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INTERNATIONAL COMPARISON OF BRAZILIAN REGULATORY STANDARDS FOR LIGHT-DUTY VEHICLE EMISSIONS

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LIST OF ACRONYMS

ABNT	Associação Brasileira de Normas Técnicas
ANP	Agência Nacional do Petróleo, Gás Natural e Biocombustíveis
CETESB	Companhia Ambiental Do Estado De São Paulo
CO	carbon monoxide
CONAMA	Conselho Nacional do Meio Ambiente
CRC	Coordinating Research Council
DNPH	2,4-dinitrophenylhydrazine
EC	European Commission
EEC	European Economic Community
EOBD	European on-board diagnostic
FAME	fatty acid methyl ester
FID	flame ionization detector
GC	gas chromatography
GDI	gasoline direct injection
GVWR	gross vehicle weight rating
HC	hydrocarbons
HD	heavy duty
HPLC	high performance liquid chromatography
IBAMA	Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
IUMPR	in-use monitor performance ratio
JRC	Joint Research Centre
LD	light duty
MDPV	medium-duty passenger vehicle
MECA	Manufacturers of Emission Controls Association
MMA	Ministério do Meio Ambiente
MSAT	mobile source air toxic
NEDC	New European Driving Cycle
NMHC	non-methane hydrocarbon
NMOG	non-methane organic gases
NO_x	nitrogen oxides
OBD	on-board diagnostic
ORVR	onboard refueling vapor recovery
PEMS	portable emissions measurement system
PFI	port fuel injection
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PN	particle number
PROCONVE	Programa de Controle de Poluição do Ar por Veículos Automotores
RDE	Real Driving Emissions
SFTP	Supplemental Federal Test Procedures
SHED	Sealed Housing for Evaporative Determination
SPMA	São Paulo Metropolitan Area
SUV	sport utility vehicle
THC	total hydrocarbons
U.S. EPA	U.S. Environmental Protection Agency
WHO	World Health Organization
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

EXECUTIVE SUMMARY

Motor vehicles are a significant source of air pollutant emissions in Brazil. These emissions contribute to urban air quality problems, negative human health outcomes, and climate change, and have other detrimental impacts on the environment, such as crop damage and visibility impairment.

The Brazilian regulatory program for vehicle emissions control, Programa de Controle de Poluição do Ar por Veículos Automotores (PROCONVE), has been instrumental in improving the emission performance of new vehicles sold in the country and, since its introduction in 1986, has offset some of the impacts of the rapidly growing Brazilian fleet. With the full implementation of the current phase of PROCONVE L6 for light-duty (LD) vehicles completed in 2015, Brazilian regulators should consider the evolution of the program to mitigate the risks to human health and the environment associated with motor vehicle pollution from a growing LD fleet.

This paper aims to inform the next phase of PROCONVE for LD vehicles by assessing important components of PROCONVE L6 and their relative strengths and weaknesses compared with similar programs in the United States and the European Union. The U.S. and EU programs were selected for this comparison because they have progressed furthest in controlling emissions from motor vehicles, and are often models for other countries implementing vehicle emission control programs.

This comparison highlights a number of areas in which the Brazilian program can be improved upon. A key insight that emerges from this comparison relates to the evolution of PROCONVE relative to the development of U.S. and EU regulatory programs. In Brazil, the stringency of successive stages of PROCONVE has been increased largely through the adoption of more stringent emission limits. In contrast, U.S. and EU programs have developed through the implementation of advanced certification test procedures and specifications in addition to more stringent emission limits. Some of these changes have been highlighted in this paper, and include longer vehicle useful lifetimes, drive cycles covering a broader range of expected operating conditions, real-world driving test requirements, and more challenging evaporative emission testing. These improvements to U.S. and EU programs serve to enhance the representativeness of the vehicle certification process and lead to more effective control of real-world emissions from LD vehicles. Table ES1 highlights the areas where PROCONVE L6 lags behind international best practices, along with potential improvements to be considered for the next phase of PROCONVE L7.

Of the programs considered here, the U.S. Tier 3 regulation provides the most comprehensive approach to LD vehicle emissions control. The Tier 3 regulation combines stringent emission limits with certification procedures that encourage effective real-world emissions control. In addition to the recommendations in Table ES1, Brazilian regulators should also consider a road map toward Tier 3 level emission standards. While the full scope of these changes may not be achievable in the near term, important advances toward this goal can be made through modernization of certification test procedures and adoption of more stringent emission limits.

Table ES1. Shortcomings of PROCONVE L6 and recommended improvements for PROCONVE L7.

Program component	Areas where PROCONVE L6 lags behind international best practices	Recommended changes for PROCONVE L7
Vehicle classification	Large SUVs and passenger vans may be excluded from LD vehicle regulatory program	Adopt medium-duty passenger vehicle classification so all passenger vehicles are subject to same regulatory program
Regulated pollutants	Diesel and Otto cycle vehicles subject to different emission standards	Adopt fuel-neutral emission standards
	NMHC standard does not include important classes of organic gases; unburned ethanol emissions are unregulated	Regulate organic gas emissions with a NMOG standard; maintain aldehyde standard
Tailpipe emission limits	LD commercial NO_x emission limits and LD diesel PM limits lag far behind current limits in the United States and European Union	Tighten PM and NO_x emission limits
	Generally, tailpipe emission limits remain less stringent than international best practices	Develop road map for achieving U.S. Tier 3 emission level performance
Test driving cycles and certification procedures	NBR 6601 driving cycle does not cover potential high-emission driving modes	Adopt SFTP standards
Durability requirements	Useful life period is not representative of modern vehicle lifetimes	Increase useful life specification to 160,000 km at minimum
Evaporative emission requirements	Evaporative emission certification test procedures are not representative of real-world conditions	Adopt U.S. 48-hour and 72-hour evaporative emissions tests along with more stringent emission limits Introduce running loss test and emission limit
	No requirements for control of refueling emissions in place	Require ORVR systems for new vehicles. Consider Stage I and II controls to accelerate emission reductions in areas with severe ozone problems
OBD system requirements	Scope of system components subject to monitoring lags behind international best practices	At minimum, adopt Euro 6-2 EOBD system requirements; consider California OBD II as better alternative
	OBD threshold limits set well above certification emission limits	Lower threshold limits to levels more in line with international best practices

MOTOR VEHICLES AND AIR QUALITY IN BRAZIL

Air pollution levels in Brazilian cities pose significant risks to human health and the environment. In 2015, 52,284 deaths in Brazil were attributable to exposure to fine particulate matter ($PM_{2.5}$) and 3,109 to ozone pollution (Institute for Health Metrics and Evaluation, 2016). Motor vehicles are a major source of air pollutant emissions in the country. Directly emitted species from motor vehicles include both gases—carbon monoxide (CO), nitrogen oxides (NO_X), organic gases, and hydrocarbons (HC)—and particulate matter (PM). In addition, motor vehicles are a significant source of pollutant species that are precursors to secondary air pollutants, such as ozone and secondary PM, which are formed in the atmosphere through photochemical processes. Exposure to these pollutants, over both the short and long term, has been associated with a broad spectrum of adverse human health outcomes, including cardiovascular and pulmonary disease, asthma, and lung cancer.

As a significant source of air pollutant emissions, particularly in urban areas, LD vehicles contribute to poor air quality in Brazilian cities. Control of PM pollution remains an ongoing challenge in the country. Figure 1 shows annual average $PM_{2.5}$ concentrations in 40 Brazilian cities as reported in the World Health Organization (WHO) Ambient Air Quality Database (WHO, 2014). In all cities save one, $PM_{2.5}$ levels exceed the WHO air quality guideline of 10 μg/m³, shown in the figure with a solid red line. In Brazil's most populous cities, São Paulo and Rio de Janeiro, $PM_{2.5}$ concentrations exceed WHO guidelines by 60% and 360%, respectively. LD vehicles, particularly those powered with diesel engines, are an important source of primary PM emissions, and emissions of HC and NO_X from the LD fleet also contribute to the formation of secondary PM.

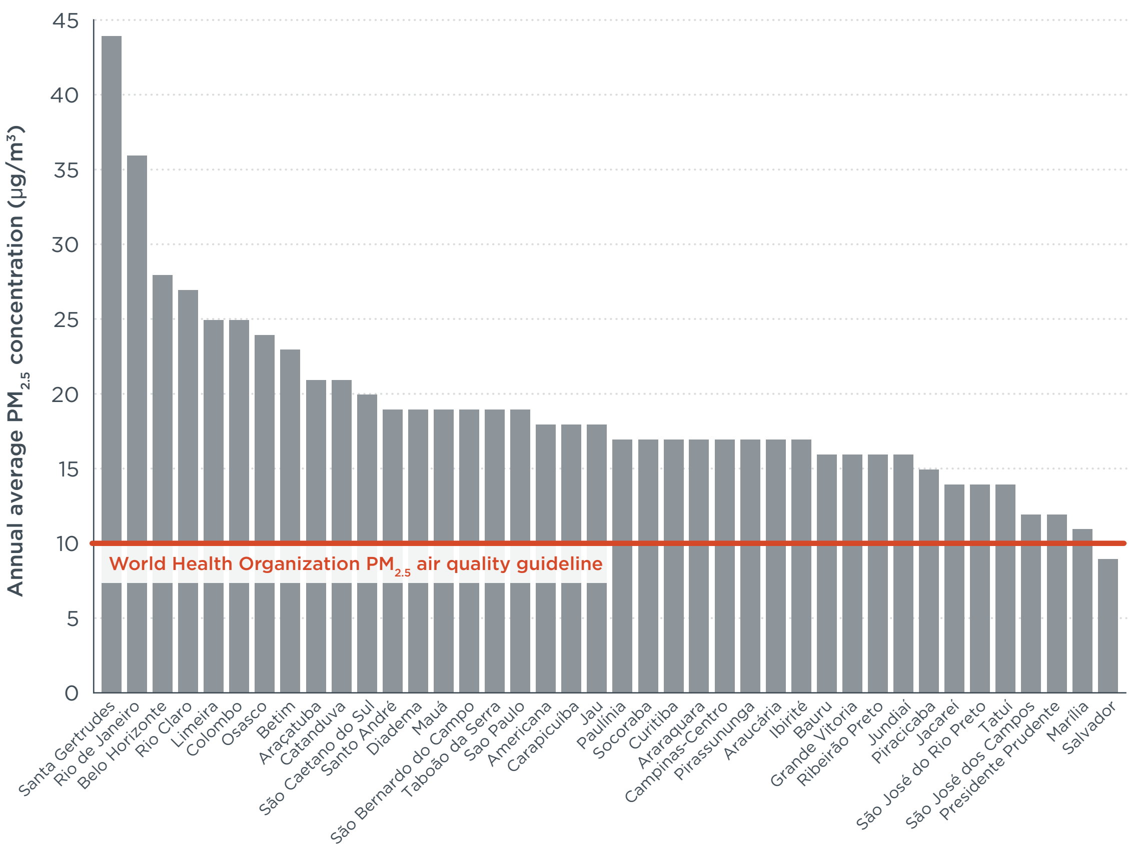

Figure 1. Annual mean $PM_{2.5}$ concentrations in Brazilian cities.

In addition to PM, Brazil also struggles with ozone pollution problems. A clear example of the current challenges facing Brazilian cities can be seen in long-term trends of ozone pollution in the São Paulo Metropolitan Area (SPMA). Figure 2 shows the number of annual exceedances of the ambient 8-hr ozone standard of 140 μg/m³ from 2006 to 2015 (Companhia Ambiental Do Estado De São Paulo [CETESB], 2016)[1]. These data show no improvement over the past 10 years in the number of days each year with high ozone levels. In fact, the 4-year period with the most exceedances was between 2011 and 2015. The results shown here are supported by a recent analysis of ambient air quality monitoring data, which showed no significant change in ozone concentrations between 2000 and 2013 (Pérez-Martínez, de Fatima Andrade, & de Miranda, 2015). Motor vehicles are the primary source of ozone precursor emissions (NO_X and HC) in the SPMA, with LD vehicles in particular contributing significantly to the HC emission inventory (CETESB, 2016). Ozone pollution is a complex problem, and mitigation strategies must take into account the nonlinear nature of ozone formation and the role of influencing parameters such as precursor emission rates, meteorology, and regional transport. However, it is clear that the continued control of precursor emissions from LD vehicles should be an important component in air quality management strategies to address persistent ozone problems in the SPMA and other Brazilian cities.

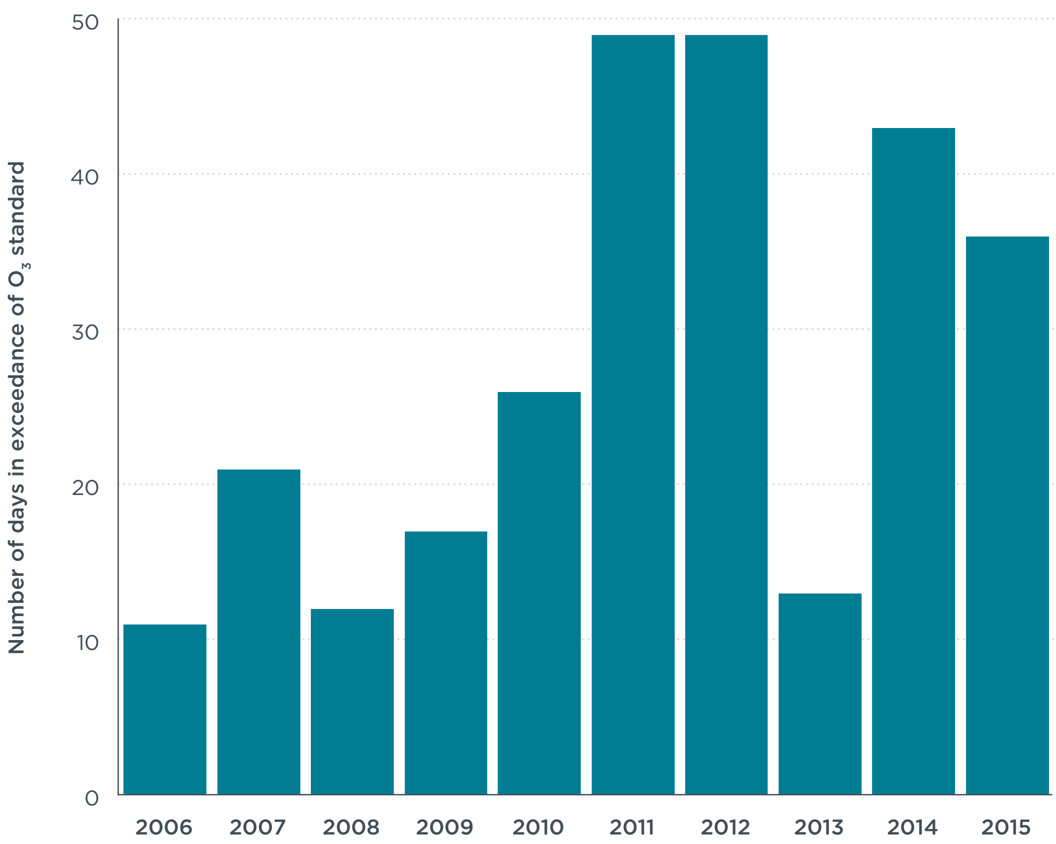

Figure 2. Historical trends of annual number of days in exceedance of 8-hour ozone standard of 140 μg/m³ in the SPMA.

