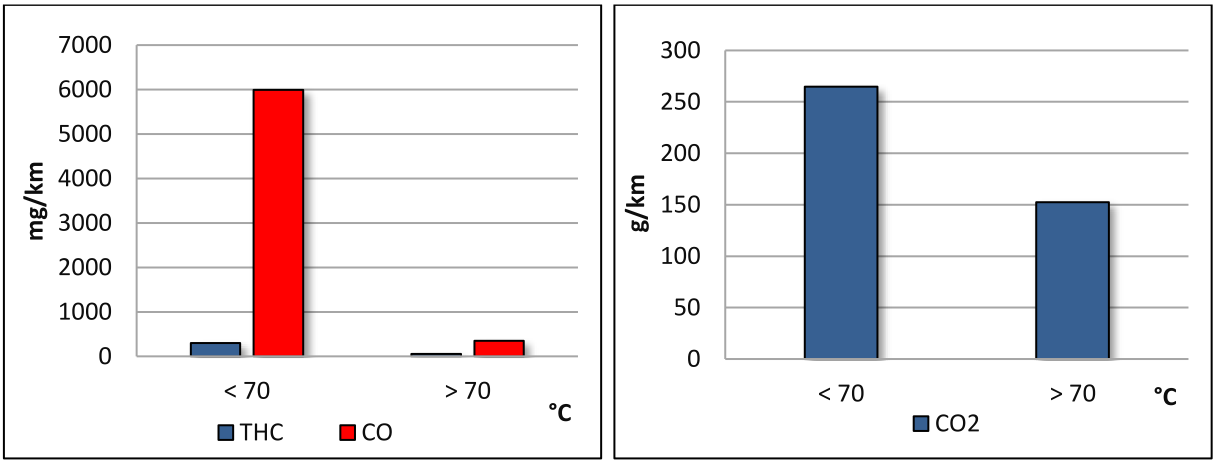


Figure 75 – EF for THC, CO, and CO_2 in g/km according to engine temperature – E100

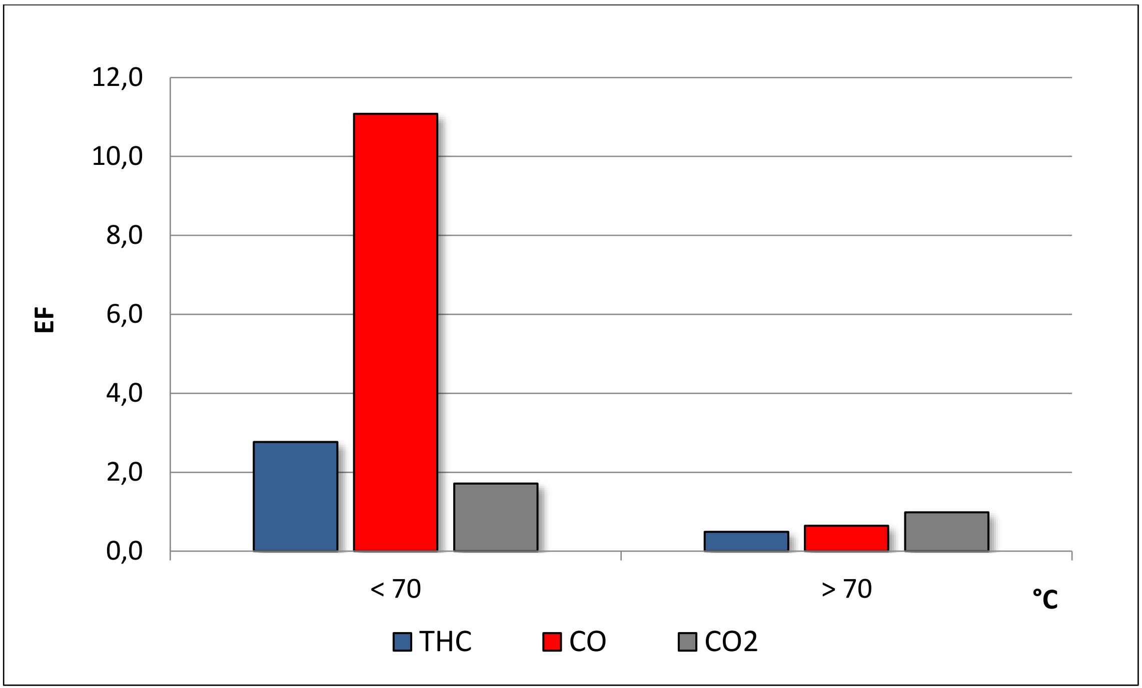


Table 43 – EF and emissions of THC and CO in g/l according to engine temperature

Engine temp	THC		CO	
		E22		
°C	g/l	EF	g/l	EF
< 70	2.47	6.67	20.67	9.35
> 70	0.83	2.24	3.22	1.46
Lab reference	**0.37**	-	**2.21**	-
		E100		
< 70	1.34	1.34	35.22	7.05
> 70	0.87	0.87	8.42	1.68
Lab reference	**0.99**	-	**4.99**	-