1 The ambient ozone standard of 140 μg/m³ was established in 2013. Pre-2013 data in Figure 2 shows the number of days that would have been in exceedance of the 140 μg/m³ standard if it had been in place in those years.

Ongoing PM and ozone pollution problems make clear that air quality challenges persist in Brazil. However, it is important to highlight the progress that has been made in mitigating the impact of motor vehicles on air quality in the country. For example, the implementation of PROCONVE has led to significant reductions in emissions of CO from LD vehicles through the widespread adoption of three-way catalytic converters. The benefits of these reductions are reflected in clear downward trends in ambient concentrations of CO in major Brazilian cities over the past 15 to 20 years (Carvalho, Freitas, Martins, Martins, Mazzoli, & Andrade, 2015; Pérez-Martínez et al., 2015). There have been no recorded exceedances of the ambient CO standard in the SPMA since 2008. Though air quality monitoring data for HC is less robust than for CO, researchers have estimated similar long-term downward trends for ambient HC concentrations (Dominutti, Nogueira, Borbon, de Fatima Andrade, & Fornaro, 2016). These decreases have occurred despite significant increases in vehicle population and activity over the same time period. In this sense, the progression of PROCONVE has helped to offset some of the air quality impacts of the rapidly growing Brazilian LD vehicle fleet.

Looking forward, continued improvement of PROCONVE is needed to build upon these initial successes. Emerging challenges related to the introduction of new technologies such as gasoline direct injection (GDI) engines, the increasing popularity of diesel-powered sport utility vehicles (SUVs) and pickup trucks, and growing concerns about real-world emissions performance, among others, require an objective assessment of the current state of PROCONVE and clear recommendations on how the next phase of the program can be strengthened. These steps are necessary to properly address the ongoing risks to human health and the environment associated with motor vehicle pollution. The remainder of this paper gives an overview of the Brazilian LD fleet and PROCONVE, with specific emphasis on phase L6, and compares it against U.S. and EU programs. Through this comparison, key areas for the improvement of PROCONVE will be identified.

BRAZILIAN LD VEHICLE FLEET CHARACTERIZATION

Motor vehicles in Brazil include a wide variety of on-road vehicle types used primarily for passenger transport and goods movement applications. The focus of this paper is on LD vehicles, which are classified and regulated as distinct from heavy-duty (HD) vehicles. In PROCONVE, LD vehicles are classified as vehicles with maximum total weight less than or equal to 3,856 kg and running weight less than or equal to 2,720 kg[2]. The LD vehicle category is subdivided into two classes based on application, LD passenger vehicles and LD commercial vehicles. LD passenger vehicles are defined as vehicles designed for the transportation of up to 12 passengers or their derivatives for goods transportation. The LD commercial vehicle class includes vehicles designed for goods transportation, for the transportation of more than 12 passengers, or with special characteristics for off-road use[3]. For regulatory purposes, LD commercial vehicles are further divided into two subclasses based on weight. For this paper, LD commercial vehicles with a test weight[4] less than or equal to 1,700 kg are referred to as the LCV1 subclass and those with test weight greater than 1,700 kg are referred to as the LCV2 subclass.

FUELS OVERVIEW

LD vehicles in Brazil are predominately powered with Otto cycle or diesel engines. Major fuel types used in these engines are summarized in Table 1. Brazil is unique internationally in the relative maturity and scope of its biofuels program. In November 1975, Brazil established the National Alcohol Program (PROALCOOL) to promote domestic ethanol production and offset some of the negative impacts of large-scale use of imported gasoline (Anderson, 2009). The first phase of this program required fuel suppliers to blend 10% anhydrous ethanol with gasoline; a second phase in 1979 supported the production of hydrous ethanol as a replacement for gasoline. Subsequent revisions to the program have served to increase the blend requirements for anhydrous ethanol in commercial gasoline to 20-25% in the early 1990s and, most recently, to 27% beginning in March 2015.

These actions have led to the market availability of several types of LD Otto cycle vehicles, designed to be fueled with either: a blend of gasoline and anhydrous ethanol, also referred to as gasohol; hydrous ethanol only; or any combination of gasohol and hydrous ethanol. Prior to 2003, when flex-fuel vehicles were introduced to the Brazilian market, consumers were limited to gasohol or hydrous ethanol fueled vehicles. In this case, vehicle owners were more sensitive to fluctuations in the market price of gasohol and ethanol fuels. Flex-fuel vehicles can be fueled with gasohol, ethanol, or any combination of the two fuels, and have helped to alleviate the impacts of fluctuations in the price of any given fuel. As such, flex-fuel vehicles have grown to dominate the LD passenger vehicle market (Posada & Façanha, 2015).

2 Maximum designed loaded weight as specified by manufacturer, also referred to as gross vehicle weight rating (GVWR). Running weight, or curb weight, is defined as weight of vehicle with bodywork, fitted with all electrical equipment required for normal vehicle operation plus weight of lubricants, coolant, washer fluid, fuel (tank filled to at least 90% capacity), spare wheel, standard spare parts, and tools.

3 As specified in CONAMA Resolution No. 15/1995, vehicles specified for off-road use are those with 4-wheel drive and at least four of the following characteristics: minimum scoping angle of 25 degrees, minimum output angle of 20 degrees, minimum break-over angle of 14 degrees, ground clearance between axles of at least 200 mm, and ground clearance under the front and rear axles of at least 180 mm.

4 Test weight is defined as the vehicle running weight plus 136 kg.

In addition to ethanol, Brazil has also promoted the production of biodiesel as a substitute for petroleum-derived diesel fuels. Brazil's Federal Law No. 11,097/2005 established the legal requirement for blending biodiesel with petroleum-derived diesel. The initial blend ratio was set to 2% by volume beginning in 2008 and has subsequently been increased to 7%. In March 2016, new mandatory blend ratios were set for 2017 (8%), 2018 (9%) and 2019 and onward (10%).

Brazil has a longstanding ban on the sale of diesel fuel for use in LD passenger vehicles (Dallmann & Façanha, 2016). This ban was instituted in 1976 to conserve diesel fuel for commercial vehicles and reduce petroleum imports. In 1994, the nature of the ban was changed to apply only to passenger vehicles with a payload capacity of less than 1,000 kg. Recently, efforts led by the automotive industry have resulted in governmental consideration of a repeal of these restrictions, but no action has been taken.

Alternative vehicle types, such as natural gas vehicles, have seen some penetration into the Brazilian fleet, though they remain somewhat of a niche market. Similarly, the adoption of hybrid electric, plug-in hybrid, and battery electric vehicles remains limited in the country. However, maturation of these technologies and any future governmental actions targeting carbon dioxide emissions from LD vehicles will likely influence market adoption of these alternative drivetrains.

Table 1. Common fuel types for LD vehicles in Brazil

Fuel type	Description
Gasoline/Gasolina A	Petroleum-derived gasoline fuel. Produced only to be blended with anhydrous ethanol to produce gasohol.
Gasohol/Gasolina C	Blend of gasoline and anhydrous ethanol (≤ 0.7% water content by volume). Percentage of anhydrous ethanol in mixture set by PROCONVE (22%) and the government (currently 27% by ANP).
Hydrous ethanol	Ethanol derived from fermentation of biomass feedstock with water content ≤ 7.4% by volume. Used in engines designed to run on E100 or flex-fuel vehicles. Sugarcane is the primary feedstock for ethanol production in Brazil.
Diesel	Petroleum-derived diesel fuel. Sale of diesel fuel banned for passenger vehicles with payload capacity less than 1,000 kg.
Biodiesel	Fatty acid methyl ester (FAME) produced from vegetable oil or animal fat feedstocks through a transesterification process. Soybean oil is the primary feedstock for Brazilian biodiesel production. Blended with diesel at volume percentage set by government to produce commercial diesel fuels.

LD Vehicle Market Overview

LD vehicle populations in Brazil have grown substantially in the past 35 years. Figure 3 shows LD vehicle populations for 1980 to 2012 as reported in the most recent Brazilian national motor vehicle emissions inventory (Ministério do Meio Ambiente [MMA], 2014). Between 1980 and 2000, LD passenger and commercial vehicle populations increased by about a factor of two. The Brazilian LD vehicle population almost doubled again between 2000 and 2012, increasing from 17.8 million to 33.4 million vehicles in this time frame. As of 2013, Brazil was the world's fifth largest vehicle market (Posada & Façanha, 2015).

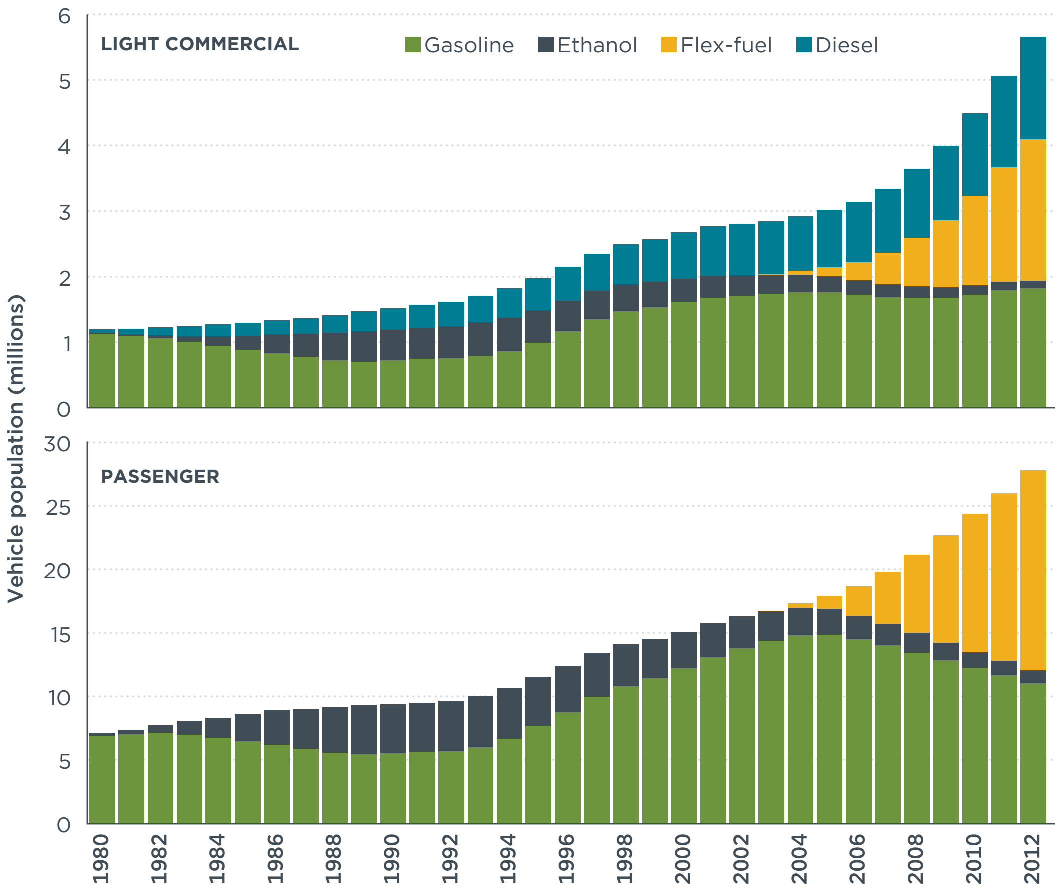

Figure 3. Historical trends in LD commercial vehicle (top panel) and passenger vehicle (bottom panel) populations by fuel type.

Until 2003, LD passenger vehicles were designed to run on either gasohol or hydrous ethanol. Sales of these two types of vehicles fluctuated over time in response to economic conditions and national biofuel policies. Ethanol vehicles accounted for the majority of new vehicle sales in the 1980s, leading to a decrease in the overall LD gasoline vehicle population between 1982 and 1989. Following shortages in domestic ethanol production in 1989 and 1990, sales of new ethanol vehicles dropped substantially and gasoline vehicles dominated the LD passenger vehicle market throughout the 1990s (Anderson, 2009).

Flex-fuel vehicles were introduced into the Brazilian market in 2003, and have almost entirely displaced gasoline and ethanol vehicles. Between 2003 and 2012, flex-fuel vehicles grew from 0% to 57% of the total in-use LD passenger vehicle fleet. New vehicle registrations, presented for the past 5 years in Figure 4, show that flex-fuel vehicles account for more than 90% of passenger vehicle sales in Brazil today.