Figure 76 – THC and CO emissions in g/l according to engine temperature – E22

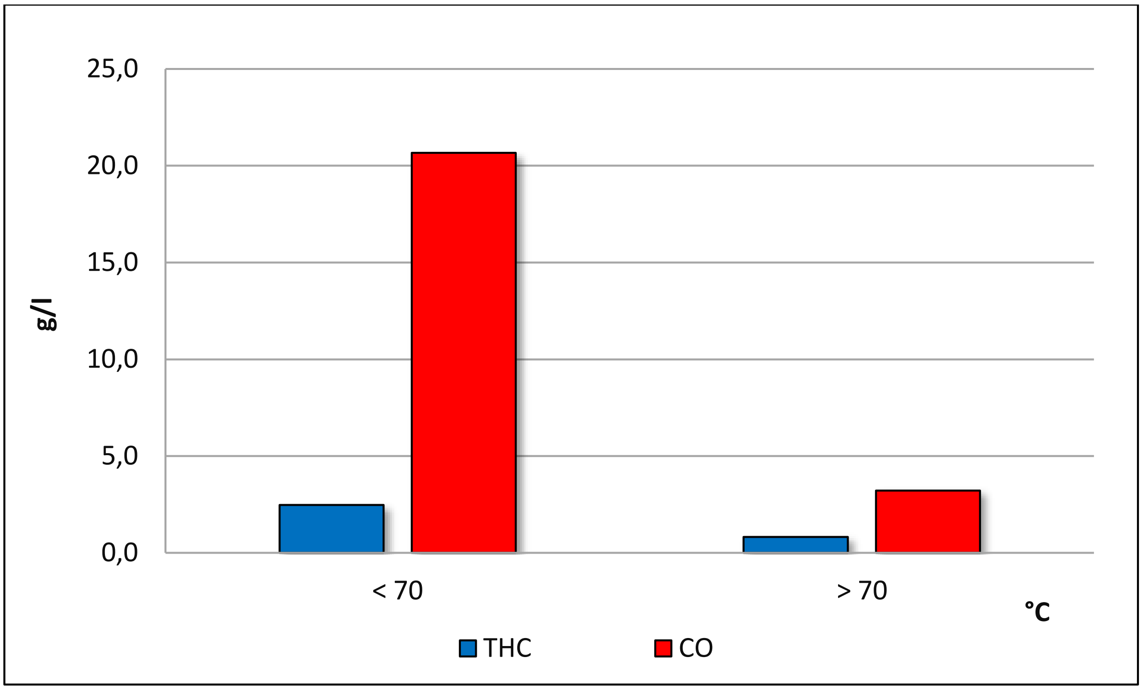


Figure 77 – EF for THC and CO in g/l according to engine temperature – E22

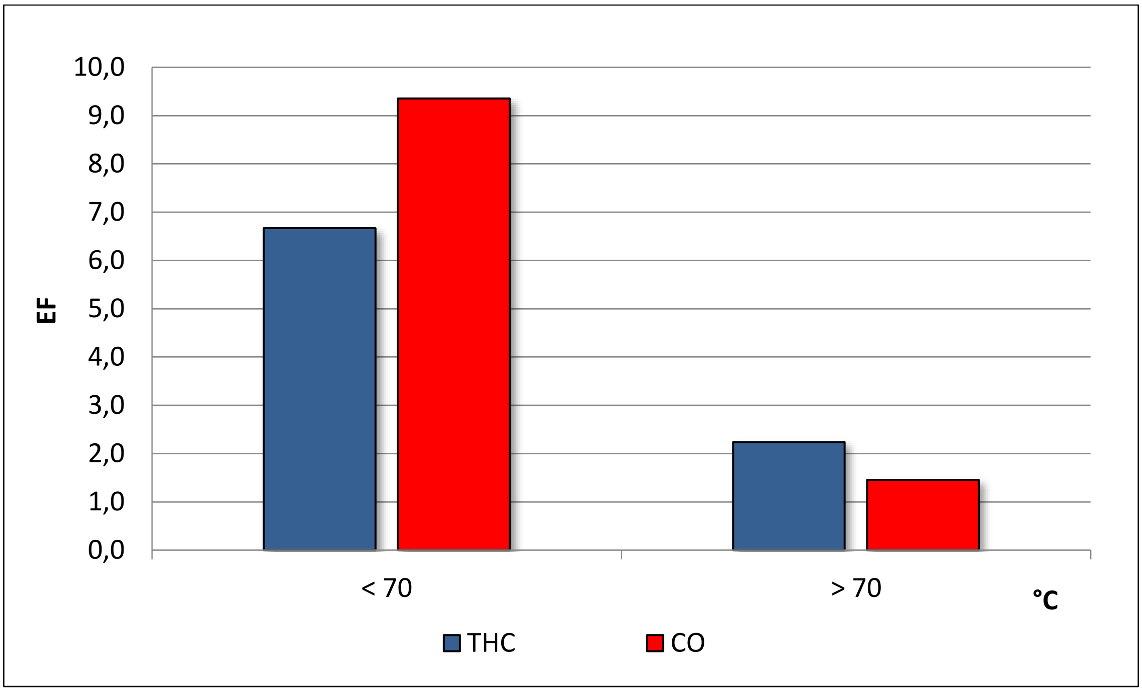


Figure 78 – THC and CO emissions in g/l according to engine temperature – E100

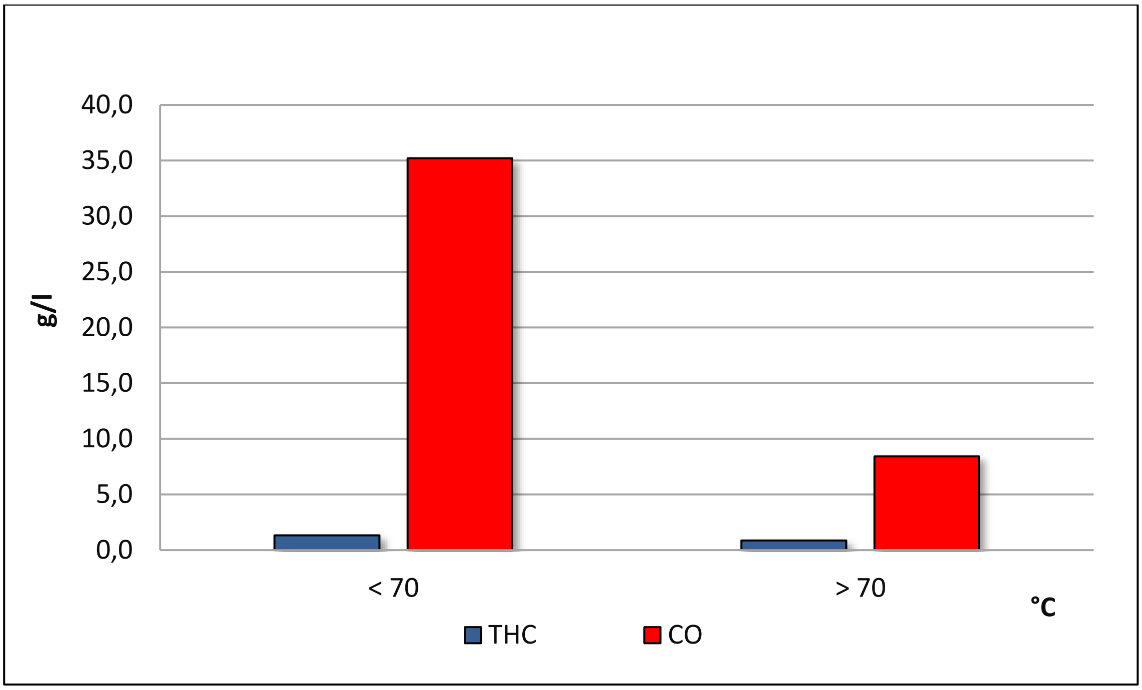
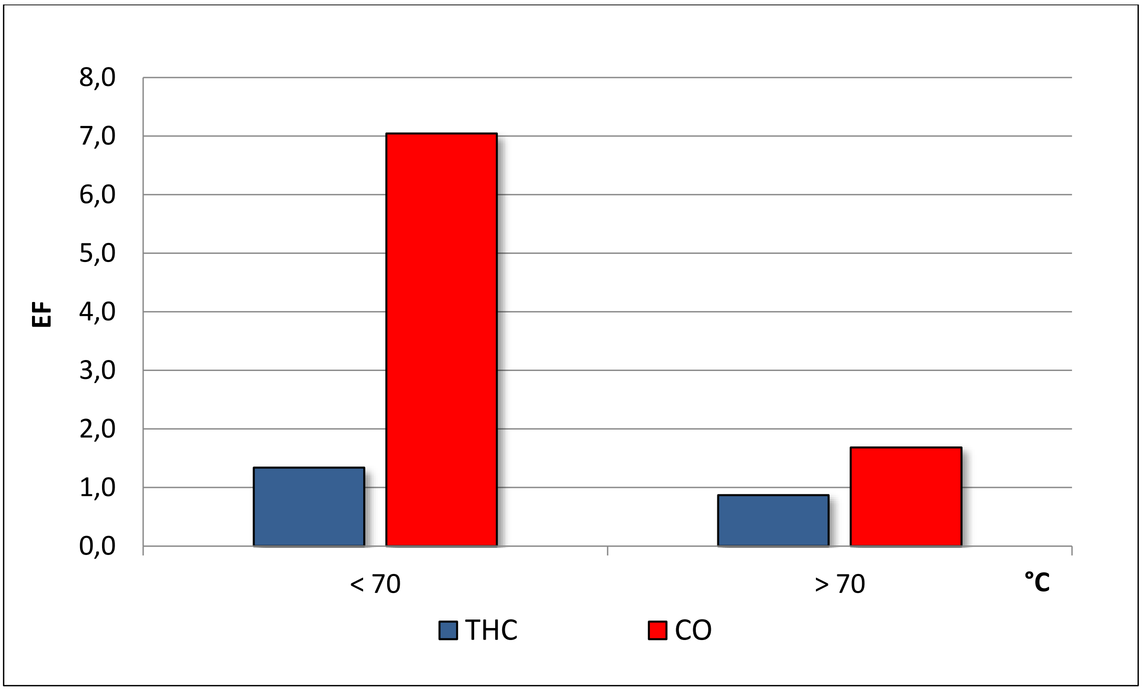


Figure 79 – EF for THC and CO in g/l according to engine temperature – E100



The EF for THC and CO in g/km and g/l, for both fuels, reported a significant increase when the engine is cold, with exception of THC for E100, with an EF of only 2.76 in comparison to the laboratory, while other factors are above 10.0. This low EF cannot be explained with the available data, it is possible to be caused by the LCP limitations for measuring ethanol compounds. Despite the CO_2 rise is not so high as for THC and CO, the results still show a significant difference, caused by the fuel mixture enrichment.

The EF for engine temperature indicates that the cold start must be carefully considered in the mathematic models because different inputs for averaged travel distance will change the ratio between cold and hot emissions, producing different results.

6.6 Discussion about the Emission Factors

Usually, regulatory limits for vehicle emissions are expressed in g/km, and this notation is also used in laboratory reports, vehicular inventories, and in some mathematic models. The use of the emission in g/l is less frequent but it is still important, considering that at all times the EF in g/l produced less dispersion and/or trend curves with lower degrees equations, exactly because the influence of fuel consumption is taken apart.

The parameters that resulted in the most representative EF are the vehicle speed and the VSP, particularly in g/l, with coefficients of determination close to 0.90, obtained over tendency curves expressed in first- and second-degree equations.

Regarding the ambient temperature, it was expected a significant THC and CO increase at low temperatures, which was not confirmed by the LCP measurements, but the low-cost PEMS limitation to measure THC below 18°C when burning E100 surely introduced a bias in these results.

The EF points to relevant increment at urban speeds, medium to high VSP, and at cold start. Their joint influence can partially explain the divergences between EF from the CETESB emissions inventory and in-tunnel measurements because this last one evaluates real-world conditions, such as vehicles with cold engines or damaged catalysts. Therefore, results from homologation tests must be carefully applied in the mathematic models, since they have inherent divergence from the actual vehicle conditions.

CONCLUSIONS

The low-cost PEMS construction demanded close to US$ 1,000, or about R$ 5,000 by the exchange rate dollar/Brazilian real in July/2022, representing less than 0.5% of the price of a commercial PEMS. The system is light, weighing approximately 15 kg, and the power consumption is low, mainly due to the suction pump which requires itself only 50 W, like to one headlamp. The LCP is compact enough to be used in small hatches and the system is robust to lead with vibrations from irregularities of the streets, just the GPS module has some concern for rain because it is mounted in a box, outside the car. The low weight and reduced dimensions of the LCP easies its application in motorcycles but it still depends on further improvements.

A limitation of this system is the use at ambient temperatures below 20°C, particularly for THC when the car is fueled with E100, but it is still necessary to further development efforts for fixing this issue. Another point that requires some attention, due to the LCP uses ambient air to dilute the exhaust gas, that it is possible to have contamination during the tests by the background pollution, for example when the vehicle is driven behind a high-emitter vehicle or if biomass, such as dry grass or sugar cane residues, is being burned close to the road where the RDE test is running.

The low-cost PEMS reaches good accuracy for CO_2 and CO, when in comparison to the laboratory instruments, with coefficients of determination R^2 higher than 0.94 for both fuels. The results for THC, with R^2 of 0.85 for E22 and 0.73 for E100, do not accomplish the requirements of the RDE procedure for use in vehicle homologation, although they can yet be considered enough for research proposals.

The measurement of hydrocarbon compounds in the exhaust gas was more complex for being done than initially estimated in the project phase. The electro-catalyst sensor MQ-6 for THC has an exponential response curve while in contact with THC compounds, and this curve is different for each compound (ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD, 2015a). As a consequence, when exposed to propane, which is the standard gas to calibrate the THC detector in laboratory instruments, the MQ-6 produced one response curve, but it had another one when tested with ethanol and two others yet while measuring directly in the vehicle fueled with E22 and E100, due to the exhaust gas be a mixture, composed by unburned fuel and other substances produced by the fuel combustion inside the engine (BOSCH, 1993).

The results from RDE tests, when analyzed under the perspective of Emission Factors indicate some important tendencies that should be considered in the mathematic model for vehicle emissions. The vehicle tested produces up to 2.0 times more CO_2 at typical urban speeds, e.g. 20 km/h, than the historic reference from laboratory tests, with a similar increase for CO and THC. In the same way, while the engine is cold, below 70°C, the EF for CO and THC jumps to about 10.0 times higher than the reference values, with the catalyst requiring on average 5.7 minutes for lighting on.

This warming-up period can be more or less significant, depending on the traveled distance that the vehicle is being driven, so short trips will have more impact on the overall emissions. The increment for cold start also signs for the issue of vehicles running with no or damaged catalyst, because of this higher pollutant emission impact as well as the mathematic models than the metropolitan environment.

The EF based on VSP shows to be a reliable metric for the mathematic models, while embracing the influence of many variables at the same time, such as speed, acceleration, and road grade but this parameter requires more effort for collecting data from the road grid under analysis. Vehicle speed seems a simpler solution as a factor of influence in vehicle emissions because it is easier to be determined through data from GPS, monitoring sensors in traffic lights, and speed controllers, being almost as representative as VSP. Both VSP and vehicle speed reach a coefficient of determination close to 0.9, with tendency curves from first- and second-degree equations.

Despite the tendencies pointed out by the EF analysis, the divergences between CETESB emissions inventory and the tunnel measurements in MASP remain unclear. Some possible reasons for these differences are the presence of high-emitter vehicles among the fleet, with no or damaged catalyst. It is important to consider that the influence of motorcycles in the real world air pollution is also unknown, even being a significant parcel of the Brazilian fleet and which can produce up to 3 times more CO and THC per kilometer than a LDV, according to CETESB vehicular emissions inventory (COMPANHIA AMBIENTAL DO ESTADO DE SAO

PAULO, 2022a). In-tunnel measurements did not evaluate these vehicles individually and there is almost no data about real-world emissions from two-wheel vehicles, nor how many of them are running without catalysts.

FUTURE PERSPECTIVES FOR RESEARCH

An improvement needed by the low-cost PEMS is to fix the limitation presented for use at ambient temperatures below 20°C, particularly for THC when the car is fueled with E100. The possible solution for this issue would rest in applying thermal isolation on the sampler hose, for reducing the heat exchange and water condensation from the exhaust gas before the dilution head, but it is necessary to do further tests because some care must be taken to not surpass the sensor's operational temperature and humidity ranges.

There is still a margin for saving space required by the low-cost PEMS by shortening the dilution tube and it is possible to add other sensors, such as for NOx and particulate matter. A CO_2 sensor can be interesting for controlling the sample dilution during the RDE tests. As the LCP makes use of ambient air for diluting the exhaust gas sample, and it can influence the results, can be added a second set of sensors for measuring the background pollution, before the dilution head.

One more improvement is about the sensor electronic boards, which are exposed to the gas sample, thus subjected to harsh conditions, such as humidity and particulate matter, that can affect the sensors operation and lifetime, so some kind of protection can be applied, e.g. an epoxy coating in the board.

Other points for future development are the evaluation of the LCP accuracy along the time and usage and the creation of equations for calculating ppm concentration of CO and THC with different fuel mixtures than E22 and E100, where the machining learning concepts could be helpful for this task.

It is also important to have a better comprehension of which compounds form that is defined as THC, and their individual and collective influence on the O_3 formation and the resultant air pollution. Since the electro-catalyst sensor or even a FID results in values that barely reflects the THC composition, an evolution in the speciation of HC compounds from exhaust gas would require more complex and costly instruments, for example, a gas chromatographer or laser spectrometer, but with the advantage that they are able of measure simultaneously a significant range of substances.

The application of the low-cost PEMS in motorcycles also depends on some improvements. As current Brazilian bikes have no standard communication with ECU by OBD connection, it is needed another way to measure the exhaust flow, for example by sensors in the intake manifold for air pressure and temperature, plus speed engine (rpm) and distance, and so calculating the gas flow. It is also neither clear if the sensors can handle the pollutant concentrations produced by motorcycles. Equally, it is important that two- and four-wheel vehicles be evaluated in more comprehensive ambient and traffic conditions.

The difference between EF applied in the CETESB vehicular emissions inventory in comparison to the EF from tunnel measurements has to be better understood. Remote sensing studies probably can shed light on this issue because this method can measure a great number of vehicles in real-world conditions and identify which of them are out of standard.

FINAL CONSIDERATIONS

The initial goal was the use of a state-of-the-art gas analyzer as the core instrument for the PEMS, but the circumstances lead to re-direct the research for the utilization of low-cost sensors. They are easily found in specialized shops for electronic devices and applied in kits for educational proposals and air quality monitoring networks but its use for measuring vehicle emissions was not usual, due to their limited temperature and humidity working ranges, and cross-sensibility for other compounds than those measured.

The low-cost PEMS demonstrated to be reliable and with enough accuracy for academic research, bringing interesting data about vehicle emissions. The system is reproducible, open for being customized, and, depending on further developments, able to be used in other vehicles, e.g. motorcycles.

Although these results, the system was tested in only one vehicle, lacking data from other models, even if the LCP requires adaptations for working in them without issues. It was not studied the stability of the LCP, being presumed that the equations for converting the sensors signal to ppm pollutant concentration are valid over time, not considering a possible deterioration or contamination in the system. The impact of the cold start was briefly evaluated but would be interesting to collect more data on this condition, as well as the influence of heavy traffic congestion on vehicle emissions.

REFERENCES

3D-ATX. **Par SYNC**. 2020. Disponível em: https://3datx.com/parsync/. Acesso em: 25 fev. 2020.

ABDULLAH, Nik Rosli; ISMAIL, Hazimi; MICHAEL, Zeno; RAHIM, Asiah Ab; SHARUDIN, Hazim. Effects of air intake temperature on the fuel consumption and exhaust emissions of natural aspirated gasoline engine. **Jurnal Teknologi**, *[S. l.]*, v. 76, n. 9, p. 25–29, 2015. DOI: 10.11113/jt.v76.5639.

AGARWAL, Avinash Kumar; MUSTAFI, Nirendra Nath. Real-world automotive emissions: Monitoring methodologies, and control measures. **Renewable and Sustainable Energy Reviews**, *[S. l.]*, v. 137, n. May 2020, p. 110624, 2021. DOI: 10.1016/j.rser.2020.110624. Disponível em: https://doi.org/10.1016/j.rser.2020.110624.

AIT-HELAL, W. et al. On-road measurements of NMVOCs and NOx: Determination of light-duty vehicles emission factors from tunnel studies in Brussels city center. **Atmospheric Environment**, *[S. l.]*, v. 122, n. x, p. 799–807, 2015. DOI: 10.1016/j.atmosenv.2015.09.066.

ALVIM, Débora Souza. **Estudo dos Principais Precursores de Ozônio na Região Metropolitana de São Paulo**. 2013. Universidade de São Paulo, Sao Paulo, Brazil, 2013. DOI: 10.11606/T.85.2013.tde-08112013-102012.

ANDRADE, Maria de Fatima et al. Air quality in the megacity of São Paulo: Evolution over the last 30 years and future perspectives. **Atmospheric Environment**, *[S. l.]*, v. 159, p. 66–82, 2017. DOI: 10.1016/j.atmosenv.2017.03.051. Disponível em: https://www.sciencedirect.com/science/article/pii/S1352231017302212.

ANDRADE, Maria de Fatima; YNOUE, Rita Y.; FREITAS, Edmilson Dias; TODESCO, Enzo; VELA, Angel Vara; IBARRA, Sergio; MARTINS, Leila Droprinchinski; MARTINS, Jorge Alberto; CARVALHO, Vanessa Silveira Barreto. Air quality forecasting system for Southeastern Brazil. **Frontiers in Environmental Science**, *[S. l.]*, v. 3, n. FEB, p. 1–14, 2015. DOI: 10.3389/fenvs.2015.00009.

ARCHER, Greg. **Dieselgate: Who? What? How? Transport and Environment**, 2016. Disponível em: https://www.transportenvironment.org/sites/te/files/publications/2016_09_Dieselgate_report_who_what_how_FINAL.pdf. Acesso em: 25 nov. 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, ABNT. **NBR 14008 - Veículos rodoviários automotores leves - Determinação do fator de deterioração das emissões de gases durante**

o acúmulo de rodagem. Rio de Janeiro, Brazil .ABNT - Associação Brasileira de Normas Técnicas, , 2011.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, ABNT. **NBR 10312 - Veiculos rodoviarios automotores leves - Determinação da resistencia ao deslocamento por desaceleração livre em pista de rolamento e simulação em dinamometro**. Rio de Janeiro, Brazil .ABNT - Associação Brasileira de Normas Técnicas, , 2019.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, ABNT. **NBR 6601 - Veiculos rodoviarios automotores leves — Determinação de hidrocarbonetos, monoxido de carbono, oxidos de nitrogénio, dioxido de carbono e material particulado no gas de escapamento**. Rio de Janeiro, Brazil .ABNT - Associação Brasileira de Normas Técnicas, , 2021.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, ABNT. **NBR 17011 - Veículos rodoviários automotores leves — Determinação de gases orgânicos não metano, hidrocarbonetos, monóxido de carbono, óxidos de nitrogênio e dióxido de carbono no gás de escapamento em tráfego real**. Rio de Janeiro, Brazil .ABNT - Associação Brasileira de Normas Técnicas, , 2022.

AVL. **Avl M.O.V.E GAS iS+**. 2022. Disponível em: https://www.avl.com/-/avl-m-o-v-e-is. Acesso em: 26 dez. 2016.

BALDINO, Chelsea; MUNCRIEF, Rachel; KODJAK, Drew. **CAN WE PREVENT ANOTHER PREVENT ANOTHER DIESELGATE?** London, UK, 2017. Disponível em: https://www.fiafoundation.org/connect/publications/can-we-prevent-another-dieselgate.

BORKEN-KLEEFELD, Jens; DALLMANN, Tim. **Remote Sensing of vehicle exhaust emissions**. **International Council on Clean Transportation**Washington DC, USA, 2018. Disponível em: https://www.theicct.org/sites/default/files/publications/Remote-sensing-emissions_ICCT-White-Paper_01022018_vF_updated.pdf. Acesso em: 7 ago. 2018.

BOSCH, Robert. **Automotive Handbook**. 3rd. ed. Düsseldorf, Germany: Robert Bosch Gmbh, 1993.

BOSCH SENSORTECH GMBH. **Datasheet BME280**. Reutlingen, Germany, 2018. Disponível em: https://www.alldatasheet.com/datasheet-pdf/pdf/1132060/BOSCH/BME280.html.

BRAZIL, Ministério de Minas e Energia. **teor de etanol anidro na gasolina**. 2022. Disponível em: https://www.gov.br/mme/pt-br/assuntos/noticias/cnpe-passa-a-ter-competencia-para-fixar-teor-de-etanol-anidro-na-gasolina. Acesso em: 2 nov. 2022.

CALIFORNIA AIR RESOURCES BOARD, CARB. **History**. 2021. Disponível em: https://ww2.arb.ca.gov/about/history. Acesso em: 7 dez. 2021.

CANDIDO, Gradimilo. **Sensor de Gás MQ-135 e a família de sensores MQ**. 2017. Disponível em: https://portal.vidadesilicio.com.br/sensor-de-gas-mq-135/. Acesso em: 8 abr. 2020.

COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, CETESB. **Qualidade do Ar - Histórico**. 2021a. Disponível em: http://ar.cetesb.sp.gov.br/. Acesso em: 22 out. 2021.

COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, CETESB. **Qualidade do ar no Estado de São Paulo 2020**. Sao Paulo, Brazil .CETESB - Companhia Ambiental do Estado de São Paulo, , 2021. b. DOI: ISBN 978-65-5577-018-6. Disponível em: https://cetesb.sp.gov.br/ar/wp-content/uploads/sites/28/2021/05/Relatorio-de-Qualidade-do-Ar-no-Estado-de-Sao-Paulo-2020.pdf.

COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, CETESB. **Emissões veiculares no Estado de São Paulo - Fatores de emissão 2020**. Sao Paulo, BrazilCompanhia Ambiental do Estado de São Paulo, CETESB, , 2022. a. Disponível em: https://cetesb.sp.gov.br/veicular/relatorios-e-publicacoes/.

COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, CETESB. **Emissão veicular**. 2022b. Disponível em: https://cetesb.sp.gov.br/veicular/laboratorio-de-emissao-veicular/. Acesso em: 28 fev. 2022.

COMPANHIA AMBIENTAL DO ESTADO DE SAO PAULO, CETESB. **Procedimento operacional padronizado - pop sq pr/lb-044 execução de correlação interlaboratorial - sq pr/lb-044 1 -**. Sao Paulo, Brazil, 2022. c.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO, CETESB; COORD. ALVES, João Wagner Silva; GONZALEZ; TICIANELLI, Josilene; FERRER, Vannuzini. **1o. Inventário de Emissões Antrópicas de Gases de Efeito Estufa Diretos e Indiretos do Estado de São Paulo**. **Companhia Ambiental do Estado de Sao Paulo**Sao Paulo, Brazil, 2011.

CONSELHO NACIONAL DO MEIO AMBIENTE, CONAMA. RESOLUÇÃO Nº 491, DE 19 DE NOVEMBRO DE 2018 Dispõe sobre padrões de qualidade do ar.Brasilia, Brazil, 2018a. p. 5. Disponível em: https://www.in.gov.br/web/guest/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/51058895/do1-2018-11-21-resolucao-n-491-de-19-de-novembro-de-2018-51058603.

CONSELHO NACIONAL DO MEIO AMBIENTE, CONAMA. Resolucao n. 492 de 20 de dezembro de 2018 - Estabelece as Fases PROCONVE L7 e PROCONVE L8 de exigências do Programa de Controle da Poluição do Ar por Veículos Automotores - PROCONVE para veículos automotores leves novos de uso rodoviário, altera a ResoluBrasilia, Brazil, 2018b. p. 13. Disponível em: http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=742.

CRETESCU, Igor; LUTIC, Doina; MANEA, Liliana Rosemarie. Electrochemical Sensors for Monitoring of Indoor and Outdoor Air Pollution. *In*: M. M. RAHMAN; ASIRI, A. M. (org.). **Electrochemical Sensors Technology**. [s.l.] : IntechOpen, 2017. DOI: 10.5772/intechopen.68512. Disponível em: https://www.intechopen.com/chapters/55305. Acesso em: 13 mar. 2022.

CROSS, Eben S.; WILLIAMS, Leah R.; LEWIS, David K.; MAGOON, Gregory R.; ONASCH, Timothy B.; KAMINSKY, Michael L.; WORSNOP, Douglas R.; JAYNE, John T. Use of electrochemical sensors for measurement of air pollution: Correcting interference response and validating measurements. **Atmospheric Measurement Techniques**, *[S. l.]*, v. 10, n. 9, p. 3575–3588, 2017. DOI: 10.5194/amt-10-3575-2017.

DALLMANN, Timothy R.; DEMARTINI, Steven J.; KIRCHSTETTER, Thomas W.; HERNDON, Scott C.; ONASCH, Timothy B.; WOOD, Ezra C.; HARLEY, Robert A. On-road measurement of gas and particle phase pollutant emission factors for individual heavy-duty diesel trucks. **Environmental Science and Technology**, *[S. l.]*, v. 46, n. 15, p. 8511–8518, 2012. DOI: 10.1021/es301936c.

DARDIOTIS, Christos; MARTINI, Giorgio; MANFREDI, Urbano. **Revision of Low Temperature Emission Standards for Petrol Vehicles**. Ispra, Italy. DOI: 10.2788/30306. Disponível em: https://policycommons.net/artifacts/2162216/revision-of-low-temperature-emission-standards-for-petrol-vehicles/2917715/ on 04 Aug 2022. CID: 20.500.12592/dgc5pn.

DELPHI. **Worldwide emissions standards Passenger Cars and Light Duty Vehicles 2020-21**. , 2020. Disponível em: https://www.delphi.com/sites/default/files/2020-04/DELPHI booklet emission passenger cars 2020 online complet.pdf.

ENGELJEHRINGER, K. Emission trend. *In*: AVL SOUTH AMERICA TECHDAY 2019, **Anais** [...]. [s.l: s.n.] p. 80.

EUROPEAN COMMISSION, EC. REGULATION (EC) No 715/2007 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maiEurope, 2007. Disponível em: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32007R0715.

EUROPEAN COMMISSION, EC. REGULATION (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)Europe, 2016a. p. 98. Disponível em:

http://data.europa.eu/eli/reg/2016/427/oj.

EUROPEAN COMMISSION, EC. REGULAMENTO (UE) 2016/646 DA COMISSÃO de 20 de abril de 2016 que altera o Regulamento (CE) n.692/2008 no que respeita às emissões dos veículos ligeiros de passageiros e comerciais (Euro 6)Europe, 2016b. Seção 2, p. 22. Disponível em: http://data.europa.eu/eli/reg/2016/646/oj.

EUROPEAN COMMISSION, EC. REGULAMENTO (UE) 2017/1154 DA COMISSÃO de 7 de junho de 2017 que altera o Regulamento (UE) 2017/1151 que completa o Regulamento (CE) n. o 715/2007 do Parlamento Europeu e do Conselho relativo à homologação dos veículos a motor no que respeita às emissõesEurope, 2017. p. 643. Disponível em: https://eur-lex.europa.eu/legal-content/PT/LSU/?uri=CELEX:32017R1151.

EUROPEAN COMMISSION, EC. Regulamento 2018/1832 da Comissão. Melhoria dos ensaios e procedimentos de homologação e introdução de dispositivos para monitorar o consumo de combustível e energia elétrica.European Union, 2018. p. 314. Disponível em: https://eur-lex.europa.eu/eli/reg/2018/1832/oj.

EUROPEAN COMMISSION, EC. **CIRCABC: old EMROAD versions**. 2019. Disponível em: https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp?FormPrincipal:_idcl=FormPrincipal:_id1&FormPrincipal_SUBMIT=1&id=217673df-7a0b-48ba-a031-c5494c781d1d&javax.faces.ViewState=rgLlpzwcYKAAo%2BnfzypnPFOJCCbS9gdf0DkXkpirl3N4YbMwInicci. Acesso em: 15 nov. 2019.

EUROPEAN COMMISSION, EC. **Air quality standards**. 2021. DOI: 10.1007/978-1-84882-602-1_4. Disponível em: https://ec.europa.eu/environment/air/quality/standards.htm. Acesso em: 14 out. 2021.

FORCETTO, Andre Luiz Silva; DE SALVO JUNIOR, Orlando; FILHO, Francisco Fernando Maciel; ANDRADE, Maria de Fatima; FILHO, Flavio Guilherme Vaz de Almeida. Improving the assessment of RDE dynamics through vehicle-specific power analysis. **Environmental Science and Pollution Research International**, *[S. l.]*, 2022. DOI: 10.1007/s11356-022-19925-1. Disponível em: https://pubmed.ncbi.nlm.nih.gov/35389170/.