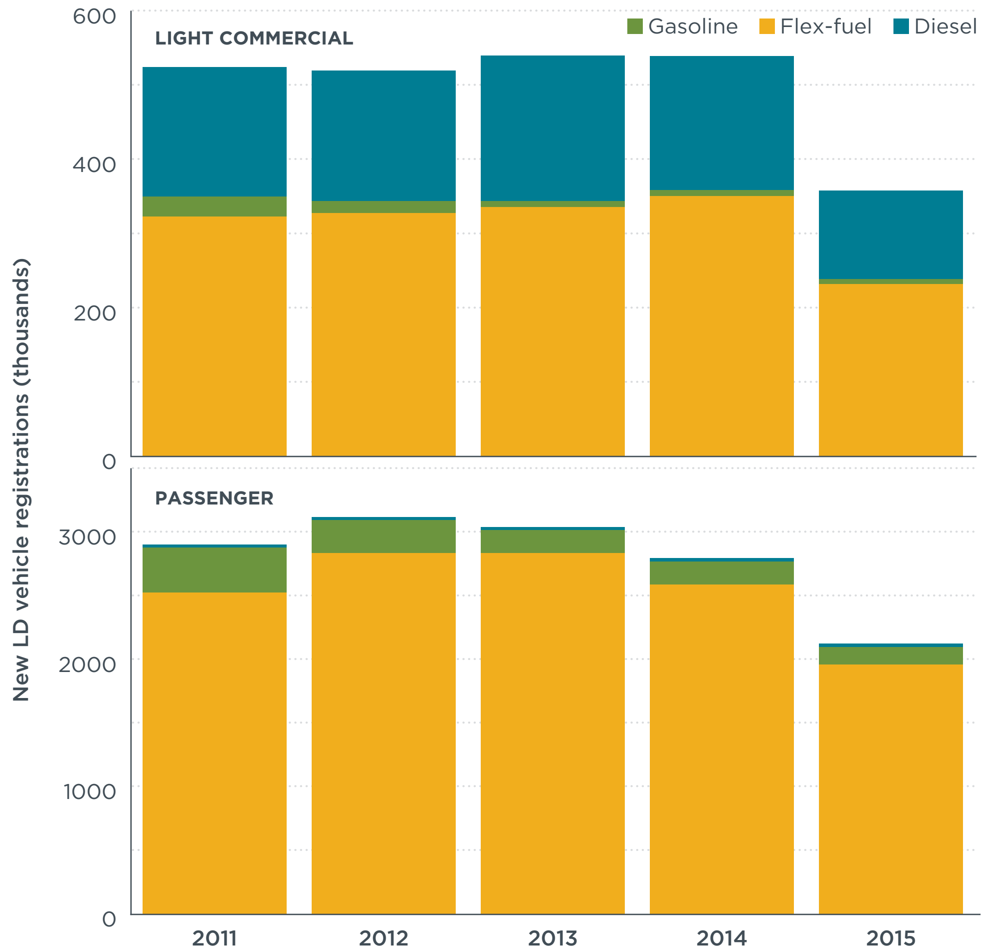

Figure 4. New LD vehicle registrations by fuel type, 2011-2015 (Associação Nacional dos Fabricantes de Veículos Automotores, 2016).

Long-term population trends for Otto cycle LD commercial vehicles are similar to those for passenger vehicles. However, in the case of commercial vehicles, diesel vehicles also make up a significant portion of the fleet. Between 1980 and 2012, diesels grew from less than 5% to 27% of the total in-use light commercial vehicle fleet. Data presented in Figure 4 show a slightly higher diesel penetration for new vehicles between 2011 and 2015, where diesels account for between 33% and 36% of new light commercial vehicle registrations and about 5% of total LD vehicle registrations. It is important to note that certain diesel vehicles entering the market as light commercial vehicles (e.g., some sport utility vehicles and pickup trucks) are able to legally circumvent restrictions on diesel passenger vehicles, even though they may be used primarily for passenger transport applications.

From a regulatory perspective, diesel light commercial vehicles are largely subject to less stringent emission standards than their Otto cycle counterparts. PROCONVE divides the light commercial vehicle category into two subclasses by vehicle test weight, with each subclass subject to separate emission standards. Diesel vehicles tend to be heavier than similar Otto cycle vehicles. As shown in Figure 5, diesel vehicles being sold in Brazil today fall exclusively into the LCV2 subclass, while greater than 80% of Otto cycle sales are of LCV1 subclass vehicles. As will be discussed below, diesel vehicles classified as LCV2 are subject to less stringent emission standards than vehicles classified as LCV1.

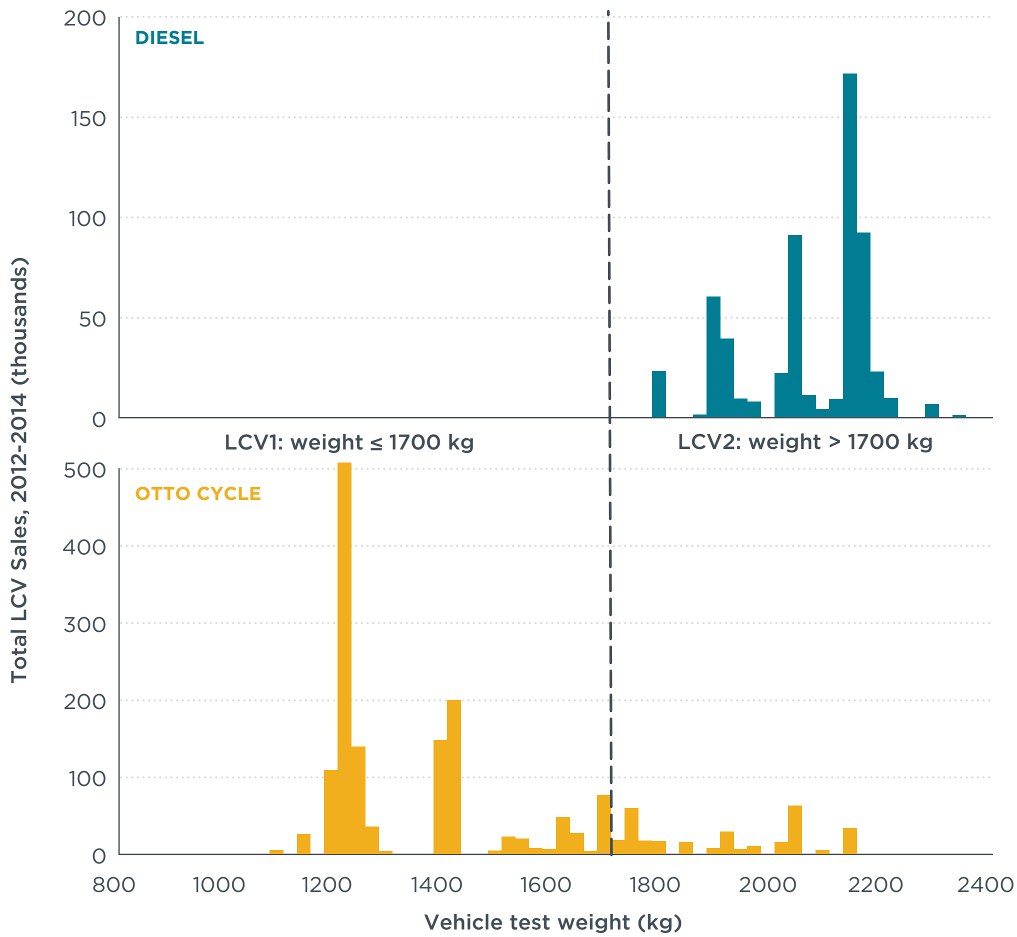

Figure 5. Light commercial vehicle sales in Brazil by engine type and vehicle test weight, 2012-2014 (ADK Automotive Consultoria de Marketing, 2015). Vehicle test weight was calculated as reported vehicle running weight plus 136 kg.

LD VEHICLE AIR POLLUTANT EMISSIONS

Both LD Otto cycle and diesel vehicles contribute to urban air quality problems in Brazil, though their relative importance as emission sources varies by pollutant type. Owing largely to fundamental differences in combustion processes in these two engine types, Otto cycle vehicles tend to have higher emission rates of CO and HC, while diesel vehicles tend to have higher emission rates of NO_x and PM. These emission rates are influenced by many factors and can change significantly with the application of advanced engine designs and aftertreatment control equipment, though this generalization is more or less reflective of the current Brazilian LD fleet. Recent national motor vehicle emission inventory estimates, shown in Figure 6, indicate Otto cycle vehicles are the predominant light-duty source of CO and non-methane hydrocarbon (NMHC) emissions in the country. Otto cycle passenger vehicles, in particular, contribute about 85% of total CO and NMHC emissions from the Brazilian LD vehicle fleet. Diesel vehicles tend to be more important as a source of NO_x and PM emissions. Despite making up only about 5% of the LD fleet, diesel vehicles account for 40% and 80% of total LD vehicle NO_x and PM emissions, respectively.

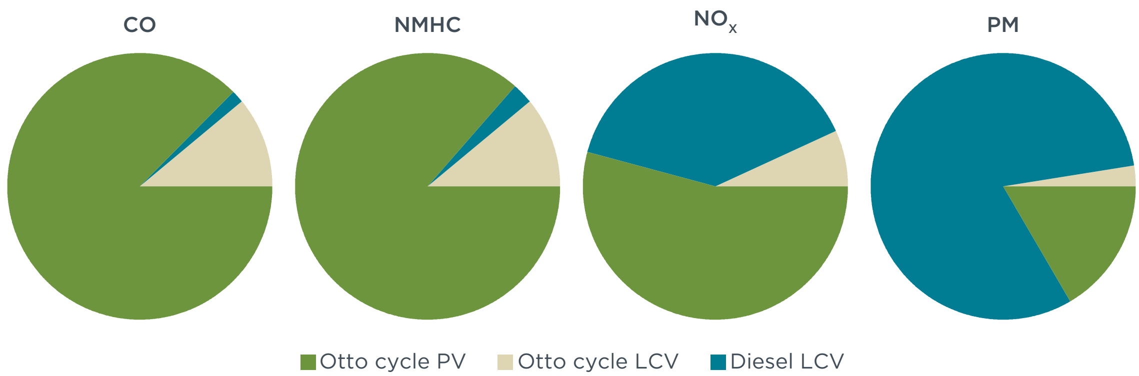

Figure 6. Relative contributions of LD vehicle types to air pollutant emissions in Brazil (MMA, 2014).

The widespread use of ethanol as a transportation fuel in Brazil also has important implications for air pollutant emissions from the LD vehicle fleet. Ethanol use leads to emissions of unburned ethanol and higher emission rates of acetaldehyde and formaldehyde relative to gasoline (Hubbard, Anderson, & Wallington, 2013). Acetaldehyde is also formed through the photochemical processing of unburned ethanol emitted into the atmosphere. The U.S. Environmental Protection Agency (EPA) classifies both formaldehyde and acetaldehyde as mobile source air toxics (MSATs) due to their association with serious health effects. However, the relative toxicity of these aldehyde species is lower than the MSATs benzene and 1,3-butadiene, which are commonly emitted species from gasoline combustion. Thus, researchers have found that the overall toxicity of exhaust emissions from gasoline and ethanol fuel blends tends to decrease with increased ethanol content (Stein, Anderson, & Wallington, 2013).

For other species, the impacts of increased ethanol use are less clear. An extensive study of the impact of ethanol and gasoline fuel blends on emissions from flex-fuel vehicles found no trend in CO or NO_x emissions as fuel ethanol content was increased from 6% to 85%. For the same ethanol blend range, a statistically significant decrease in NMHC emissions was reported for vehicles tested over the US06 driving cycle (Coordinating Research Council [CRC], 2011). Similar results were reported in a more recent study conducted by Ford Motor Company, which found a decrease in NMHC emissions and no change in CO emissions from a flex-fuel vehicle when fuel ethanol content was increased from 0% to 80%. These authors did report a decrease in NO_x emissions of about 50% over this same blend range, though this was attributed to the engine calibration of the tested vehicle, rather than changes to fuel chemistry caused by ethanol blending (Hubbard et al., 2013). In each of these studies, test vehicles were certified to U.S. emission standards. Results may not be representative of emissions of flex-fuel vehicles certified in regions with different emission standards and certification test procedures or vehicles applying different emission control strategies. A more detailed discussion of differences in vehicle certification requirements in Brazil, Europe, and the United States is included in the following sections.

Ethanol can also impact evaporative emissions from LD vehicles through changes to fuel vapor pressure and interactions with fuel system components. Evaporative emissions from motor vehicles are sensitive to fuel vapor pressure, with higher vapor pressure fuels typically associated with greater evaporative emission rates. Pure ethanol has a lower vapor pressure than gasoline due to stronger intermolecular bonding. When blended with gasoline at low levels, these intermolecular bonds are disrupted and the vapor pressure of the mixture is greater than that of pure ethanol or pure gasoline. This vapor pressure enhancement peaks at a mixture of about 10% ethanol and decreases with increasing blend ratios (Stein et al., 2013).

Other effects of ethanol on evaporative emissions come from interactions with fuel system components. When blended with gasoline, ethanol can change how the fuel mixture interacts with plastic or rubber components of the fuel system (e.g., hoses and tanks) leading to increased permeation emissions of hydrocarbons (CRC, 2010). Additionally, ethanol can reduce the long-term efficiency of activated carbon canisters, the primary technology used to control evaporative emissions from Otto cycle vehicles (Joint Research Centre [JRC], 2012).

REGULATORY BACKGROUND

Brazil's first coordinated efforts to control air pollutant emissions from LD vehicles were in 1986 through the adoption of Resolução N° 18/1986 by the Conselho Nacional do Meio Ambiente (CONAMA, 1986). This resolution established the Brazilian motor vehicle air pollution control program, PROCONVE, and set the framework for the first three phases of the program's implementation. Subsequently, the program was endorsed with the passing of Federal Law No. 8.723/1993 and has evolved through the implementation of supporting resolutions by CONAMA and technical amendments issued by the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

PROCONVE was generally modeled after similar programs established in the United States and Europe to control air pollutant emissions from motor vehicles. The key control mechanism in these programs is the establishment of limits on allowable emission rates of specific air pollutants. Vehicle manufacturers are required to demonstrate compliance with these limits through laboratory testing of vehicles over established driving cycles on a chassis dynamometer while operating with reference fuels meeting regulated specifications representative of commercially available fuels. Other program components supplement mass emission limits and aim, in part, to ensure that emissions performance of new vehicles in laboratory testing is maintained throughout their full in-use lifetimes. These components will be discussed in more detail below and include durability requirements, evaporative emission limits, and on-board diagnostic (OBD) system requirements. In Brazil, vehicle models meeting these requirements are issued a License for Use of the Vehicle or Engine Configuration (LCVM) and can be sold in or imported to the country.

To date, six phases of PROCONVE have been implemented for LD vehicles in Brazil. Table 2 gives an overview of the established legislation and implementation dates for each phase. Initial phases of PROCONVE (L1-L3) set emission limits at successively more stringent levels to promote the application of best available engine design strategies and aftertreatment control devices. These include electronic fuel injection and engine controls and three-way catalytic converters. The widespread adoption of catalytic converters in this time period was enabled by the addition of ethanol and phase-out of tetraethyl lead as antiknock additives to gasoline fuels. Subsequent phases of

PROCONVE have continued to set more stringent emission limits for LD vehicles, with a specific focus on addressing urban ozone pollution problems through better control of NO_x and HC emissions. Beginning in 1994, LD diesel vehicles were also explicitly included in PROCONVE regulation.

Table 2. Overview of PROCONVE program for control of emissions from LD vehicles (IBAMA, 2011).