FRANCO, Vicente; POSADA SÁNCHEZ, Francisco; GERMAN, John; MOCK, Peter. Real-world exhaust emissions from modern diesel cars. Part 1: Aggregated results. **ICCT - The International Council on Clean Transportation**, *[S. l.]*, n. October, p. 59, 2014. Disponível em: http://www.theicct.org/sites/default/files/publications/ICCT_PEMS-study_diesel-cars_20141010.pdf.

FREY, H. Christopher; ZHANG, Kaishan; ROUPHAIL, Nagui M. Vehicle-Specific Emissions Modeling Based upon on-Road Measurements. **Environmental Science & Technology**, *[S. l.]*,

v. 44, n. 9, p. 3594–3600, 2010. DOI: 10.1021/es902835h. Disponível em: https://pubs.acs.org/doi/10.1021/es902835h.

GASTEC CORPORATION. **Non-dispersive infrared absortion sensors**. 2022. Disponível em: https://www.gastec.co.jp/en/product/detail/id=2206. Acesso em: 25 mar. 2022.

GERMAN, John. **The emissions test defeat device problem in Europe is not about VW**. 2016. Disponível em: http://www.theicct.org/blogs/staff/emissions-test-defeat-device-problem-europe-not-about-vw. Acesso em: 25 nov. 2016.

GIECHASKIEL, Barouch et al. Implementation of portable emissions measurement systems (PEMS) for the real-driving emissions (RDE) regulation in Europe. **Journal of Visualized Experiments**, *[S. l.]*, v. 2016, n. 118, p. 1–15, 2016. DOI: 10.3791/54753.

GIECHASKIEL, Barouch et al. Effect of extreme temperatures and driving conditions on gaseous pollutants of a euro 6d-temp gasoline vehicle. **Atmosphere**, *[S. l.]*, v. 12, n. 8, 2021. DOI: 10.3390/atmos12081011.

GLOBAL MRV. **Firefly micro-portable emissions measurement/monitoring systems (PEMS)**. 2020. Disponível em: https://www.globalmrv.com/firefly-micro-pems/. Acesso em: 16 abr. 2020.

GONÇALVES, Carlos Henrique Bezerra; ORTEGA, Gustavo Oliveira; SANTOS, Vitor Benício Silva. **SISTEMA ON BOARD DE MONITORAMENTO DE FROTAS**. Santo Andre, Brazil, 2018. Disponível em: http://fatecsantoandre.edu.br/arquivos/TCC/135-Eletronica/135-TCC0027.pdf.

HARANTOVÁ, Veronika; OTÁHALOVÁ, Zuzana; KASANICKÝ, Martin. Estimation of fuel consumption based on data from opening fuel injector valve. **Transportation Research Procedia**, *[S. l.]*, v. 40, p. 236–243, 2019. DOI: 10.1016/j.trpro.2019.07.036. Disponível em: https://doi.org/10.1016/j.trpro.2019.07.036.

HE, H.; YANG, L. **China's stage 6 emission standard for new light-duty vehicles (final rule)**. 2017. Disponível em: https://theicct.org/publications/chinas-stage-6-emission-standard-new-light-duty-vehicles-final-rule. Acesso em: 15 fev. 2021.

HORIBA. **OBS-ONE PEMS**. 2022. Disponível em: https://static.horiba.com/fileadmin/Horiba/Products/Automotive/Emission_Measurement_Systems/OBS-ONE/OBS-ONE_Brochure_English.pdf. Acesso em: 1 ago. 2022.

HUANG, Cheng et al. Evaluation of emission factors for light-duty gasoline vehicles based on chassis dynamometer and tunnel studies in Shanghai, China. **Atmospheric Environment**, *[S. l.]*, v. 169, p. 193–203, 2017. DOI: 10.1016/j.atmosenv.2017.09.020.

IBARRA-ESPINOSA, Sergio. **Air pollution modeling in São Paulo using bottom-up vehicular emissions inventories**. Sao Paulo, Brazil, 2017. Disponível em: https://www.teses.usp.br/teses/disponiveis/14/14133/tde-29052018-140319/publico/t_sergio_a_i_espinosa_corrigida.pdf.

IBARRA-ESPINOSA, Sergio; YNOUE, Rita Yuri; ROPKINS, Karl; ZHANG, Xuelei; DE FREITAS, Edmilson Dias. High spatial and temporal resolution vehicular emissions in south-east Brazil with traffic data from real-time GPS and travel demand models. **Atmospheric Environment**, *[S. l.]*, v. 222, n. November 2019, p. 117136, 2020. DOI: 10.1016/j.atmosenv.2019.117136. Disponível em: https://doi.org/10.1016/j.atmosenv.2019.117136.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, IBGE. **ESTIMATIVAS DA POPULAÇÃO RESIDENTE NOS MUNICÍPIOS BRASILEIROS**. 2021. Disponível em: https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao?=&t=resultados. Acesso em: 11 out. 2021.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICAS, IBGE. **Estatísticas 2022: pesquisa frota veículos**. 2022. Disponível em: https://cidades.ibge.gov.br/brasil/pesquisa/22/28120?localidade1=35&ano=2021. Acesso em: 9 jul. 2022.

INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS, IBAMA. **PROCONVE - Programa de controle da poluição do ar por veículos automotores**. Brasilia, 2011. Disponível em: http://www.ibama.gov.br/phocadownload/veiculosautomotores/manual proconve promot_portugues.pdf.

INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS RENOVÁVEIS, IBAMA. Instrução Normativa Ibama Nº 11 de 25/07/2014**Diário Oficial da União, Brazil**, Brasilia, Brazil, 2014. p. 2. Disponível em: http://www.ibama.gov.br/component/legislacao/?view=legislacao&legislacao=133670.

JACOBSON, Mark Z. **Atmospheric Pollution: History, Science and Regulation**. Cambridge, UK: CAMBRIDGE UNIVERSITY PRESS, 2002. DOI: 10.1017/CBO9780511802287.

JAMRISKA, Milan; MORAWSKA, Lidia; THOMAS, Steven; HE, Congrong. Diesel bus emissions measured in a tunnel study. **Environmental Science and Technology**, *[S. l.]*, v. 38, n. 24, p. 6701–6709, 2004. DOI: 10.1021/es030662z.

JIMÉNEZ-PALACIOS, José Luis. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. **Massachusetts Institute of Technology, Cambridge**, *[S. l.]*, n. 1993, p. 361, 1999.

KADIJK, Gerrit; LIGTERINK, Norbert; MENSCH, Pim Van; SMOKERS, Richard. **NOx emissions of Euro 5 and Euro 6 diesel passenger cars-test results in the lab and on the road**. Delft, The Netherlands, 2016. Disponível em: https://www.researchgate.net/publication/308201738.

KHAN, T.; FREY, H. C. Evaluation of Light-Duty Gasoline Vehicle Rated Fuel Economy Based on In-Use Measurements. **Journal of the Transportation Research Board**, *[S. l.]*, n. 2570, p. 21–29, 2016. DOI: 10.3141/2570-03.

KHAN, T.; FREY, H. C. Comparison of real-world and certification emission rates for light duty gasoline vehicles. **Science of The Total Environment**, *[S. l.]*, v. 622–623, n. December, p. 790–800, 2018. DOI: 10.1016/j.scitotenv.2017.10.286. Disponível em: https://doi.org/10.1016/j.scitotenv.2017.10.286.

KOUPAL, John; CUMBERWORTH, Mitch; MICHAELS, Harvey; BEARDSLEY, Megan; BRZEZINSKI, David. Design and Implementation of MOVES: EPA's New Generation Mobile Source Emission Model. *In*: 12TH INTERNATIONAL EMISSION INVENTORY CONFERENCE - "EMISSION INVENTORIES - APPLYING NEW TECHNOLOGIES" 2003, San Diego, USA. **Anais** [...]. San Diego, USA: U.S. Environmental Protection Agency, 2003. p. 15. Disponível em: https://www3.epa.gov/ttnchie1/conference/ei12/mobile/koupal.pdf.

KUMAR, Prashant; MORAWSKA, Lidia; MARTANI, Claudio; BISKOS, George; NEOPHYTOU, Marina; DI SABATINO, Silvana; BELL, Margaret; NORFORD, Leslie; BRITTER, Rex. The rise of low-cost sensing for managing air pollution in cities. **Environment International**, *[S. l.]*, v. 75, p. 199–205, 2015. DOI: 10.1016/j.envint.2014.11.019.

LASKOWSKI, Piotr; ZASINA, Damian; ZIMAKOWSKA-LASKOWSKA, Magdalena; ORLIŃSKI, Piotr. Modelling Hydrocarbons Cold-start Emission from Passenger Cars. **Advances in Science and Technology Research Journal**, *[S. l.]*, v. 15, n. 3, p. 117–125, 2021. DOI: 10.12913/22998624/138764.

LEATHERMAN, Jordan Matthew. **Comparison of emissions measurement between a sensor-based compact emissions meter and a standard PEMS**. Morgantown, USA, 2018. DOI: https://doi.org/10.33915/etd.3683. Disponível em: https://researchrepository.wvu.edu/etd/3683.

MACDONELL, Margaret; RAYMOND, Michelle; WYKER, David; FINSTER, Molly; CHANG, Young-soo; RAYMOND, Thomas; TEMPLE, Bianca; SCOFIELD, Marcienne. **RESEARCH AND DEVELOPMENT HIGHLIGHTS : MOBILE SENSORS AND APPLICATIONS Prepared by**. Argonne, USA, 2013. Disponível em: https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=518291&Lab=NERL.

MANZOLI, Anderson. **Análise das emissões veiculares em trajetos urbanos curtos com localização por gps**. Sao Carlos, Brazil, 2009. DOI: 10.11606/T.18.2009.tde-26052009-170127. Disponível em: https://teses.usp.br/teses/disponiveis/18/18143/tde-26052009-170127/pt-br.php.

MARTIN, Randal S.; WOODS, Clay; THOMAS, Joe. **Assessment of Automobile Start and Idling Emissions under Utah Specific Conditions: Cold Start, Hot Start, and Idle Emissions as Measured on Northern Utah Vehicles**. **Project Final Report**Logan, USA, 2017. Disponível em: https://documents.deq.utah.gov/air-quality/technical-analysis/DAQ-2017-011068.pdf.

MARTINHO, João Ricardo Morgado. **Estudo da aplicabilidade de sensores de baixo custo para monitorização de dióxido de azoto no ar ambiente**. 2014. Instituto Superior Politécnico de Viseu, Viseu, Portugal, 2014.

MARTINS, L. D. **Sensibilidade da formação do ozônio troposférico às emissões veiculares na Região Metropolitana de São Paulo**. 2006. Universidade de São Paulo, *[S. l.]*, 2006. DOI: 10.11606/T.14.2007.tde-02062007-162434. Disponível em: https://www.teses.usp.br/teses/disponiveis/14/14133/tde-02062007-162434/pt-br.php.

MAY, J.; BOSTEELS, D.; FAVRE, C. An assessment of emissions from light-duty vehicles using PEMS and chassis dynamometer testing. **SAE International Journal of Engines**, *[S. l.]*, v. 7, n. 3, p. 10, 2014. DOI: 10.4271/2014-01-1581. Disponível em: www.aecc.eu/wp-content/uploads/2016/08/2014-01-1581.pdf%0A.

MILLER, Josh; FRANCO, Vicente. **Impact of Improved Regulation of Real-World NOx Emissions From Diesel Passenger Cars in the EU, 2015-2030**. **ICCT - The International Council on Clean Transportation**Washington DC, USA, 2016. Disponível em: https://theicct.org/publications/impact-improved-regulation-real-world-nox-emissions-diesel-passenger-cars-eu-2015−2030.

MOREIRA, Raphael Garcia. **SENSORIAMENTO DE MISTURAS DE H2, CH4 E CO POR MEIO DE UMA MATRIZ DE QUIMIORESISTORES**. 2014. Universidade de São Paulo, *[S. l.]*, 2014. DOI: 10.11606/D.3.2014.tde-13102014-150854. Disponível em: https://www.teses.usp.br/teses/disponiveis/3/3140/tde-13102014-150854/en.php.

NGK SPARK PLUG CO. **NCEM NTK Compact Emissions Meter**. 2020. Disponível em: https://www.ntk-ncem.com/en/. Acesso em: 21 jun. 2020.

NOGUEIRA, Thiago et al. Evolution of Vehicle Emission Factors in a Megacity Affected by

Extensive Biofuel Use: Results of Tunnel Measurements in São Paulo, Brazil. **Environmental Science & Technology**, *[S. l.]*, p. 6677–6687, 2021. DOI: 10.1021/acs.est.1c01006.

NTZIACHRISTOS, Leonidas; GKATZOFLIAS, Dimitrios; KOURIDIS, Chariton; SAMARAS, Zissis. COPERT: A European Road Transport Emission Inventory Model. **Information Technologies in Environmental Engineering**, *[S. l.]*, p. 491–504, 2009. DOI: 10.1007/978-3-540-88351-7. Disponível em: http://apps.isiknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=1&SID=S1jFL1GGc8M4MbMK9AG&page=1&doc=15.

OECD/EUROPEAN COMMISSION. The growth of metropolitan areas. *In*: **Cities in the world - a new persperctive on urbanization**. Paris: OECD Publishing, 2020. p. 111–137. DOI: https://doi.org/10.1787/9b73e35d-en. Disponível em: https://www.oecd-ilibrary.org/urban-rural-and-regional-development/cities-in-the-world_d0efcbda-en.

ORLANDO, João Paulo; ALVIM, Débora Souza; YAMAZAKI, Amélia; CORRÊA, Sergio Machado; GATTI, Luciana Vanni. Ozone precursors for the São Paulo Metropolitan Area. **Science of the Total Environment**, *[S. l.]*, v. 408, n. 7, p. 1612–1620, 2010. DOI: 10.1016/j.scitotenv.2009.11.060.

PENZA, Michele. Perspectives and Challenges for Real Applications. *In*: U.S. EPA AIR SENSORS 2018 2018, Durham, USA. **Anais** [...]. Durham, USA p. 35. Disponível em: https://www.epa.gov/sites/production/files/2020-02/documents/session_01_d_penza.pdf.

PEREIRA, THALITA NAYARA DA CUNHA. **VILA CARIOCA, DOS ANOS 20 À ATUALIDADE: UM ESTUDO DA CONTAMINAÇÃO DO SOLO NA CIDADE DE SÃO PAULO**. 2012. UNIVERSIDADE PRESBITERIANA MACKENZIE, *[S. l.]*, 2012. Disponível em: https://dspace.mackenzie.br/handle/10899/25929.

PETROBRAS. **Preços de Venda de Combustíveis**. 2021. Disponível em: https://petrobras.com.br/pt/nossas-atividades/precos-de-venda-de-combustiveis/%0A. Acesso em: 4 nov. 2021.

PINHO, M. **São Paulo bate a marca de 8 milhões de veículos**. 2015. Disponível em: https://g1.globo.com/sao-paulo/noticia/2015/05/sao-paulo-bate-marca-de-8-milhoes-de-veiculos.html. Acesso em: 7 jun. 2022.

POURESMAEILI, M. A.; AGHAYAN, I.; TAGHIZADEH, S. A. Development of Mashhad driving cycle for passenger car to model vehicle exhaust emissions calibrated using on-board measurements. **Sustainable Cities and Society**, *[S. l.]*, v. 36, p. 12–20, 2018. DOI: 10.1016/j.scs.2017.09.034. Disponível em: https://www.sciencedirect.com/science/article/abs/pii/S221067071730728X?via%3Dihub.

POWVER. **Real Driving Emissions**. 2020. Disponível em: https://www.powver.org/real-driving-emissions/. Acesso em: 16 abr. 2020.

REITENBACH, AMANDA. **Desenvolvimento de nariz eletrônico para detecção de compostos voláteis na cerveja**. 2016. Universidade Federal de Santa Catarina, Florianopolis, Brazil, 2016. Disponível em: https://repositorio.ufsc.br/xmlui/bitstream/handle/123456789/176718/345553.pdf?sequence=1&isAllowed=y.

ROZEN, Marcos. **40 curiosidade do VW Gol em seus 40 anos de história**. 2020. Disponível em: https://autoesporte.globo.com/carros/colunistas/post-coluna/2020/05/40-curiosidades-do-vw-gol-em-seus-40-anos-de-historia.ghtml. Acesso em: 20 abr. 2022.

SALVO, Alberto; HUSE, Cristian. Build it, but will they come? Evidence from consumer choice between gasoline and sugarcane ethanol. **Journal of Environmental Economics and Management**, *[S. l.]*, v. 66, n. 2, p. 251–279, 2013. DOI: 10.1016/j.jeem.2013.04.001. Disponível em: http://dx.doi.org/10.1016/j.jeem.2013.04.001.

SCHULTZ, Martin G. et al. Tropospheric Ozone Assessment Report: Database and metrics data of global surface ozone observations. **Elementa**, *[S. l.]*, v. 5, 2017. DOI: 10.1525/elementa.244.

SCHWEHR, Beth. **Definitions of VOC and ROG Last Revised January 2009**. 2009. Disponível em: https://www.arb.ca.gov/ei/speciate/voc_rog_dfn_1_09.pdf. Acesso em: 1 dez. 2021.

SICILIANO, Bruno; DA SILVA, Cleyton Martins; LOUREIRO, Luciana N.; VICENTINI, Pedro C.; ARBILLA, Graciela. Hydrocarbon emissions in flex fuel vehicles using ethanol: Preliminary results using a method implemented in Brazil. **Fuel**, *[S. l.]*, v. 287, n. October 2020, p. 119506, 2021. DOI: 10.1016/j.fuel.2020.119506. Disponível em: https://doi.org/10.1016/j.fuel.2020.119506.

SMITH, Anthony. Getting “real” about emissions testing. **Ricardo Quartely Review Q42015**, West Sussex, UK, p. 16–21, 2015.

TAKAI, S.; ISHII, H. Vehicle compliance programs in Japan. *In*: US EPA COMPLIANCE SUMMIT 2016, Michigan, USA. **Anais** [...]. Michigan, USA p. 26.

THOMPSON, Gregory J.; CARDER, Daniel K.; BESCH, Marc C.; THIRUVENGADAM, Arvind; KAPPANNA, Hemanth K. **In-use emissions testing of light-duty diesel vehicles in the U.S. | International Council on Clean Transportation**. Morgantown WV, USA. Disponível em: http://www.theicct.org/use-emissions-testing-light-duty-diesel-vehicles-us.

TUTUIANU, Monica; MAROTTA, Alessandro; STEVEN, Heinz; ERICSSON, Eva; HANIU, Takahiro; ICHIKAWA, Noriyuki; ISHII, Hajime. **Development of a World-wide Worldwide harmonized Light duty driving Test Cycle (WLTC)**. Geneva, Belgium, 2014. Disponível em: https://www.unece.org/fileadmin/DAM/trans/doc/2014/wp29grpe/GRPE-68-03e.pdf.

U-BLOX. **U-blox NEO-6 GPS modules**. Thalwil, Switzerland, 2011. Disponível em: https://content.u-blox.com/sites/default/files/products/documents/NEO-6_DataSheet_%28GPS.G6-HW-09005%29.pdf.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Methodology for developing modal emission rates for EPA's multi-scale motor vehicle & equipment emission system**. **United States Environmental Protection Agency, U.S. EPA**Raleigh, USAAssessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, , 2002. Disponível em: http://permanent.access.gpo.gov/lps71724/420r02027.pdf.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Volkswagen Violations - Learn About Volkswagen Violations**. 2016a. Disponível em: https://www.epa.gov/vw/learn-about-volkswagen-violations. Acesso em: 30 nov. 2016.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. 40 CFR § 86.109–94United States of America, USA, 2016b. p. 632–641. Disponível em: https://www.govinfo.gov/app/details/CFR-2016-title40-vol21/CFR-2016-title40-vol21-sec86-109-94/context.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Criteria Air Pollutants**. 2021a. Disponível em: https://www.epa.gov/criteria-air-pollutants. Acesso em: 26 nov. 2021.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Ecosystem Effects of Ozone Pollution. Ground-level Ozone Pollution**. 2021b. Disponível em: https://www.epa.gov/ground-level-ozone-pollution/ecosystem-effects-ozone-pollution. Acesso em: 21 nov. 2021.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Sulfur Dioxide Basics**. 2021c. Disponível em: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects. Acesso em: 26 nov. 2021.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Nitrogen Dioxide (NO2) Pollution**. 2021d. Disponível em: https://www.epa.gov/no2-pollution/basic-information-about-no2#What is NO2. Acesso em: 26 nov. 2021.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. Chapter 2: Characterizing Ozone and Modeling Tools Used in This Analysis. *In*: **Final Ozone NAAQS Regulatory Impact Analysis**. EPA-452/R- ed. Research Triangle Park, USA: U.S. Government Publishing Office, 2021. e. p.

11. Disponível em: https://www3.epa.gov/ttnecas1/regdata/RIAs/2-ozoneriachapter2.pdf.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **NAAQS Table**. 2021f. Disponível em: https://www.epa.gov/criteria-air-pollutants/naaqs-table. Acesso em: 14 out. 2021.

U.S. ENVIRONMENTAL PROTECTION AGENCY, U. S. EPA. **Air Pollutants sources**. 2022. Disponível em: https://www3.epa.gov/airtoxics/pollsour.html. Acesso em: 8 jul. 2022.

UNECE, Economic Commission for Europe. **Proposal for a new UN Regulation on uniform provisions concerning the approval of light duty passenger and commercial vehicles with regards to real driving emissions (RDE)**. Geneva, 2020. Disponível em: https://unece.org/DAM/trans/doc/2020/wp29grpe/ECE-TRANS-WP29-GRPE-2020-15e.pdf.

VARELLA, R. A.; FARIA, M. V; MENDOZA-VILLAFUERTE, P.; BAPTISTA, P. C.; SOUSA, L.; DUARTE, G. O. Assessing the influence of boundary conditions , driving behavior and data analysis methods on real driving CO2 and NOx emissions. **Science of the Total Environment**, *[S. l.]*, v. 658, p. 879–894, 2019. DOI: 10.1016/j.scitotenv.2018.12.053. Disponível em: https://doi.org/10.1016/j.scitotenv.2018.12.053.

VELA, Ángel Liduvino Vara. **Avaliação do impacto da mudança dos fatores de emissão veicular na formação de ozônio troposférico na Região Metropolitana de São Paulo (RMSP)**. Sao Paulo, Brazil, 2013. DOI: 10.11606/D.14.2019.tde-26022019-100407. Disponível em: https://www.teses.usp.br/teses/disponiveis/14/14133/tde-26022019-100407/pt-br.php.

VOJTISEK-LOM, Michal; JAMES T COBB, Jr. Vehicle mass emissions measurement using a portable 5-gas exhaust analyzer and engine computer data. **Proceedings of Emission Inventory: Planning for the Future Conference Air & Waste Manage- ment Association Pittsburgh, PA (USA)**, *[S. l.]*, n. November, p. 656–669, 1997. Disponível em: https://www.researchgate.net/profile/Michal_Vojtisek-Lom/publication/240393978_Vehicle_Mass_Emissions_Measurement_using_a_Portable_5Gas_Exhaust_Analyzer_and_Engine_Computer_Data/links/54a26ade0cf256bf8baf9102/Vehicle-Mass-Emissions-Measurement-using-a-Por.

VOJTISEK-LOM, Michal; ZARDINI, Alessandro A.; PECHOUT, Martin; DITTRICH, Lubos; FORNI, Fausto; MONTIGNY, Francois; CARRIERO, Massimo; GIECHASKIEL, Barouch; MARTINI, Giorgio. A miniature Portable Emissions Measurement System (PEMS) for real-driving monitoring of motorcycles. **Atmospheric Measurement Techniques**, *[S. l.]*, v. 13, n. 11, p. 5827–5843, 2020. DOI: 10.5194/amt-13-5827-2020.

WEISS, Martin.; BONNEL, Pierre; HUMMEL, Rudolf; MANFREDI, Urbano; COLOMBO, Rinaldo; LANAPPE, Gaston; LIJOUR, Philippe Le; SCULATI, Mirco. **Analyzing on-road emissions of**

light-duty vehicles with portable emission measurement systems (PEMS). **JRC Scientific and Technical Reports**Ispra, Italy, 2011. DOI: 10.2788/23820.

WORLD HEALTH ORGANIZATION, WHO. **Health Impact**. 2021a. Disponível em: https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/health-impacts. Acesso em: 25 nov. 2021.

WORLD HEALTH ORGANIZATION, WHO. **WHO global air quality guidelines - particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide**. (World Health Organization WHO, Org.)Geneva, Belgium, 2021. b. Disponível em: https://creativecommons.org/licenses/by-nc-sa/3.0/igo).

WWW.ALPHABET.COM. **From NEDC to WLTP**. 2019. Disponível em: https://www.alphabet.com/en-ww/wltp. Acesso em: 16 dez. 2019.