Phase	Regulation	Implementation Dates
Phase 1 (L1)	CONAMA Resolution N° 18/1986	1 January 1989
Phase 2 (L2)	CONAMA Resolution N° 18/1986	1 January 1992 1 March 1994 (LD diesel vehicles)
Phase 3 (L3)	CONAMA Resolution N° 15/1995	1 January 1997
Phase 4 (L4)	CONAMA Resolution N° 315/2002	1 January 2005: 40% annual production 1 January 2006: 70% annual production 1 January 2007: 100% annual production
Phase 5 (L5)	CONAMA Resolution N° 315/2002	1 January 2009
Phase 6 (L6)	CONAMA Resolution N° 415/2009	1 January 2013: diesel vehicles 1 January 2014: new Otto cycle models 1 January 2015: all vehicle models

To better portray the evolution of PROCONVE, emission limits for LD passenger vehicles at each program phase are shown in Figure 7. Emission limits for CO, HC, and NO_x have been reduced by 95% or more in the 26-year period between the implementation of phase L1 in 1989 and the full phase-in of L6 standards in 2015. As noted above, these efforts have helped to offset some of the air quality impacts of a growing LD fleet.

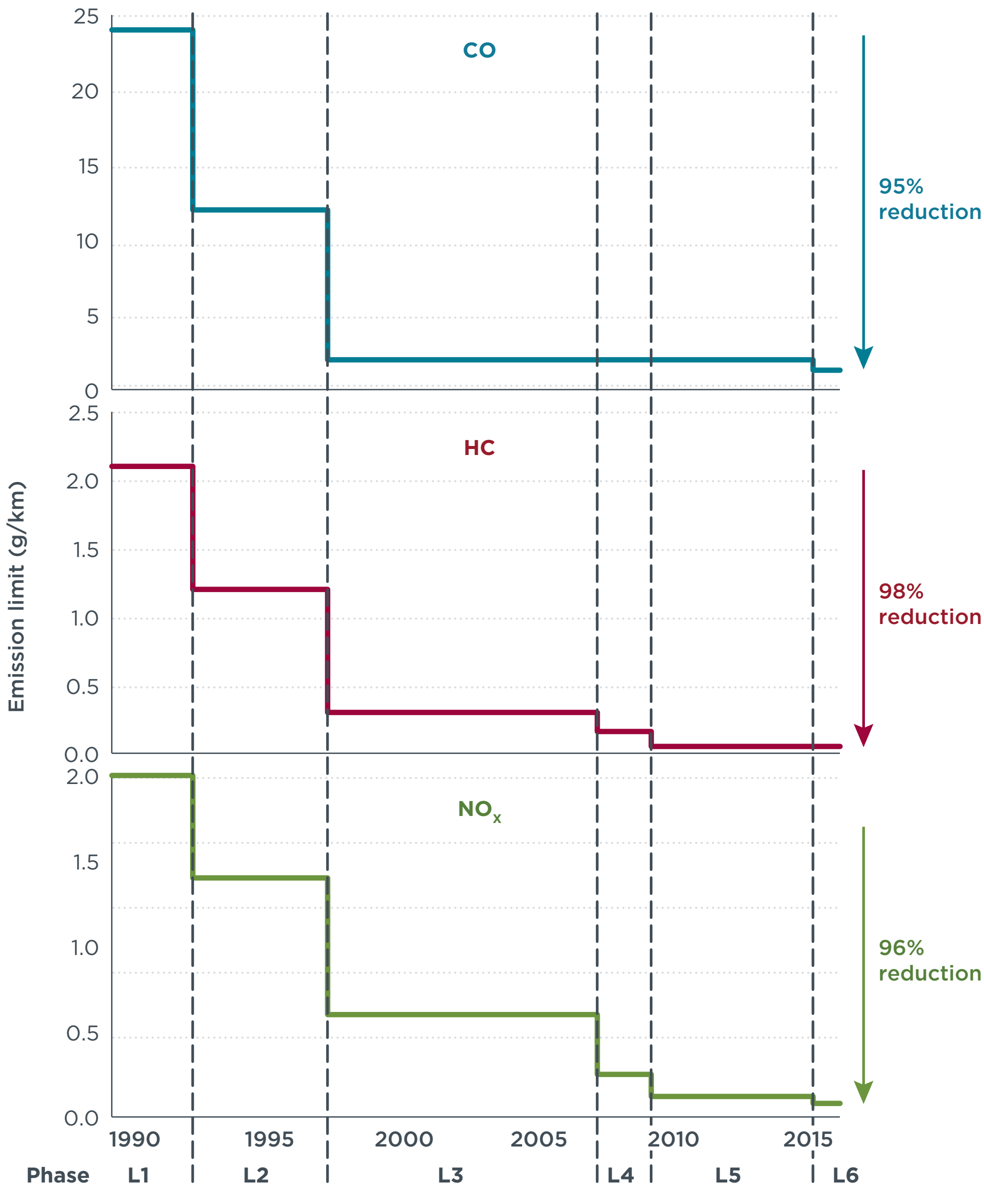

Figure 7. Evolution of PROCONVE mass emission limits for Otto cycle passenger vehicles. Note HC limit shown for Phases L4 through L6 is for NMHC. Phase L4 was phased in between 2005 and 2007.

Brazil has made considerable progress in controlling emissions from LD vehicles through PROCONVE. However, it has been 7 years since the approval of the most recent L6 standards in 2009. With the full implementation of phase L6 achieved in 2015, Brazilian regulators should consider the further evolution of PROCONVE and what steps are needed to better control air pollutant emissions from LD vehicles. An important first step in the development of the L7 stage of PROCONVE is to identify those areas where phase L6 lags behind current best practices established in the regulatory programs of other global regions. To this end, the remainder of this paper will explore various aspects of PROCONVE phase L6 and compare them with current and adopted programs in the United States and European Union. Areas where phase L7 can be improved to better control emissions form LD vehicles will be highlighted.

INTERNATIONAL COMPARISON OF REGULATORY STANDARDS

The following sections focus on comparing specific requirements of PROCONVE L6 with similar components in U.S. and EU regulatory programs. We will first provide an overview of the U.S. and European programs and a description of the vehicle classifications in each of those regions. Then we will address the specific program components, which are: (a) regulated pollutants, (b) emission standards, (c) dynamometer test cycles and other certification test requirements, (d) durability requirements, (e) evaporative emission standards and test procedures, and (f) OBD specifications.

OVERVIEW OF U.S. AND EUROPEAN PROGRAMS

Generally speaking, programs to control air pollutant emissions from motor vehicles have been in place in the United States and European Union since the early 1970s. U.S. national emission standards were first adopted in 1968, following early action by the state of California. These initial standards were supported by the passage of the Clean Air Act in 1970, which called for a 90% reduction in emissions of CO, HC, and NO_X from motor vehicles (Faiz, Weaver, & Walsh, 1996). Subsequent legislation in California and at the federal level has further developed emission control programs in the country through tightened emissions standards and improved certification test procedures. Today, LD vehicles sold in the United States are subject to Tier 2 level emission standards, which were adopted in 2000 and phased in between 2004 and 2009 (U.S. EPA, 2000). In March 2014, Tier 3 emission standards were finalized and will be phased in between 2017 and 2025. Tier 3 standards reduce allowable emissions of HC and NO_X by 80% and PM by 70% relative to Tier 2 levels (U.S. EPA, 2014).

Individual countries in Europe took the initial efforts to control motor vehicle pollution. Recognizing the impact of disparate emission standards on the European market, the European Economic Community (EEC) adopted Regulation 15 of the United Nations Economic Commission for Europe in 1970, which established a standardized motor vehicle emission regulatory framework for Europe (EEC, 1970). This directive was amended throughout the 1970s and 1980s and updated with the adoption of the Consolidated Emissions Directive in 1991, which significantly revised and strengthened the European vehicle emission control program (EEC, 1991). Successive directives and regulations have defined the continued evolution of the EU program through six stages, leading to the currently applicable Euro 6 level standards (European Commission [EC], 2007). Euro 6 standards for LD vehicles were adopted in 2007 and fully implemented in 2015. Amendments to the initial Euro 6 regulation have led to the continued development of this emission control stage.

For this paper, Brazilian PROCONVE L6 standards are compared with U.S. Tier 2 and 3 and EU Euro 6 programs.

LD VEHICLE CLASSIFICATION

Each of the three regulatory programs considered here classify LD vehicles on the basis of vehicle weight. In the United States and Brazil, LD vehicle regulations apply to vehicles with a maximum weight less than or equal to 3,856 kg. The maximum weight, also referred to as gross vehicle weight rating (GVWR), is specified by the manufacturer and includes total vehicle weight plus fluids, passengers, and cargo. Brazil also includes a specification for the maximum running weight for LD vehicles of 2,720 kg. The running weight, or curb weight, is equivalent to the GVWR minus the weight of passengers and cargo. The United States includes a similar curb weight specification in its definition of light-duty trucks. In the European Union, LD vehicle regulations apply to vehicles with a reference weight (curb weight plus 100 kg) less than or equal to 2,610 kg[5].

In each of the three regions, LD vehicles are further classified according to vehicle type and application. In general, distinctions are made between vehicles designed for passenger transport and those designed for goods movement or with off-road characteristics (e.g., pickup trucks). Table 3 includes a listing of vehicle classes and subclasses included in each LD regulatory program. In Brazil and the European Union, emission standards are set independently for individual vehicle classes. In contrast, the United States has primarily adopted a corporate averaging approach, where vehicle manufacturers must meet fleet-average emission standards set for their entire vehicle fleet.

Table 3. Vehicle types included in Brazilian, U.S., and EU LD vehicle regulatory programs.

Region	Vehicle class	Vehicle subclass	Description
Brazil	**Passenger vehicle**		Vehicles designed for the transportation of up to 12 passengers or their derivatives for goods transportation
	Light commercial vehicle	LCV1	Vehicles designed for goods transportation, for the transportation of more than 12 passengers, or with special characteristics for off-road use. Test weight ≤ 1,700 kg.
		LCV2	Vehicles designed for goods transportation, for the transportation of more than 12 passengers, or with special characteristics for off-road use. Test weight > 1,700 kg.
U.S.	**Passenger vehicle**	Light-duty vehicle	Passenger car or passenger car derivative seating 12 passengers or less
		Medium-duty passenger vehicle (MDPV)	SUVs and passenger vans rated at between 3,856 and 4,536 kg GVWR
	Light-duty truck	Light light-duty truck	Vehicle with GVWR ≤ 2,721 kg and vehicle frontal area ≤ 45 ft2 designed primarily for goods transport, transport of more than 12 passengers, or with special features enabling off-road use.
		Heavy light-duty truck	Vehicle with GVWR > 2,721 kg and vehicle frontal area ≤ 45 ft2 designed primarily for goods transport, transport of more than 12 passengers, or with special features enabling off-road use.
EU	**Passenger vehicle**	M1	Vehicle designed for passenger transport with no more than 8 seats in addition to the driver's seat and maximum weight ≤ 3,500 kg
		M2	Vehicle designed for passenger transport with more than 8 seats in addition to the driver's seat and maximum weight ≤ 3,500 kg
	Light commercial vehicle	N1 Class I	Vehicle designed for goods transport with maximum weight ≤ 3,500 kg and reference weight ≤ 1,305 kg
		N1 Class II	Vehicle designed for goods transport with maximum weight ≤ 3,500 kg and reference weight > 1,305 and ≤ 1,760 kg
		N1 Class III	Vehicle designed for goods transport with maximum weight ≤ 3,500 kg and reference weight > 1,760 kg
	Commercial vehicle	N2	Vehicle designed for goods transport with maximum weight > 3,500 kg and ≤ 12,000 kg

5 At request of a manufacturer, type approval under the Euro 6 regulation may be extended to vehicles with reference mass not exceeding 2,840 kg

Although Brazil largely follows the U.S. vehicle classification scheme, it has yet to fully adopt important changes made by the United States beginning with Tier 2 standards. At this time, the United States expanded the scope of its LD regulatory program through the inclusion of medium-duty passenger vehicles (MDPVs). The MDPV class includes SUVs and passenger vans with a GVWR between 3,856 kg and 4,536 kg. This ensured that essentially all vehicles designed for passenger use were included in the Tier 2 program. Brazil should consider updating its vehicle classification scheme to include the MDPV class so that all passenger vehicles are subject to the same regulatory requirements[6].

REGULATED POLLUTANTS

At the core of each LD vehicle regulatory program are limits on the allowable emissions of individual pollutants that have been found to be harmful to public health and the environment. As shown in Table 4, each program considered here addresses the same common set of pollutants of concern from internal combustion engines—CO, NO_x, organic gases, and PM. However, the three programs have some important differences in their regulation approach. For example, Europe and Brazil set separate standards for Otto cycle (positive ignition) and diesel (compression ignition) vehicles, while U.S. standards are fuel neutral. This means that, in Europe and Brazil, LD vehicles with different engine types do not face the same emission control requirements.

Table 4. Regulated pollutants by emission control program.

Species		PROCONVE L6		U.S. Tier 2	U.S. Tier 3	Euro 6	
		Otto cycle	Diesel			Positive ignition (Otto cycle)	Compression ignition (Diesel)
CO		✔[1]	✔	✔	✔	✔	✔
NO_x		✔	✔	✔	✔[4]	✔	✔
Organic gases	THC	✔[2]	✖	✖	✖	✔	✔[6]
	NMHC	✔	✔	✖	✖	✔	✖
	NMOG	✖	✖	✔	✔[4]	✖	✖
	Aldehydes	✔	✖	✔[3]	✔[3]	✖	✖
Particulate matter	PM mass	✖	✔	✔	✔	✔[5]	✔
	PN	✖	✖	✖	✖	✔[5]	✔
Non-tailpipe	Evaporative emissions	✔	✖	✔	✔	✔	✖

CO: carbon monoxide; NO_x: Nitrogen oxides; THC: Total hydrocarbons; NMHC: Non-methane hydrocarbons; NMOG: Non-methane organic gases; PM: Particulate matter; PN: Particle number
[1]Additional limit for CO exhaust concentration at idle speed applies.
[2]Applies to natural gas powered vehicles only
[3]Formaldehyde only
[4]Combined NO_x+NMOG limit
[5]Applies to vehicles equipped with direct injection engines only
[6]Combined THC+NO_x limit

6 PROCONVE L6 does include a provision by which Otto cycle vehicles with GVWR between 3,856 and 4,536 kg may be tested for certification as light commercial vehicles of the LCV2 class. However, this provision is optional and does not ensure all vehicles designed for passenger use, including diesels, are subject to equivalent certification requirements.