WWW.BRITANNICA.COM. **Perfect gas law**. 2022. Disponível em: https://www.britannica.com/science/perfect-gas-law. Acesso em: 7 abr. 2022.

WWW.DIESELNET.COM. **Emission Test Cycles FTP-75**. 2019. Disponível em: https://dieselnet.com/standards/cycles/ftp75.php%0Ahttps://www.dieselnet.com/standards/cycles/ftp75.php. Acesso em: 16 dez. 2019.

WWW.LABDEGARAGEM.COM. **Como diminuir ruídos na porta analógica Arduino**. 2021. Disponível em: https://labdegaragem.com/forum/topics/como-diminuir-ru-dos-na-porta-anal-gica-arduino. Acesso em: 28 fev. 2021.

ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD. **Flammable Gas Sensor MQ-6**. Zhengzhou, China, 2015. a. Disponível em: https://www.winsen-sensor.com/d/files/semiconductor/mq-6.pdf%0A.

ZHENGZHOU WINSEN ELECTRONICS TECHNOLOGY CO. LTD. **Electrochemical CO Module ZE07-CO**. Zhengzhou, China, 2015. b. Disponível em: https://www.winsen-sensor.com/d/files/PDF/Gas Sensor Module/CO Detection Module/ZE07 CO Module 1.3V.pdf.

APPENDIX 1 – PROGRAMS: RASPBERRY

It is the program developed for running in the Raspberry, wrote in Python (comments in Portughese):

```
#####  OBSERVACOES: - PROGRAMA COM THREADS
#               - GPS Ublox M8 COM GPSD
#               - OBD com ELM327
#               - Analisador Arduino LOW COST
print ('LOG DE DADOS - VERSAO FINAL')
print ('COM THREADS + GPSD + SENSOR CO WINSEN + HC MQ4 E MQ6')
print ('VALORES DE THC, CO E CH4: LEITURA DIRETA DO ARDUINO MQ4, WINSEN E MQ6')
import serial           # permite comunicacao serial
from gps import *    # carrega o modulo de gps
import time             # acessa dados de hora do sistema
import obd              # conecta com a OBD
from obd import ECU       # funcao para acessar dados de ECU
import re               # conversor de string para inteiro
import threading    # procesamento em paralelo
import csv              # acessa arquivos *.csv

#### PARAMETROS "FIXOS"
# CALCULO DE VAZAO E EMISSAO DE CO2
cil=1000                # Deslocamento volumetrico (CILINDRADA) [cm3]
Rv=0.91                 # Rendimento volumetrico do motor (era 0.94)
RE_E22=13.32            # Razao estequimetrica da gasolina E22
Uco2_E22=0.001522  # Fator Ugas para CO2 com E22
Cco2_E22=1.34e5      # Concentracao de CO2 no escape para E22

#### ZERA OS PARAMETROS PARA MONTAGEM DA LINHA DE DADOS *.csv
# Parametro       Coluna - Descricao [unidade] - observacoes
```

```
TIME=0          #  A   Contador de tempo [s]
THC=0           #  B   THC [ppm] - ARDUINO
CO=0            #  C   CO [ppm] - ARDUINO
D=0             #  D   NOx - vazio (zero)
E=0             #  E   NO - vazio (zero)
F=0             #  F   NO2 - vazio (zero)
CO2=0           #  G   CO2 [ppm] - AGORA: CALCULADO
CH4=0           #  H   CH4 [ppm] - ARDUINO
I=0             #  I   O2 - vazio (zero)
J=0             #  J   Soot – vazio (zero)
K=0             #  K   CH4 - vazio (zero)
L=0             #  L   PN - vazio (zero)
Qm_ex=0         #  M   Vazao de escape [kg/h] - kg/s*3600
N=0             #  N   Temperatura do gas de escape - vazio (zero)
TAMB=0          #  0   Temperatura ambiente [oC]
PAMB=0          #  P   Pressao do ar ambiente [mbar] - 1 kPA * 10 = mbar
Q=0             #  Q   Torque - vazio (zero)
RPM=0           #  R   Rotacao do motor [rpm]
S=0             #  S   Fuel rate - vazio (zero) - varios carros nao tem este dado
CLT=0           #  T   Temperatura da agua do motor [oC]
IAT=0           #  U   Temperatura do ar na admissao [oC]
SPD_ECU=0       #  V   Velocidade na ECU [km/h]
SPD_GPS=0       #  W   Velocidade no GPS [km/h]
LAT=0           #  X   GPS - Latitude [deg]
LNG=0           #  Y   GPS - Longitude [deg]
ALT=0           #  Z   GPS - Altitude [deg]
SAT=0           # AA   Numero satelites [#]
UR=50           # AB   Umidade relativa do ar [%]
AC=0            # AC   Engine load - vazio (zero)
AD=0            # AD   Invalid flag - vazio (zero)
AE=0            # AE   PN_d - vazio (zero)
# PARAMETROS 'EXTRAS' COM DADOS DO ARDUINO
```

```
TSENS=0;PSENS=0;URSENS=0;THC_ard=0;CO_ard=0;CH4_ard=0
# PORCENTAGEM DE ETANOL MEDIDO PELA ECU
ETR=0
# PARAMETROS UTILIZADOS DENTRO DO LACO DO GPS
LAST_LAT=LAT; LAST_LNG=LNG; F_Lambda=1
### FIM DOS PARAMETROS

#### CONEXOES
# ARDUINO
arduino = serial.Serial('/dev/ttyACM0',9600)
# GPS Ublox M8
gpsd = gps(mode=WATCH_ENABLE) #starting the stream of info
# OBD ELM327
obd_connect = obd.OBD('/dev/ttyUSB1',protocol=None,timeout=0.5)     # conecta com a saída USB
  #print(connection.protocol_name())      # Identifica o protocolo de comunicação com o OBD
### FIM DAS CONEXOES

#### INICIA A CONTAGEM DE TEMPO
TIME_START=time.time()   # Dá o valor inicial de tempo

#### COLETA DOS DADOS DO ARDUINO
def Arduino_data():
  global ard_data,THC,CO,CH4,THC_ard,CO_ard,CH4_ard,CO_ard,TSENS,PSENS,URSENS
  ard_read = arduino.readline()
  ard_data = ard_read.decode ('utf-8','ignore')
  ard_data = ard_data.split(",")
  # THC
  THC_ard=float(ard_data[2])
  THC=THC_ard
  # CO
```

```
    CO_ard=float(ard_data[1])
    CO=CO_ard
    # CH4
    CH4_ard=float(ard_data[0])
    CH4=CH4_ard
    # TEMPERATURA, PRESSAO, UMIDADE NOS SENSORES
    TSENS=round(float(ard_data[3]),0)
    PSENS=round(float(ard_data[4]),0)
    URSENS=round(float(ard_data[5]),0)
#### FIM DA def DO ARDUINO

#### COLETA DOS DADOS DE GPS
def GPS_data():
    global gpsd,LAT,LNG,ALT,SPD_GPS
    gpsd.next() # REQUISITA OS DADOS ATUALIZADOS DO GPS
    LAT = gpsd.fix.latitude
    LNG = gpsd.fix.longitude
    ALT = gpsd.fix.altitude
    SPD_GPS = round((gpsd.fix.speed)*3.6, 2)   # VELOCIDADE EM M/S, TRANSF PARA KM/H
#### FIM DA def DO GPS

#### COLETA DE DADOS DO OBD
def OBD_data():
# "GLOBAL" PERMITE LER AS VARIAVEIS FORA DA FUNÇÃO def
    global CO2,Qm_ex,TAMB,PAMB,RPM,CLT,IAT,SPD_ECU,F_Lambda,ETR
# LEITURA DA OBD
# Temperatura do ar ambiente
    TAMB_obd=obd_connect.query(obd.commands.AMBIANT_AIR_TEMP,force=True)
    TAMB=float(re.sub('[^0-9-.]','',str(TAMB_obd.value)))
# Pressão do ar ambiente
    AMBIANT_AIR_PRESS=obd.commands[1][51]
    PAMB_obd=obd_connect.query(AMBIANT_AIR_PRESS,force=True)
```

```
   PAMB=float(re.sub('[^0-9-.]','',str(PAMB_obd.value)))
# RPM
   RPM_obd=obd_connect.query(obd.commands.RPM,force=True)  #  Solicita o valor da OBD
- retorna como string
   RPM=float(re.sub('[^0-9-.]','',str(RPM_obd.value)))          # Recorta o valor do string e
transforma em numero
# Temperatura da agua do motor
   CLT_obd=obd_connect.query(obd.commands.COOLANT_TEMP,force=True)
   CLT=float(re.sub('[^0-9-.]','',str(CLT_obd.value)))
# Temperatura do ar de admissao
   IAT_obd=obd_connect.query(obd.commands.INTAKE_TEMP,force=True)
   IAT=float(re.sub('[^0-9-.]','',str(IAT_obd.value)))
# Velocidade do veiculo pela ECU
   SPD_obd=obd_connect.query(obd.commands.SPEED,force=True)
   SPD_ECU=float(re.sub('[^0-9-.]','',str(SPD_obd.value)))
# Pressao do ar de admissao
   IAP_obd=obd_connect.query(obd.commands.INTAKE_PRESSURE,force=True)
   IAP=float(re.sub('[^0-9-.]','',str(IAP_obd.value)))
# Fator Lambda
   fator_lambda=obd.commands[1][68]
   F_Lambda_obd=obd_connect.query(fator_lambda,force=True)
   F_Lambda=round(float(re.sub('[^0-9-.]','',str(F_Lambda_obd.value))),3)
# Porcentagem de etanol no combustivel
   ETR_obd=obd_connect.query(obd.commands.ETHANOL_PERCENT,force=True)
   ETR=round(float(re.sub('[^0-9-.]','',str(ETR_obd.value))),1)
# CALCULOS
# CALCULO DA VAZAO MASSICA DO ESCAPE  Qm_ex [kg/s]
   Qm_ex=(29.15e-9*IAP*cil*RPM*Rv/(IAT+273.15))*(1+(1/(F_Lambda*(RE_E22-
0.0555*(ETR-22)))))
# CALCULO DA MASSA DE CO2 m_co2 [g/s]
   if F_Lambda < 1.5:
      ### FATOR 0.96 PARA CORRIGIR O CALCULO E CORRELACIONAR COM O DINAMOMETRO
```

```
        CO2=0.96*(Cco2_E22-(243.59*(ETR-22)))  # Concentracao de CO2 no escape em ppm
        CO2=round(CO2,2)
    if F_Lambda > 1.5:
        CO2=0
#### FIM DO OBD

####  LOG DE DADOS
def Save_data():
# "GLOBAL" PERMITE LER AS VARIAVEIS FORA DA FUNÇÃO def
    global TIME,Log_dados,Qm_ex,PAMB,ETR
# CONCLUI ESTA PARTE DO PGM E GRAVA O TEMPO GASTO
    TIME=round((time.time()-TIME_START),0)     #  DESCARTA A PARTE DECIMAL
# ACERTO DE UNIDADES
    Qm_ex=round(Qm_ex*3600,2)                 #  Converte a Qm_ex de kg/s para kg/h
    PAMB=PAMB*10                              #  Converte a PAMB de kPa para mbar
# MONTA A FRASE *.csv PARA LOG DE DADOS

Log_dados=(TIME,THC,CO,D,E,F,CO2,CH4,I,J,K,L,Qm_ex,N,TAMB,PAMB,Q,RPM,S,CLT,IAT,SPD
_ECU,SPD_GPS,LAT,LNG,ALT,SAT,UR,AC,AD,AE,F_Lambda,THC_ard,CO_ard,CH4_ard,TSENS,P
SENS,URSENS,ETR)
# GRAVA OS DADOS NO ARQUIVO DE LOG
    with open ('/home/pi/Desktop/TESTE_PEMS/Log_dados_PEMS.csv','a',newline='') as
csv_file:
        writer=csv.writer(csv_file, dialect='excel', delimiter=',', quoting=csv.QUOTE_ALL)
        writer.writerow(Log_dados)
####  FIM DO LOG DE DADOS ####

#### SEPARACAO DOS PROCESSOS
def Client_hand1():
    # "GLOBAL" PERMITE LER AS VARIAVEIS FORA DA FUNÇÃO def
```

```
    global
C_CO2,Qm_ex,TAMB,PAMB,RPM,CLT,IAT,SPD_ECU,obd_connect,ard_data,THC,CO,ETANOL,
CH4,THC_ard,CH4_ard,CO_ard,TSENS,PSENS,URSENS
# ACESSO AO ARDUINO
# ACESSO AO OBD
    while True:
        OBD_data()
        Arduino_data()
#       time.sleep(0.1)
def Client_hand2():
# ACESSO AO GPS
    global LAT,LNG,LAST_LAT,LAST_LNG
    while True:
# PUXA OS DADOS DO GPS
        GPS_data()
        for x in range(8):
            if LAST_LAT == LAT and LAST_LNG == LNG:
                GPS_data()
        LAST_LAT = LAT
        LAST_LNG = LNG

# LOG DE DADOS
def Client_hand3():
# "GLOBAL" PERMITE LER AS VARIAVEIS FORA DA FUNÇÃO def
    global TIME_INI
    while True:
# MARCA O INICIO DA CONTAGEM DE TEMPO DESSA PARTE DO PGM
        TIME_INI=time.time()-TIME_START
        Save_data()
        print(Log_dados)
#  CÁLCULO DO TEMPO GASTO NO LACO
        TIME_END=time.time()-TIME_START
```

```
#  FAZ A PAUSA PARA COMPLETAR 1 Hz
    WAIT=(TIME_END-TIME_INI)
    while(WAIT)<0.915: # NAO E' 1.000 PORQUE TEM O TEMPO DE PROCESSAMENTO
      time.sleep(0.09)
      WAIT=WAIT+0.09

#### DEFINE THREADS
t1=threading.Thread(target=Client_hand1)
t2=threading.Thread(target=Client_hand2)
t3=threading.Thread(target=Client_hand3)
# RODA AS THREADS
t1.start()
t2.start()
t3.start()
# UNIFICA O FIM DO PROCESSAMENTO
t1.join()
t2.join()
t3.join()
```