One important consequence of this approach in Brazil is that the current regulatory framework may not be adequate to address the impacts of emerging technology trends. For example, GDI engines are becoming increasingly popular globally in part due to their better fuel economy and increased engine power relative to port fuel injection (PFI) engines. Unfortunately, GDI engines also emit more PM than comparable PFI engines (Zimmerman, Wang, Jeong, Wallace, & Evans, 2016). PROCONVE L6 sets limits on allowable PM emissions from diesel vehicles, but does not include PM emission standards for LD Otto cycle vehicles. This means that no provisions are in place to address the risk of increased PM emissions from increased GDI engine penetration into the LD fleet.

Europe has addressed this risk through the inclusion of PM and particle number (PN) emission limits for vehicles equipped with GDI engines in the Euro 6 program. This is an important step and Brazil would do well to consider something similar; however, a more straightforward approach would be to follow the U.S. example and adopt fuel-neutral emission standards for all regulated pollutants. In this case, the PM emission limit can be defined such that all vehicles, regardless of engine type, meet desired emission performance levels.

Other differences in pollutants included in the three regulatory programs largely involve the ways in which organic gases are regulated. Organic gases emitted at the tailpipe consist of thousands of individual chemical compounds derived from unburned or incompletely combusted fuel. Generally speaking, three main classes of organic gases are defined in LD vehicle regulatory programs: hydrocarbons, alcohols, and aldehydes. Hydrocarbons contain only hydrogen and carbon atoms, while both alcohols and aldehydes are characterized by an oxygen-containing functional group. Hydrocarbons are measured using a flame ionization detector (FID), which is sensitive to the number of carbon atoms in a given organic molecule. Alcohols and aldehydes are also detected in the FID, though the response to these species is diminished relative to their true concentrations. Thus, alcohols and aldehydes are only partially detected with an FID. An accurate measurement of the concentration of oxygenated species in vehicle exhaust requires modified analytical procedures. Alcohols are collected using an impinger sampling system and analyzed through gas chromatography (GC). Aldehydes are collected using DNPH (2,4-dinitrophenylhydrazine) cartridges and analyzed through high performance liquid chromatography (HPLC).

Each of the regulatory programs considered here regulates organic gases in a unique fashion. Measurement methods, data treatment steps, and regulated species in each program are summarized in Figure 8. In Europe, organic gases are measured using an FID. The analytical result is referred to as total hydrocarbons (THC) and includes hydrocarbons as well as partial contributions from alcohols and aldehydes, if these species are present in the sampled vehicle exhaust. The contribution of methane to the FID signal is subtracted to yield a measurement of NMHC. Again, any alcohols or aldehydes present in the sampled vehicle exhaust will be partially included in the EU FID-based NMHC result.

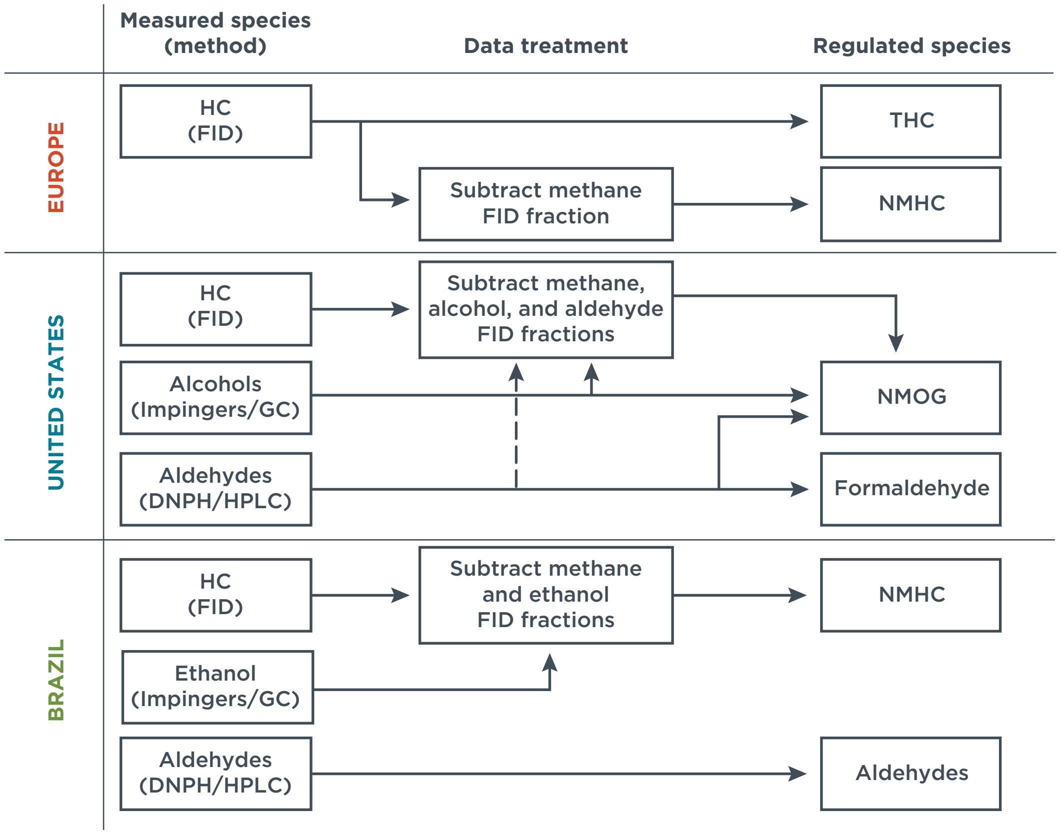

Figure 8. Comparison among EU, U.S., and Brazilian regulatory procedures for organic gas emissions from LD vehicles (Sandstroem-Dahl, Erlandsson, Gasste, & Lindgren, 2010).

The U.S. approach to organic gas emissions regulation differs from the EU approach in a number of ways. Like the European Union, the United States requires measurement of hydrocarbons using an FID. However, in the U.S. program, alcohols and aldehydes are also measured directly through modified analytical procedures. These measurements enable adjustment of the FID hydrocarbon measurement to remove contributions from alcohols and aldehydes. The methane contribution is also subtracted, resulting in a “true” measurement of NMHC (i.e., excluding alcohols and aldehydes). Emissions of NMHC, alcohols, and aldehydes are then added together to yield non-methane organic gases (NMOG). Emissions of NMOG are regulated in the U.S. program. NMOG differs from the European NMHC definition in that it represents the full contributions of oxygenated species in the sampled vehicle exhaust. Formaldehyde emissions are also regulated separately in the U.S. program.

Brazil’s approach to regulating organic gas emissions includes limits on emissions of NMHC for Otto and diesel cycle vehicles and aldehydes for Otto cycle vehicles. NMHC emissions are quantified using an FID with the methane contribution subtracted. In Brazil, manufacturers are also given the option to subtract the ethanol contribution from the FID NMHC result using a separate impinger/GC based measurement of the ethanol in the sampled vehicle exhaust. In this case, the final regulated NMHC result includes NMHC and partial contributions from aldehydes. Ethanol emissions are excluded completely and thus, unregulated.

NMOG and NMHC emissions tend to be similar for petroleum-derived gasoline and diesel-fueled vehicles, and differences in the approach to defining these species in each of the three regulatory programs are minimal. However, notable differences may be seen for alcohol fuels, which tend to be associated with greater emissions of oxygenates (Oak Ridge National Laboratory, 2011). In Brazil, unburned ethanol can account for a significant fraction of total organic gas emissions from LD Otto cycle vehicles.

The regulatory approach to organic gas emissions in Brazil could be improved by the replacement of the NMHC standard with an NMOG standard to explicitly include alcohols, such as unburned ethanol. Also, aldehydes can be an important fraction of HC emissions from diesel engines (Gentner et al., 2013). The current aldehyde standard is for Otto cycle vehicles only, but if applied in a fuel-neutral regulatory framework, could lead to emission reductions from diesel vehicles as well.

EMISSION LIMITS

Emission limits specify maximum allowable emission rates for regulated pollutants. Manufacturers must demonstrate that their vehicles are in compliance with these standards when tested on a chassis dynamometer while operating over specified driving cycles. In almost all cases, these standards are expressed as a mass of pollutant emitted per distance traveled, for example g/km[7].

The level at which emission limits are set is an important component in setting the overall stringency of regulatory control programs. Regulatory programs typically do not include provisions requiring specific emission control technologies. Rather, emission limits are used as the primary mechanism to ensure that efficient control technologies are brought to the market. This approach has resulted in the universal application of three-way catalytic converters to control NO_x, CO, and HC emissions from Otto cycle vehicles and, more recently, the application of diesel particulate filters (DPF) to control PM emissions from LD diesel vehicles in Europe.

Emission limits for CO, NO_x, HC, and PM are shown in Figure 9 for PROCONVE L6 (green bars), Euro 6 (orange bars), and U.S. Tier 2 and 3 (blue bars) programs. In Brazilian and European programs, standards are set by vehicle class and engine type, and all vehicle models of a given category must be certified to the corresponding standard. In contrast, the United States primarily follows a corporate averaging approach, whereby limits are set for the average emissions of a given manufacturer's entire LD vehicle fleet. This means that manufacturers have the flexibility to certify individual vehicle models to higher emission levels, or bins, as long as the sales-weighted emission rate for their entire fleet in a given model year falls below the fleet-average emission limit. The Tier 2 program set a fleet-average NO_x emission limit of 43 mg/km (Bin 5). In 2025, when Tier 3 standards are fully phased in, manufacturers must meet a fleet average NMOG+NO_x limit of 19 mg/km (Bin 30). Tier 3 PM emission limits are the exception to the corporate averaging approach. In this case, all vehicle models must meet the specified PM emission limit of 2 mg/km.

Emission limits for Brazil and the United States are directly comparable as they are measured over the same driving cycle. As will be discussed in the next section, the European Union uses a different certification driving cycle, and comparisons against Brazilian and U.S. emission limits are less straightforward. Here, we focus solely on the

7 Emission limits can also be set for the maximum concentration of a pollutant allowable in vehicle exhaust. For example, PROCONVE L6 includes an idle CO limit for Otto cycle vehicles of 0.2% by volume.

level at which emission limits are set in each regulatory program. Driving cycle effects will be addressed in following sections.

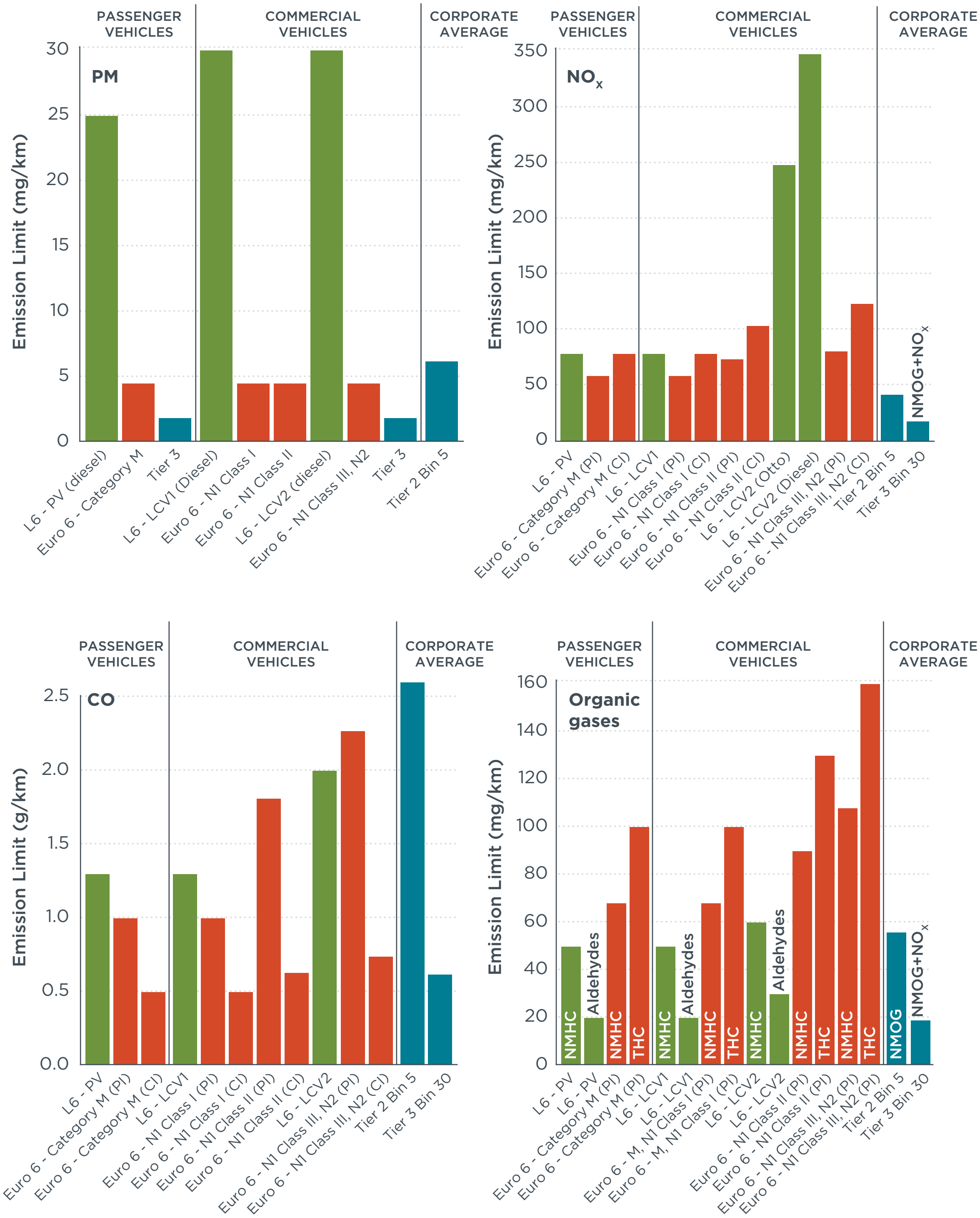

Figure 9. Tailpipe mass emission limits for LD vehicles in Brazil (green bars), the United States (blue bars), and the European Union (orange bars). Note PROCONVE L6 aldehyde limits apply to Otto cycle vehicles only.

Tailpipe emission limits shown in Figure 9 make clear the areas where Brazil lags behind regulatory programs in the United States and European Union. In particular, this is apparent in the levels at which PM emission limits are set. As mentioned above, PM emission limits in Brazil only apply to diesel vehicles. PROCONVE L6 PM limits for diesel passenger and commercial vehicles are 5 to 6 times greater than Euro 6 and Tier 2 limits and 12 to 15 times greater than the Tier 3 limit. Consequently, manufacturers are able to meet Brazilian standards without using the diesel particulate filter, which is the best available control technology for reducing PM pollution from diesel vehicles. This lax emission limit is a key reason behind the disproportionate PM emission impact of LD diesel vehicles relative to other LD vehicle types. Lowering the PM emission limit in the next phase of PROCONVE and making it applicable to all LD vehicles would be an important step toward reducing PM emissions from the LD fleet[8].

Similarly, PROCONVE L6 NO_x emission limits lag behind international best practices. The L6 NO_x limit for passenger and LCV1 class vehicles, 80 mg/km, is 33% greater than the Euro 6 limit for comparable positive ignition (i.e., Otto cycle) vehicles and almost twice as high as the U.S. Tier 2 Bin 5 limit. This disparity is even greater for larger light commercial vehicles. L6 NO_x limits for LCV2 class vehicles exceed Euro 6 limits for comparably sized vehicles by about a factor of 3. As noted above, most LCV2 class vehicles sold in Brazil have diesel engines. As is the case with PM, the lax NO_x emission limits for this vehicle class have led to a disproportionate emissions impact for LD diesel vehicles in Brazil.

The current best practice for LD vehicle NO_x control is set by the U.S. Tier 3 program, which will adopt a combined NMOG+NO_x limit of 19 mg/km when fully phased in. A similar limit for the next phase of PROCONVE would be an aspirational goal, though even adopting a NO_x limit at the Tier 2 Bin 5 level of 43 mg/km would significantly improve the NO_x emissions performance of the LD fleet.

In regards to CO, PROCONVE L6 limits lie between Euro 6 and Tier 2 Bin 5 levels. For CO, L6 emission limits generally exceed Euro 6 limits, but are between 23% and 50% lower than the Tier 2 Bin 5 limit. With the widespread application of catalytic converters, the role of CO in urban air-quality problems has been greatly diminished. Thus, relatively minor differences in CO emission limits are not expected to have a substantial impact on ambient air quality.

Limits for NMHC in PROCONVE L6 are more stringent than Euro 6 limits, and Brazil also includes a separate standard for aldehyde emissions. However, due to the different procedures used to define NMHC in the European Union and Brazil, specifically the discounting of ethanol in the Brazilian program, these limits are not directly comparable for flex-fuel vehicles. The United States regulates tailpipe organic gas emissions with a NMOG standard of 56 mg/km in the Tier 2 regulation and, when fully phased in, a NMOG+NO_x standard of 19 mg/km in the Tier 3 regulation. The Tier 2 NMOG limit is similar in magnitude to the L6 NMHC limit, though considerably more stringent for alcohol-fueled vehicles due to the full inclusion of oxygenates such as unburned ethanol. In the Tier 3 program, limits are set on the combined emissions of NMOG and NO_x. The Tier 3 corporate average

8 It is worthwhile to note that a reduction of the PM standard to a particulate filter-forcing level would need to be accompanied by parallel actions to reduce the sulfur content of commercial diesel fuels, as ultra-low sulfur fuels are required for advanced diesel emission control technologies.

NMOG+NO_x limit is initially set at 53 mg/km for model year 2017 vehicles. This limit is reduced each year through 2025, when a limit of 19 mg/km applies.

As was the case with NO_x and PM, U.S. Tier 3 limits represent current best practices for the control of emissions of CO and organic gases from LD vehicles. Long-term strategies for the continued reduction of emissions of these pollutants should aim to achieve emission levels on par with those set in the Tier 3 program.

TEST CYCLES AND PROCEDURES

During the vehicle certification, or type approval, process, vehicle manufacturers must demonstrate that their vehicles meet emission limits when tested on a chassis dynamometer. Each regulatory program includes technical specifications for the ways compliance must be demonstrated. These specifications include a simulated driving cycle or cycles over which the vehicle must be operated when emissions are measured and additional provisions designed to standardize the test process. Characteristics of a driving cycle, such as average speed, acceleration, or the number and length of stops influence emissions and thus the overall stringency of a given emission standard. Standardized driving cycles and test procedures are required to establish a systematic method for the legal certification of vehicle models. However, there are longstanding questions as to how well these laboratory tests are able to represent the real-world conditions under which emissions actually occur (Franco, Posada, German, & Mock, 2014; International Council on Clean Transportation, 2015).

In Brazil, certification test protocols are established in technical norms issued by the Associação Brasileira de Normas Técnicas (ABNT), a full listing of which can be found in the appendix. Technical norm NBR 6601 contains specifications for exhaust emission test procedures. The driving cycle used for LD vehicle certification in Brazil is the same as the U.S. Federal Test Procedure cycle (FTP-75). This cycle, referred to as the NBR 6601 cycle in Brazil, consists of three phases—a cold start transient phase, a stabilized phase, and a hot start transient phase. Emissions measured during each of the three phases are weighted to yield an average emission rate for the entire cycle. The speed pattern for the NBR 6601/FTP-75 cycle is included in Figure 10.

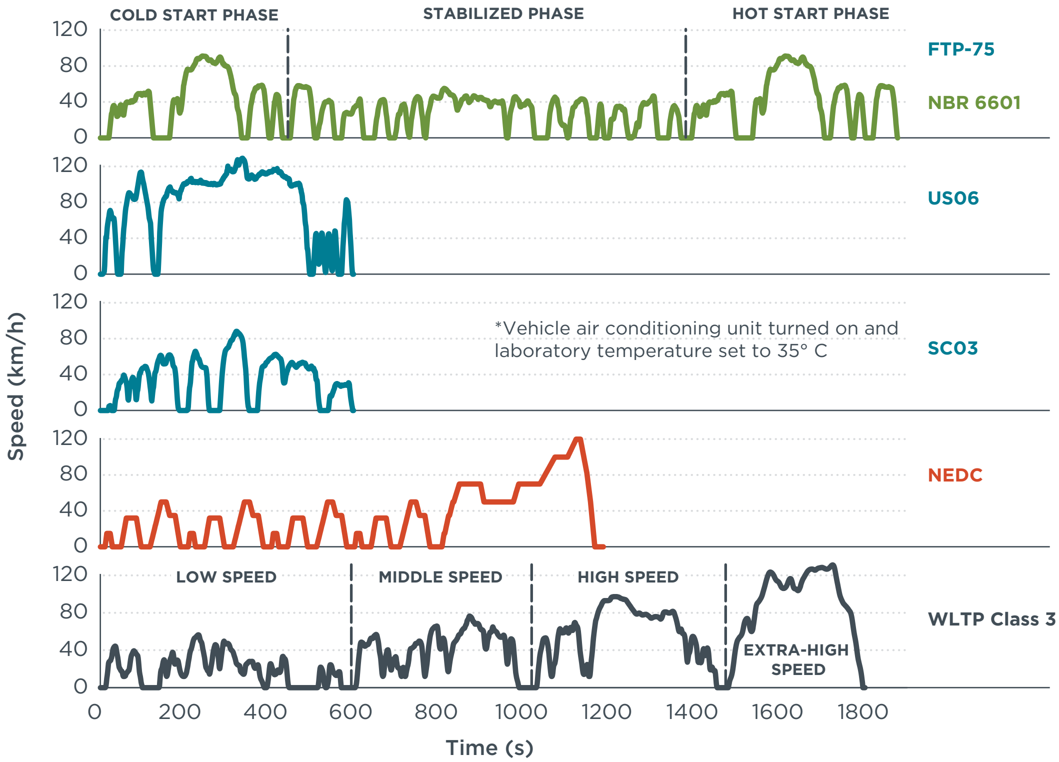

Figure 10. Emission test cycle speed patterns. FTP-75 = U.S. Federal Test Procedure; NBR 6601 = Brazilian certification driving cycle; US06 = U.S. Supplemental Federal Test Procedure high acceleration, aggressive driving cycle; SC03 = U.S. Supplemental Federal Test Procedure air conditioning driving cycle; NEDC = New European Driving Cycle; WLTP = Worldwide Harmonized Light Vehicle Test Procedure

In Brazil, the NBR 6601/FTP-75 is the sole driving cycle required for certification testing. In contrast, the United States has adopted supplemental standards, which require additional testing over driving cycles with operating modes not well represented in the FTP-75. The Supplemental Federal Test Procedures (SFTP) include emission testing on cycles representing aggressive, high-speed driving (US06) and operation at high ambient temperatures with an air conditioning load (SC03). The SFTP cover driving patterns that increase pollutant emissions and thus enhance the representativeness and strengthen the U.S. certification test program.

Recently, evidence has emerged showing deliberate actions by auto manufacturers to circumvent the vehicle certification process through the use of defeat devices. Most notably, Volkswagen was found to have used software in diesel vehicles that could recognize when vehicles were being driven on certification driving cycles. This enabled the vehicles in question to operate in a low-emissions mode to meet emission standards and in a more fuel-efficient and higher emissions mode when used in real-world operation. Consequently, real-world NO_x emissions from these vehicles were found to be up to 35 times greater than regulatory limits (Thompson, Carder, Besch, Thiruvengadam, & Kappanna, 2014). In response, the U.S. EPA has notified vehicle manufacturers that it will be expanding its compliance oversight activities by testing vehicles in unpredictable ways to deter similar actions by manufacturers in the future (U.S. EPA, 2015).

Type approval testing in the European Union is conducted over the New European Driving Cycle (NEDC). As can be seen in Figure 10, the NEDC is less dynamic than the NBR 6601/FTP-75 cycle, with more periods of constant velocity and acceleration. Overall, this results in a less aggressive, lower load cycle. Unlike the FTP-75 cycle, there is no weighting of emissions measured during subcycles of the NEDC, and any cold start effects on emissions are implicitly weighted at 100% (Kühlwein, German, & Bandivadekar, 2014). Looking forward, the European Union is in the process of transitioning from NEDC-based type approval procedures to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). The WLTP includes three driving test cycles, applicable to vehicle categories of different power-to-mass ratios. A speed trace for the WLTP Class 3 cycle is shown in Figure 10. WLTP test cycles were designed to be more characteristic of real-world driving conditions than the NEDC.

Europe is also taking steps to address longstanding disparities between type approval and real-world emissions performance. This has in particular been an issue for LD diesel vehicles in the European Union, and has contributed to persistent NO_x pollution problems in many European cities. Unlike the United States, Europe relies on a single test cycle for vehicle certification. This approach has generally been successful in controlling emissions from in-use gasoline vehicles. However, large disparities have been observed between in-use emissions from LD diesel vehicles and applicable emission limits (Chen & Borken-Kleefeld, 2014). There is now widespread recognition that the NEDC-based type approval process is not effectively controlling real-world emissions from diesel vehicles.

To address these issues, the European Union has adopted a real-world test component during the certification process (EC, 2016). For vehicle air pollutant emissions, the introduction of the Real Driving Emissions (RDE) procedure is expected to yield emission test results that are more in line with real-world driving experience. For RDE, instead of testing the vehicle only in a laboratory, additional testing will be conducted on the road under normal driving conditions. Vehicle emissions will be analyzed and recorded using portable emissions measurement system (PEMS) equipment.

International comparisons of certification test procedures highlight key areas in which the Brazilian vehicle certification program can be improved. Brazil uses the FTP-75 as the sole driving cycle for certification exhaust emissions testing. This cycle does not include certain driving patterns that can lead to higher pollution emission rates. As such, Brazil should consider adopting SFTP standards similar to those now in place in the United States to ensure these operating modes are fully represented in the vehicle testing process[9]. Given the predominance of Otto cycle vehicles in the Brazilian LD fleet, this step should lead to improvements in real-world emissions performance. Real-world testing using PEMS should be considered as part of an expanded compliance and enforcement program in Brazil.

DURABILITY REQUIREMENTS

During the vehicle certification process, vehicle manufacturers must show that emissions performance is maintained throughout a vehicle's full useful lifetime. Durability requirements in regulatory programs define the vehicle's useful life, typically expressed

9 It should be noted that the SC03 cycle test requires additional test facilities beyond what is needed for FTP-75 (NBR 6601) cycle testing. No facility upgrades would be required for US06 cycle testing.

as an accumulated mileage or vehicle age, and specify procedures for demonstrating that emission standards are met throughout this period. Generally, longer useful life periods encourage more robust emission control systems.

In Brazil, the vehicle useful life period is set at 80,000 km or 5 years of use, whichever comes first. This specification has not been changed since the inception of PROCONVE in 1986. Procedures for demonstrating compliance with emission standards over this lifetime are specified in ABNT technical norm NBR 14008. Broadly, manufacturers are required to apply deterioration factors to account for the decreased efficiency of emission control systems as a vehicle ages. Deterioration factors are stipulated for vehicles whose engine groupings have expected annual sales of fewer than 15,000 units. For vehicles with larger expected annual sales, manufacturers must determine deterioration factors experimentally through vehicle mileage accumulation testing.

The degree to which Brazil lags behind U.S. and EU durability requirements is shown clearly in Figure 11. In contrast to Brazil, U.S. and EU programs have continually increased vehicle useful life specifications with the implementation of new regulatory stages. For example, the European Union utilized a similar useful life period as Brazil, 80,000 km, in Euro 3 standards, which were implemented in 2000. The useful life period has been increased in subsequent regulatory stages and is currently set at 160,000 km. Similarly, the United States increased the full useful life period from 160,930 km to 193,120 km with the implementation of Tier 2 standards, and will extend the period to 241,400 km with the introduction of the Tier 3 program in 2017.