APPENDIX 2 – PROGRAMS: ARDUINO

This is the program running in the Arduino Leonardo device, wrote in C++ (comments in Portughese):

```
// versao para MQ4, CO Winsen, MQ6 e BMP
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BME280.h>
#define SEALEVELPRESSURE_HPA (1013.25)

Adafruit_BME280 bme;

// DEFINE A PINAGEM DOS SENSORES
int MQ4 = A0;//
// int A1 = A1;// PINO GND
int CO = A2;//
// int A3 = A3;// PINO GND
int MQ6 = A4;//
// int A5 = A5;// PINO GND
int sensorThres = 10000;// verificar se o limite dos sensores e' suficiente

void setup() {
  // DEFINE OS PINOS COMO ENTRADA
  pinMode(MQ4, INPUT);
//  pinMode(A1, INPUT); PINO GND
  pinMode(CO, INPUT);
//  pinMode(A3, INPUT); PINO GND
  pinMode(MQ6, INPUT);
//  pinMode(A5, INPUT); PINO GND
  // ATIVA A LEITURA SERIAL DO SENSOR BME
  Serial.begin(9600);
```

```
  if (!bme.begin(0x76)) {
   Serial.println("Could not find a valid BME280 sensor, check wiring!");
   while (1);
  }
}

void loop() {
  // LEITURA DOS SENSORES MQ4 CO e MQ6
  float value_MQ4 = analogRead(MQ4);
//  (A1) PINO GND
  float value_CO = analogRead(CO);
//  (A3) PINO GND
  float value_MQ6 = analogRead(MQ6);
//  (A5) PINO GND

//LEITURA DO BME - TEMP, PRESSAO E UR NOS SENSORES
  // TEMPERATURA NOS SENSORES
  float value_temp = bme.readTemperature();
  // PRESSAO ATM NOS SENSORES
  float value_press = bme.readPressure() / 100.0F;
  // UMIDADE RELATIVA NOS SENSORES
  float value_ur = bme.readHumidity();

// PRINT DOS VALORES DOS SENSORES
  Serial.print(value_MQ4);
  Serial.print(", ");
  Serial.print(value_CO);
  Serial.print(", ");
  Serial.print(value_MQ6);
  Serial.print(", ");
  Serial.print(value_temp);
  Serial.print(", ");
```

```
  Serial.print(value_press);
  Serial.print(", ");
  Serial.print(value_ur);
  Serial.print(" ");
  Serial.println();// fecha a linha de resposta do Arduino

  delay(983);
}
```

APPENDIX 3 – LOW-COST PEMS LOG FILE PROCESSING

The step-to-step for preparing the log file generated by Raspberry for be able to post-processed it by EMROAD is:

1) Transforming data file from *.csv to Excel format *.xlsx in Portuguese/Brazilian notation (number with decimal part separated with comma)

- Open the *.csv file in the Excel
- Select all rows
- Select in the Data menu the option "Text to Columns"
- In the Convert Text to Columns Wizard, select Delimited > Next
- Choose as Delimiter "Comma" > Next
- In "Advanced", change the decimal separator to point ("."), thousand separators to none and unticked the option "negative signal posterior" > Ok > Finish
- To salve the file as in Excel format, changing the original name (tip: add "EXCEL" in the end of the file name)

2) Sensors' data alignment:

- Open the Excel file, goes to the last column, AL
- Select the first ten cells from columns AG to AL. In the Excluding window, select the option "move cells to up"
- Goes to the last line of the file and exclude the last ten lines. As in the end of RDE tests there is pause of one or two minutes before shut off the PEMS, these last ten seconds are negligible

3) Eliminating outliers from Exhaust Mass Flow data:

- Select all data from column M, copy and paste in the column AN
- In the menu Insert, create a dispersion (points) graphic with column AN data
- Identify outliers and eliminate them, replacing the outrageous values, e.g. > 500 kg/h, for an average of the previous and posterior points

- With no more outliers, select the column AN, copy and paste over column M

4) Eliminating outliers from GPS data:

- Select all data from columns W, X, Y and Z
- Active search option (“Ctrl+L”), request to search “nan”
- In the cells with “nan”, which are those with loose data, replace with the values from the previous row

5) Calculating CO and THC ppm concentration:

- Insert in the column AN, row 1, the formula “=MINIMO(AIxx:AI10000), where AIxx corresponds to the first line when the engine is started. This cell will define the lowest value for HC
- Insert in the column AN, in the first row with valid values the formula “=SE((AIyy-AN1)<0;0;(AIyy-AN1))”, where AIyy corresponds to the line where this formula is being inserted
- Copy the formula and paste in the subsequent rows up to the last one. They will calculate the difference between the lowest value for THC sensor and the value from the respective rows
- Insert in the column AR, in the first row with valid values, the formula “=SE((0,054*ANyy*ANyy-2,33*ANyy)<0;0;(0,054*ANyy*ANyy-2,33*ANyy))” for E22 or “=SE((0,0183*ANyy*ANyy-0,65*ANyy)<0;0;(0,0183*ANyy*ANyy-0,65*ANyy))” for E100, where ANyy corresponds to the line where the formula is being inserted
- Copy the formula and paste in the subsequent rows up to the last one. They will calculate the value for THC in ppm from the respective rows
- Insert in the column AO, row 1, the formula “=MINIMO(AHxx:AH10000), where AHxx correspond to the first line when the engine is started. This cell will define the lowest value for CO
- Insert in the column AO, in the first row with valid values the formula “=SE((AHyy-AO1)<0;0;(AHyy-AO1))”, where AHyy correspond to the line where this formula is being inserted
- Copy the formula and paste in the subsequent rows up to the last one. They will calculate the difference between the lowest value for CO sensor and the value from the respective rows
- Insert in the column AS, in the first row with valid value, the formula “=8,06*AOzz” for E22 or “=SE((12,1*AOzz-33)<0;0;(12,1*AOzz-33))” for E100, where AOzz corresponds to the line where the formula is being inserted

- Copy the formula and paste in the subsequent rows up to the last one. They will calculate the value for CO in ppm from the respective rows
- Select all data from columns AR and AS
- Paste the values in the columns B (THC) and C (CO). Pay attention to do not paste the equations but just the values

6) Save and close the file

7) Process PEMS Excel file in the EMROAD

Attention: take care in the “Advanced Settings” for custom fuel data for E22 and E100.

APPENDIX 4 – LOW-COST PEMS – CHECK-LIST FOR RDE TEST

Activities to do before starting the test:

- □ Notebook battery charged
- □ Raspberry battery charged
- □ Disconnect GPS and OBD reader of the Raspberry
- □ Turn on the Raspberry
- □ Turn on the notebook
- □ Connect Raspberry to notebook with LAN cable
- □ Notebook: open the VNC Viewer
- □ Raspberry:
  - Connect notebook to Raspberry through VNC, after Operation System of Raspberry has been fully operational
  - Connect in the USP ports:
    - Arduino
    - GPS
    - OBD reader (do not change this sequence)
  - Open Lx Terminal, type “cgps -s” + Enter: wait up to 7 satellites has been connected (see column “Used”) and altitude is stable
    - Type Ctrl+C to finish the application
    - Close Lx Terminal window
    - Attention: in case of fail of GPS data, reboot Raspberry
  - Open archive folder “TESTE PEMS”
  - In the folder “TEST PEMS”, open the file “0_PGM_LOG_TESTE12D.py” with IDE executor Thonny or similar
  - The file for log data “LOG_dados_PEMS.csv” must have a size of about 527 bytes. If bigger, replace it with the file “LOG_dados_PEMS BLANK.csv”, erasing the part “ BLANK” in the name
- □ Verify if the condensate separator is empty
- □ Connect sample hose in the exhaust pipe and in the condensate separator
- □ Turn on the aspirator (blower)
- □ In the cell phone with GPS routes:

  - Turn on the phone
  - Connect the phone in the 12V charger
  - Open app “Tomtom Navigation”
  - Select the urban route
  - When finishing the urban part, select the rural route
- ◻ Wait for the sensors are warm, about 15 minutes
- ◻ Close the trunk door and lock it with adhesive tape (“American tape”, “Silvertape” or similar)
- ◻ Turn on the air conditioner
- ◻ Turn on the vehicle headlights
- ◻ Fasten the seat belt
- ◻ Turn on the vehicle, but with engine off
- ◻ Start data logging: start button in IDE Thonny
- ◻ Check out if the program is correctly receiving data from:
  - GPS
  - OBD
  - Arduino sensors
  - Wait for 20 s in order to confirm that everything is ok
- ◻ Turn on the engine
- ◻ Start RDE test

After the RDE test:

- ◻ Keep on the vehicle in idle for approximately 20-30 s, for stabilizing and finish data logging
- ◻ Stop the data logging in IDE Thonny
- ◻ Turn off the engine
- ◻ Wait for 3-5 minutes, to clean out the sample hose, and turn off the blower
- ◻ In the folder “TESTE PEMS”: copy and paste the file “LOG_dados_PEMS.csv” with another name
- ◻ Transfer this new file to the notebook through VNC option “file transfer”
- ◻ Disconnect the sample hose
- ◻ Drain out the condensate separator
- ◻ Turn off the Raspberry

- □ Disconnect GPS and OBD of Raspberry
- □ Disconnect Raspberry battery for charging
- □ Turn off the cell phone

The above cited log file "Log_dados_PEMS BLANK.csv" has just two lines:

Column 1, row 1:
Time,y_THC,y_CO,y_NOx,y_NO,y_NO2,y_CO2,y_CH4,y_O2,c_Soot,y_CH4,c_PN,Exhaust Mass Flow,Exhaust Temperature,Ambient Temperature,Ambient Pressure,Torque,Engine Speed,Fuel Rate,Coolant Temperature,Intake Manif. Temperature,Velocity ECU,Velocity GPS,GPS Latitude,GPS Longitude,GPS Altitude,GPS Satellites,Relative Humidity,Engine Load,Invalid Flag,PN_d,Lambda,HC/MQ4,CO,HC/MQ6,Tsens,Psens,Ursens,%_Etanol