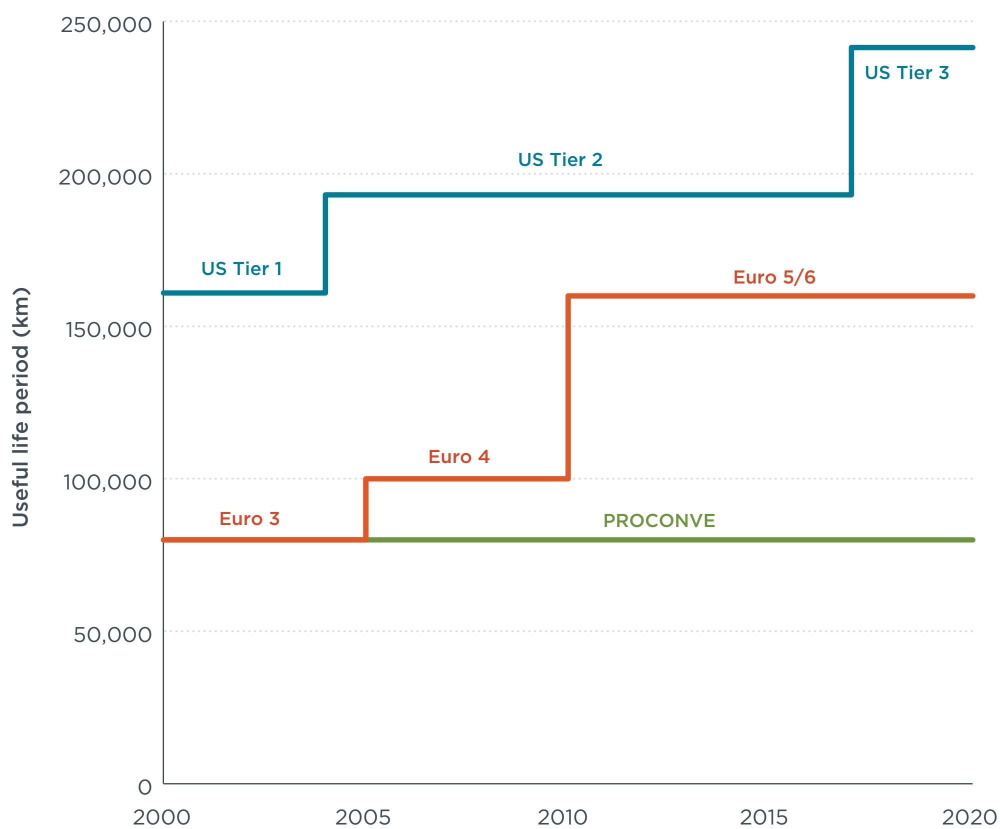

Figure 11. Vehicle useful lifetimes in LD vehicle regulatory programs.

Relative to Brazilian standards, the useful life periods adopted in the European Union and, especially, in the United States better reflect actual usage patterns of modern LD vehicles. In 2015, the average vehicle age for passenger cars in Brazil was 9 years (Sindicato Nacional da Indústria de Componentes para Veículos Automotores [Sindepeças], 2016). If it is assumed that vehicles travel on average 16,500 km per year (MMA, 2014), the average LD passenger vehicle in Brazil has an accumulated mileage of about 150,000 km. This value is nearly twice as high as the PROCONVE useful life period, and only represents the average vehicle in the Brazilian fleet. Many in-use vehicles are older and likely have been driven farther than this average value[10]. The PROCONVE useful life period is no longer representative of modern vehicle lifetimes and should be extended in future updates to the program. At a minimum, the 160,000 km useful life period adopted in current EU standards should be considered for Brazil. This step would better ensure that emission control systems are verified during the certification process to function efficiently throughout actual expected vehicle lifetimes.

Evaporative Emission Requirements

Evaporative emissions are a non-tailpipe source of HC emissions from motor vehicles. These emissions occur when hydrocarbon components of fuels volatilize and escape through the fuel system. Evaporative emissions can account for a significant fraction of total HC emissions from Otto cycle vehicles. This is especially true for regions where stringent tailpipe HC limits have been adopted without parallel regulatory actions to better control evaporative emissions (Liu et al., 2015). Evaporative emissions from diesel vehicles are generally not a concern due to the low volatility of diesel fuels. Thus, regulatory control programs typically only include evaporative emission requirements for Otto cycle engines.

Evaporative emissions are derived from a number of distinct processes and points within the fuel system, and can be broadly classified into five categories: diurnal, permeation, hot soak, running loss, and refueling emissions. Descriptions of these emission types are included in Table 5, along with information on main influencing parameters and control technologies. The degree to which evaporative emissions are addressed in regulatory programs varies by region. The United States has the most comprehensive approach, with stringent requirements in place for all major evaporative emission categories. Europe, and especially Brazil, lag behind the United States, and evaporative emission requirements thus represent a key area in which LD vehicle regulatory programs in these regions can be improved.

10 Sindipeças estimates that 28% of the Brazilian vehicle fleet is older than 10 years.

Table 5. Evaporative emission modes, influencing parameters, and control technologies

Emission mode	Description	Influencing parameters	Control methods	Included in regulatory program?		
				PROCONVE L6	Euro 6	US Tier 2/3
Diurnal	Daily temperature variations cause heating of fuel tank and venting of fuel vapors.	Diurnal temperatures, volatility of fuel, length of time vehicle is parked, carbon canister size and purge strategy	Carbon canister, air induction system HC trap	✔	✔	✔
Permeation[a]	Diffusion of fuel molecules through plastic and rubber components of the fuel system (e.g., tank, hoses, seals)	Materials used for fuel system components, fuel composition	Low permeation materials for fuel system components	✖	✔	✔
Hot soak	Evaporation of fuel caused by residual heat in engine and exhaust system following vehicle shut-off	Fuel pump technology	Carbon canister, air induction system HC trap	✔	✔	✔
Running loss	Evaporative emissions occurring during normal vehicle operation due to heating of fuel tank	Fuel pump technology, fuel return, driving conditions, tank temperature profile, tank pressure relief valve venting	Carbon canister	✖	✖	✔
Refueling	Fuel vapors in tank displaced by liquid fuel during vehicle refueling	Temperature and vapor pressure of fuel in vehicle tank and storage tank, fuel type blending in flex-fuel vehicles	Onboard refueling vapor recovery (ORVR) Stage II recovery (at fuel pump)	✖	✖[b]	✔

[a]Permeation emissions are not directly regulated in U.S. and EU programs. However, these emissions contribute to the total evaporative emissions measured during diurnal SHED testing. The compressed time-scale of the Brazilian diurnal emissions test (1 hour vs. 24, 48, or 72 hour) means permeation emissions are not well represented.
[b]In Europe, refueling emissions are controlled using Stage II systems installed at fuel dispensing stations.

The stringency of regulatory programs influences the extent to which manufacturers apply best available technologies for the control of evaporative emissions. The primary technology used to control evaporative emissions from motor vehicles is the carbon canister. Highly adsorbent activated carbon particles housed within the canister trap fuel vapors that would otherwise be emitted to the atmosphere. During normal vehicle operation, trapped vapors are purged from the canister and routed to the engine where they are combusted (Manufacturers of Emission Controls Association [MECA], 2010). Two main parameters that influence carbon canister effectiveness include the size of the canister and canister purging strategies. Larger canisters can accommodate greater amounts of activated carbon and thus are able to trap more fuel vapor before becoming saturated. The purging strategy, or calibration, influences how quickly trapped vapors are removed during canister regeneration. Generally, canister size and purge strategies are designed to meet certification test requirements adopted in a given region. As such, more challenging test procedures and stricter emission limits encourage more effective evaporative emission control systems.

Refueling emissions differ from other evaporative emission types in that they can be controlled either on the vehicle or at the fuel pump. Stage II controls refer to systems installed at the fuel pump, which are designed to capture vapor displaced from vehicle fuel tanks during the refueling process. In contrast, onboard refueling vapor recovery (ORVR) systems are installed in vehicles and route displaced vapors to the vehicle's carbon canister. Vehicle-based ORVR systems are generally considered to be more efficient and cost-effective than Stage II controls (Fung & Maxwell, 2011). In the United States, initial refueling emissions control was achieved using Stage II systems. However, beginning in 1998, new vehicles sold in the United States were required to be equipped with ORVR, and Stage II vapor control programs are now being phased out. Stage II controls are required for all new fuel dispensing stations built in the European Union, and existing stations with fuel throughput greater than 3,000 m^3 per year will be also be required to install Stage II controls before 2019 (EC, 2009). No ORVR requirements are in place for vehicles sold in the European Union. With no refueling emission control requirements in place currently, Brazil lags significantly behind the United States and European Union in this area.

Evaporative emission requirements for vehicle certification vary by region, though each of the regulatory programs considered here sets limits on diurnal and hot soak emissions and specifies test procedures for evaluating these emissions. Emission testing is conducted using a gas tight enclosure known as a Sealed Housing for Evaporative Determination (SHED) in which the vehicle is parked during testing. The basic components of the test procedure include pre-conditioning of the vehicle and carbon canister, dynamometer drive cycles, hot soak emissions testing, and diurnal emissions testing. For the hot soak portion of the test, the vehicle is parked with the engine off in the SHED following a dynamometer drive cycle. The test length is one hour, and evaporative emissions are determined through measurements of the HC concentration in the sealed test chamber. Similarly, diurnal emissions testing is conducted in the SHED following vehicle conditioning. In this case, emissions resulting from simulated temperature changes representative of typical diurnal profiles are evaluated. In the United States and European Union, diurnal temperature profiles are simulated by changing the air temperature in the SHED enclosure over time periods ranging from 24 to 72 hours (1-3 days). In contrast, the Brazilian test procedure calls for a 1-hour test during which the fuel tank is heated directly to simulate the effect of diurnal temperature changes on fuel temperature and evaporative emissions. For all programs, limits are set for the sum of hot soak and diurnal emissions.

The hot soak and diurnal emissions test program adopted in the United States is the most challenging in terms of emission limits, as well as test conditions. The U.S. program consists of separate 48-hour and 72-hour diurnal tests. The two tests are designed to encourage the use of evaporative emission control systems that can perform efficiently under conditions representative of real-world vehicle use. The 72-hour test establishes a design benchmark for achieving adequate canister storage capacity to allow for several days of parking on hot summer days, in addition to requiring vehicle designs that prevent emissions during high-temperature driving and shut-down conditions. The 48-hour test ensures purge strategies that create enough canister capacity to capture two days of diurnal emissions after limited driving (U.S. EPA, 2014). Emission limits for these tests are summarized in Table 6.

Evaporative emission requirements for LD vehicles in the European Union are less stringent. An analysis conducted by the European Commission Joint Research Centre (JRC) identified the key areas where EU evaporative test requirements lag behind U.S. requirements (JRC, 2012). These include:

» Diurnal test length: The European Union requires a single 24-hour diurnal emissions test. The compressed length relative to 48-hour and 72-hour U.S. tests means extended park situations are not well represented.

» Emission limits: The Euro 6 limit of 2.0 g/test is significantly greater than U.S. Tier 2 and 3 program limits (see Table 6).

» Test drive cycle: The drive cycle preceding diurnal emissions testing is nearly twice as long in the European Union (59 minutes) relative to the U.S. 48-hour test (31 minutes). The longer drive cycle enables more time for regeneration of the carbon canister and, consequently, does not promote aggressive canister purging calibrations. The extended drive time is not representative of urban conditions where vehicle trips are typically less than 1 hour.

As a result of the less challenging test procedures and higher emission limits, as well as the lack of ORVR requirements, evaporative emission control systems deployed on vehicles sold in the European Union are typically less efficient (e.g., smaller carbon canister capacity, less aggressive purge calibration) than those used for vehicles sold in the United States (Liu et al., 2015). Revisions to EU type-approval specifications for evaporative emissions are expected in upcoming amendments to the Euro 6 legislation; these revisions include introduction of multi-day diurnal testing.

Brazilian procedures for evaporative emissions testing are specified in ABNT technical norm 11481. The PROCONVE L6 program sets a limit for combined hot soak and diurnal emissions at 1.5 g/test. While the hot soak portion of the evaporative emission test generally follows procedures adopted in the United States and European Union, the diurnal portion differs significantly. In Brazil, diurnal emissions are measured using a 1-hour test, during which the fuel tank is heated to raise the fuel temperature from 16°C to 29°C. This heating simulates warming that occurs as the temperature changes during the course of a day. Hydrocarbon concentrations in the SHED enclosure are measured at the beginning and end of the test period to evaluate evaporative emissions. These diurnal test procedures are similar to methods used in the United States and European Union in the 1980s and 1990s. As described above, both of these regions transitioned away from fuel tank heating for diurnal testing and now require single or multi-day tests that are more characteristic of real-world vehicle evaporative emissions.

In addition to more stringent hot soak and diurnal emissions requirements, U.S. Tier 2 and 3 regulations also include additional evaporative emission requirements not included in EU or Brazilian programs. These provisions are summarized in Table 6 and include running loss, refueling, and canister bleed[11] limits; vapor leak detection requirements; in-use verification; and more stringent durability specifications.

11 Canister bleed limit introduced in Tier 3 program

Table 6. Regulatory program components for LD vehicle evaporative emissions.

Program components		Limit Values				
		Euro 3-5	**Euro 6c (proposed)**	**US Tier 2**	**US Tier 3**	**PROCONVE L6**
NBR 11481: 1-hr fuel tank heating + 1-hr hot soak						1.5 g/test
24-hr diurnal + 1-hr hot soak		2.0 g/day				
48-hr diurnal + 1-hr hot soak			2.0 g/day	0.65 g/day[1]	0.300 g/day[1]	
72-hr diurnal + 1-hr hot soak				0.50 g/day[1]	0.300 g/day[1]	
Running loss				0.03 g/km	0.03 g/km	
Vapor leak limits					0.5 mm	
Refueling	**Onboard**			0.053 g/L (95% efficiency)	0.053 g/L (95% efficiency)	
	At fuel dispensing station	90% efficiency 80-90% of stations	90% efficiency 80-90% of stations	90% efficiency 30% of stations	95% efficiency CA only	
Canister bleed					0.020 g/test	
Durability				193,000 km	241,000 km	Deterioration factor set at 10%
In-use verification				48-hr and refueling at 10,000, 50,000, and 100,000 miles	48-hr and refueling at 10,000, 50,000, and 100,000 miles	

[1]Tier 2 and 3 diurnal + hot soak limits shown in table are for LDV class vehicles. Limits are relaxed for LLDT, HLDT, and MDPV class vehicles.

Brazil lags far behind international best practices for control of evaporative emissions from LD vehicles. The PROCONVE program only addresses a subset of evaporative emission categories and relies on outdated certification test procedures that do not adequately represent real-world conditions. As a result, manufacturers can meet Brazilian standards using evaporative emission control systems that are less robust than those applied in other regions. Given persistent ozone problems in Brazilian cities, improvement of evaporative emissions control should be a key objective for future updates of PROCONVE. Perhaps the most effective regulatory step in this direction would be the adoption U.S. 48-hour and 72-hour evaporative emission test requirements along with more restrictive emission limits[12]. The more challenging test program would promote the use of larger carbon canisters and more aggressive purge calibrations, both of which would lead to real-world improvements in the evaporative emissions performance of LD vehicles. A shift to more stringent test procedures could be accompanied by an ORVR requirement to ensure this highly effective technology is introduced to the Brazilian LD vehicle fleet. Additionally, the inclusion of emission types that are not currently regulated, such as running loss and refueling emissions, would

12 Laboratory capacity may be a near-term barrier for implementation of a 72-hr SHED test in Brazil.

extend the scope of PROCONVE and provide for more comprehensive assessment and control of evaporative emissions.