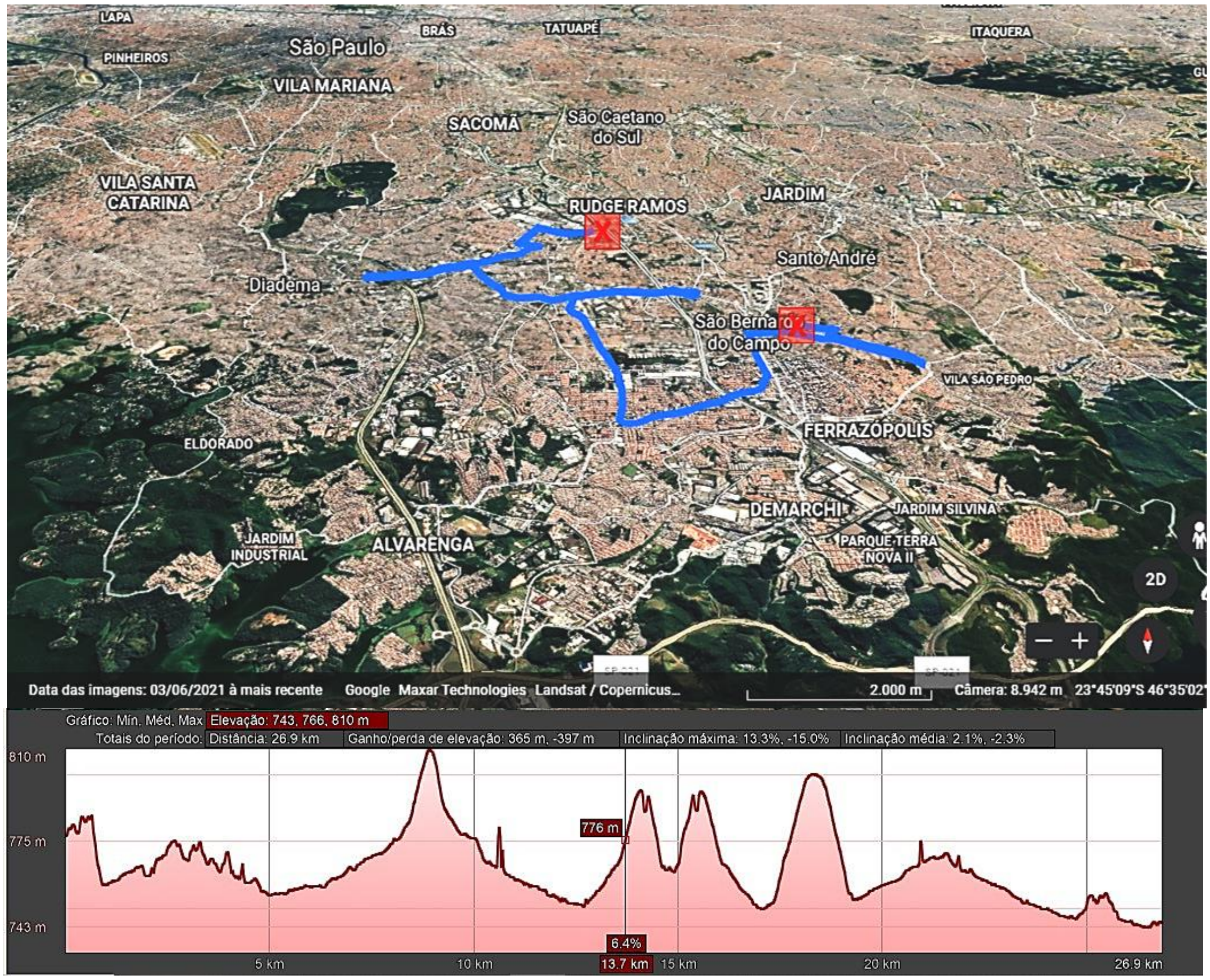
Column 1, row 2:

s,ppm,ppm,ppm,ppm,ppm,ppm,ppm,%,mg/cm3,ppm,p/cm3,kg/h,degC,degC,mbar,Nm,rpm,g/s,degC,degC,km/h,km/h,deg,deg,m,[],%,%,[],[]

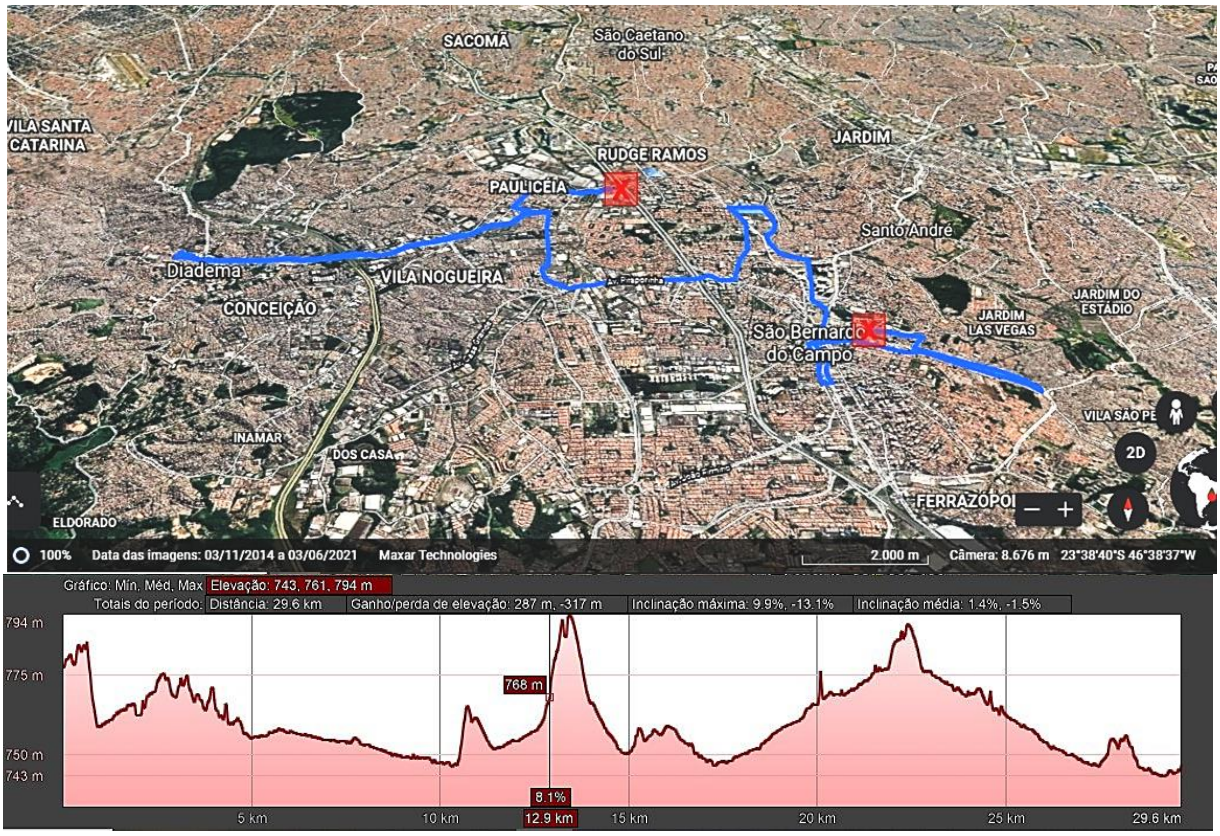
APPENDIX 5 – RDE ROUTES

All urban routes used in the RDE tests start and finish in the same place, and the rural part used just one option, named São Bernardo Rural. The urban routes begin at CETESB vehicular emission laboratory in the Rua dos Vianas 625, Sao Bernardo do Campo, Sao Paulo State, Brazil, and coordinates 23.699082512695675, 46.54690762087351. They finish at Anchieta Motorway access, with coordinates -23.66739, -46.57453. The rural part starts in this same point, finishing at -23.717667, -46.558482.

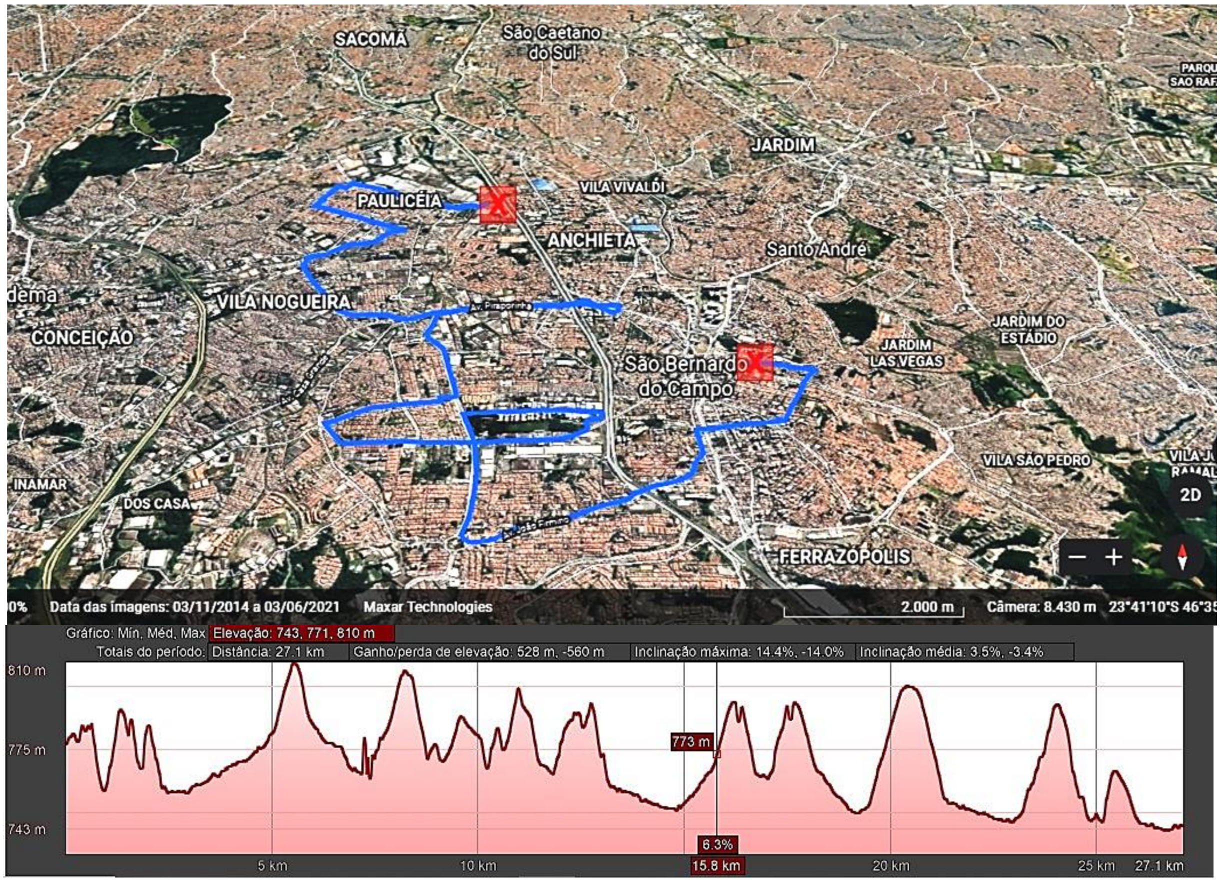
1) São Bernardo Urban – regular altitude gain – 3D view and topographic profile



2) São Bernardo Urban low altitude gain – 3D view and topographic profile



3) São Bernardo Urban high altitude gain



4) Santo Andre Urban – 3D view and topographic profile

5) São Bernardo Rural – 3D view and topographic profile

APPENDIX 6 – ARTICLE: Improving the assessment of RDE dynamics through vehicle-specific power analysis

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RESEARCH ARTICLE

Improving the assessment of RDE dynamics through vehicle-specific power analysis

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Abstract
Vehicles are an important source of air pollutants and greenhouse gases. Their emissions have been controlled since the 1970s by laboratory tests but there are often found divergences to real-world emissions. Real driving emissions procedure is in implementation in many countries, for evaluating vehicles closer to actual operation. In order to reduce the dispersion of the results, some dynamic parameters, such as speed, acceleration, and CO_2 emissions, are controlled; however, sometimes they are into the limits but divergences remain. This paper has the goal of applying VSP as an additional parameter for improving the evaluation of the vehicle dynamics, because it can better represent the engine power required for running as well as the road grade influence.

Keywords Pollutant emission · Real driving emission · Vehicle-specific power · Driving behavior · PEMS · Road grade

Introduction

More than half of urban population in the world is exposed to air pollution levels above the safety standard (WHO 2018). It has been estimated that in 2016, air pollution resulted in 4.2 million deaths worldwide; aside from this, there is a long list of adverse effects related to air pollution such as cardiovascular and respiratory diseases, cancer, and adverse birth outcomes (WHO 2018, 2020).

Vehicles are a relevant source of greenhouse gases (GHG) like carbon dioxide (CO_2) and methane (CH_4) and primary pollutants: carbon monoxide (CO), nitrous oxide (NOx), particulate matter (PM), unburned hydrocarbons (HC), and other volatile organic compounds (VOC). Vehicle emissions of VOC and NOx play also an important role in the formation of ozone (O_3) and secondary PM, the main pollutants in many metropolitan areas worldwide (CETESB 2019; WHO 2020).

The vehicle emission measurement can be done with different methods, e.g., remote sensing, laboratory tests, or in the real-world driving, e.g., the Real driving emissions (RDE) test, where the vehicle is evaluated on the streets and roads; however, the results are subjected to an inherent uncertainty due to lack of precision in the instruments and variations in trip conditions such as traffic, accelerations, topography, and temperature (Giechaskiel et al. 2018).

In order to reduce dispersion of results, the European RDE procedure determines the control of some parameters, such as cumulative positive altitude gain, speed, acceleration, and CO_2 emission. However, it is common to find yet variations in the tests, even when these regulatory parameters are in the tolerances, because they are not fully able to evaluate the vehicle's dynamic; so, RDE procedure can be

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