Refueling emissions, in particular, represent an important target for urban HC emission reductions. Options for addressing these emissions include requirements for ORVR systems on new vehicles and/or Stage II and Stage I control requirements for fuel dispensing stations[13]. As mentioned above, ORVR requirements are generally considered to be the more efficient and cost-effective option. It should be noted, however, that ORVR requirements would only apply to new vehicles, and time scales for fleet-wide refueling emissions control would be on the order of 10 years (i.e., time period for fleet turnover). An alternative, hybrid approach consisting of ORVR requirements for new vehicles along with Stage II controls in areas with severe ozone problems has been proposed as a way to accelerate refueling emissions reductions (Szwarc, A., Farah, E.L., Branco, G., & Branco, F., 2014).

Any changes to evaporative emission requirements in PROCONVE should be made with a full consideration of the unique challenges imposed by the widespread use of ethanol in the Brazilian LD fleet.

ON-BOARD DIAGNOSTIC SYSTEM REQUIREMENTS

On-board diagnostic (OBD) systems are a monitoring and reporting tool used to evaluate the performance of engine and aftertreatment components, including those responsible for controlling emissions. OBD systems are designed to prevent high in-use emissions due to malfunctioning emission control equipment, reduce the time between the occurrence of a malfunction and its repair, and allow for the quick diagnoses of emission-related malfunctions. These functions are achieved through monitoring of the performance of important components of engine and aftertreatment systems to ensure they operate within designed parameters. OBD systems have also emerged as an important tool for vehicle inspection and maintenance programs.

Regulatory programs in each of the three regions considered here include requirements for OBD systems. These regulatory specifications define OBD system monitoring requirements, the conditions for monitoring, and the pollutant threshold values, which, if exceeded, indicate malfunctions of emission-related vehicle components. In Brazil, OBD requirements for Otto cycle vehicles were introduced in CONAMA Resolution N° 354/2004 (CONAMA, 2014) and implemented in two stages. The first stage, OBDBr-1, was phased in between 2007 and 2009. OBDBr-1 systems were relatively basic. These systems only included functionality monitoring of a limited number of emission-related components, and were not calibrated to a specific level of emission performance. More stringent requirements were introduced with the second stage of the Brazilian OBD program, OBDBr-2, which was phased in between 2010 and 2011. Additional monitoring requirements for OBDBr-2 systems include misfire detection, catalyst conversion efficiency (NMHC only), deterioration of the primary oxygen sensor, and canister purge faults. The shift to OBDBr-2 systems also introduced threshold limits. Specifications for OBD systems for LD diesel vehicles are included in IBAMA normative instruction Nº 5/2013, and are referred to as OBDBr-D.

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13 Stage I systems control emissions from the fuel storage tank at the filling station.

OBD system requirements for Brazilian LD Otto cycle vehicles are less comprehensive than those for vehicles sold in the United States and European Union. OBDBr-2 system requirements are similar to those for Euro 4 level European OBD (EOBD) systems (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, 2014). The European Union has since introduced additional monitoring requirements and more stringent threshold limits in Euro 5 and 6 legislation. In Tier 3 rulemaking, the United States adopted California OBD II requirements. The California OBD II program is considered to be the most comprehensive program in the world, and generally exceeds the EOBD program in applying threshold limits to specific emission control systems (Posada & German, 2016).

A comparison of important OBD system requirements for the three regulatory programs is shown in Table 7. OBDBr-2 systems omit a number of important monitoring requirements included in U.S. and EU programs. These include, but are not limited to, catalyst NO_x conversion efficiency, oxygen sensor downstream of the catalyst, fuel system monitoring, and in-use monitor performance ratio specifications. The omission of downstream O_2 sensor monitoring, in particular, is a serious shortcoming of the current OBDBr-2 system requirements.

Table 7. Comparison of important OBD system requirements for Otto cycle engines in the United States, European Union and Brazil[14].

System/component	U.S.: OBD II	EU: EOBD	Brazil: OBDBr-2
Catalyst efficiency (NMHC)	✔	✔	✔
Catalyst efficiency (NO_x)	✔	✔	✖
Upstream O_2 sensor	✔	✔	✔
Downstream O_2 sensor	✔	✔	✖
Misfire detection	✔	✔	✔
Fuel system monitoring	✔	✔	✖
Electrical diagnosis	✔	✔	✔
Secondary air monitor	✔	✔	✖
Cylinder imbalance diagnosis	✔	✖	✖
In-use monitor performance ratio (IUMPR)	✔	✔	✖
Flex-fuel systems (E19-E100)	✖	✖	✔

Threshold limits in Brazilian OBD specifications are also higher than those in EU or U.S. OBD programs. Ratios of OBD threshold limits to certification emission limits for each program are shown in Figure 12. This ratio is a useful metric to gauge how likely a poorly performing emission control system component is to trigger a malfunction indication. Higher ratios mean OBD systems are less likely to report malfunctions with deterioration or failure of emission control system components. Especially for NO_x and HC, threshold limits in Brazilian regulations are far higher than limits in the European Union and United States. This is partly due to the fact that threshold limits remained unchanged as Brazil adopted more stringent certification emission limits in the transition from PROCONVE L5 to PROCONVE L6.

14 Table adapted from Tautiva, Junior, and Furlan (2013).

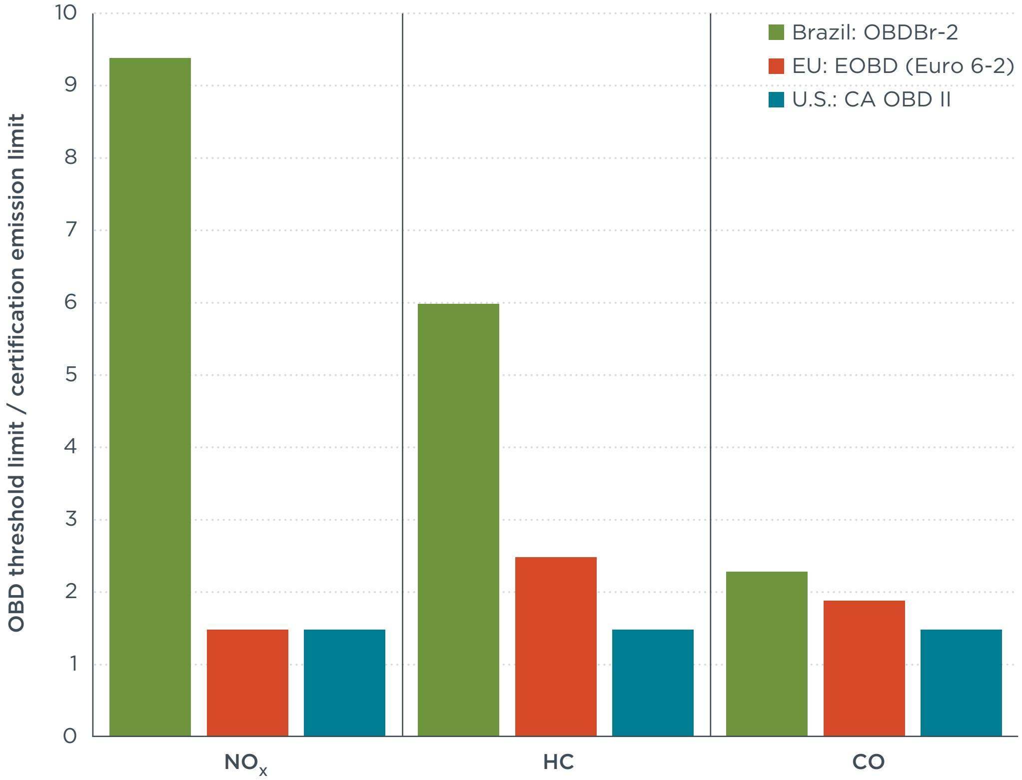

Figure 12. Ratio of OBD threshold limits to certification emission limits by pollutant and regulatory control program. Note that a ratio of 2.5 applies for NO_x and NMOG catalytic converter conversion efficiency in the California OBD II program.

In the next phase of PROCONVE, Brazil should consider updating OBD system requirements for LD vehicles. Improvements to the program can be made through expansion of monitoring requirements, adoption of in-use monitor performance ratios (IUMPRs) to better specify required monitoring frequency, and tightening of OBD threshold limits. Given that Brazil has largely followed the European framework for OBD requirements, a logical next step would be to expand the OBDBr program to include additional provisions introduced in Euro 5 and 6 legislation. A more forward-looking step would be to shift to an OBD program based on the more comprehensive California OBD II requirements.

POLICY RECOMMENDATIONS

This comparison of PROCONVE phase L6 with U.S. and EU regulatory programs highlights a number of areas in which the Brazilian program can be improved upon. A key insight that emerges from this comparison relates to the evolution of PROCONVE relative to the development of U.S. and EU regulatory programs. In Brazil, the stringency of successive stages of PROCONVE has been increased largely through the adoption of more stringent emission limits. In contrast, U.S. and EU programs have developed through the implementation of advanced certification test procedures and specifications in addition to more stringent emission limits. Some of these changes have been highlighted in this paper, and include longer vehicle useful lifetimes, drive cycles covering a broader range of expected operating conditions, real-world driving test requirements, and more challenging evaporative emission testing. In sum, these improvements to U.S. and EU programs serve to enhance the representativeness of the vehicle certification process and lead to more effective control of real-world emissions from LD vehicles.

Brazilian test procedures and specifications have not undergone similar development and represent a key area in which PROCONVE can be improved. In this paper, we have identified a number of the specific areas in which the Brazilian program to control emissions from LD vehicles lags behind international best practices. These shortcomings are summarized in Table 8, along with potential improvements to be considered for the next phase of PROCONVE, L7.

Table 8. Shortcomings of PROCONVE L6 and recommended improvements for PROCONVE L7.

Program component	Areas where PROCONVE L6 lags behind international best practices	Recommended changes for PROCONVE L7
Vehicle classification	Large SUVs and passenger vans may be excluded from LD vehicle regulatory program	Adopt medium-duty passenger vehicle classification so that all passenger vehicles are subject to same regulatory program
Regulated pollutants	Diesel and Otto cycle vehicles subject to different emission standards	Adopt fuel-neutral emission standards
	NMHC standard does not include important classes of organic gases; unburned ethanol emissions are unregulated	Regulate organic emissions with a NMOG standard; maintain aldehyde standard
Tailpipe emission limits	NO_x emission limits for LD commercial vehicles and PM limits for LD diesels lag far behind current limits in the U.S. and EU	Tighten PM and NO_x emission limits
	Generally, tailpipe emission limits remain less stringent than international best practices	Develop road map for achieving U.S. Tier 3 emission level performance
Test driving cycles and certification procedures	NBR 6601 driving cycle does not cover potential high-emission driving modes	Adopt SFTP standards

Program component	Areas where PROCONVE L6 lags behind international best practices	Recommended changes for PROCONVE L7
Durability requirements	Useful life period is not representative of modern vehicle lifetimes	Increase useful life specification to 160,000 km at minimum
Evaporative emission requirements[1]	Evaporative emission certification test procedures are not representative of real-world conditions	Adopt U.S. 48-hour and 72-hour evaporative emissions tests along with more stringent emission limits Introduce running loss test and emission limits
	No requirements for control of refueling emissions in place	Require ORVR systems for new vehicles. Consider Stage I and II controls to accelerate emissions reductions in areas with severe ozone problems
OBD system requirements	Scope of system components subject to monitoring lags behind international best practices	At minimum, adopt Euro 6-2 EOBD system requirements; consider California OBD II as better alternative
	OBD threshold limits set well above certification emission limits	Lower threshold limits to levels more in line with international best practices

[1]Changes to evaporative emission requirements should also consider the effects of the widespread use of ethanol in Brazil. Additional research is needed to ensure test procedures developed in the United States and European Union fully capture the effects of higher ethanol content of Brazilian fuels.

Future developments of PROCONVE should be made with the goal of aligning Brazilian standards with the U.S. Tier 3 program. Tier 3 regulations provide the most comprehensive approach to controlling emissions from LD vehicles, combining stringent emission limits with certification procedures that encourage effective real-world emissions control. This transition would involve extensive revisions and updates to many aspects of PROCONVE, and would need to be phased in over a number of years. However, in the near term it will be important for Brazilian regulators to develop a road map for implementing Tier 3 level emission standards.

CONCLUSIONS

Light-duty vehicles represent a significant source of air pollutant emissions in Brazil and contribute to longstanding urban particulate matter and ozone pollution problems in the country. Beginning with its introduction in 1986, PROCONVE has been instrumental in improving the emissions performance of new vehicles sold in the country, and has offset some of the impacts of the rapidly growing Brazilian fleet. The continued growth of the LD fleet, emerging challenges related to new engine technologies, increased dieselization of the LD commercial vehicle fleet, and other changes mean continued progress is needed to mitigate the risks to human health and the environment associated with motor vehicle pollution.

The full implementation of the current phase of PROCONVE, L6, began in 2013 and was fully achieved in 2015. Brazilian regulators should now consider the evolution of the program. The primary goal of this paper was to contribute to this process through an objective analysis of important components of PROCONVE L6 and their relative strengths and weaknesses compared with similar components of U.S. and EU regulatory programs. While not exhaustive, this review considers main elements of these regulatory programs, including vehicle classification, regulated pollutants, emission limits, test cycles and procedures, durability requirements, evaporative emission requirements, and OBD system requirements.

The main findings presented here show the Brazilian program for LD vehicle emissions control lags behind international best practices in many key areas. Brazil has failed to match increasingly stringent emission limits with parallel developments in other important program components. Advanced certification test procedures and specifications adopted in the United States and European Union, such as supplemental drive cycles and multi-day evaporative emission testing, have yet to be integrated into the Brazilian program. Similarly, useful life specifications in Brazil remain unchanged from the inception of PROCONVE in 1986, and no longer reflect actual lifetimes of modern LD vehicles. Adopting more advanced certification procedures alone would help to improve the real-world emissions performance of LD vehicles in Brazil. Additional improvements can be achieved through the tightening of pollutant emission limits, which generally are less stringent than those in the United States and European Union. In particular, NO_x and PM emission limits for LD commercial vehicles remain substantially higher than international best practices, and are a main reason for the disproportionate emissions impact of LD diesel vehicles in Brazil.

U.S. and EU programs provide examples for the advancement of the PROCONVE program. Of the programs considered here, the U.S. Tier 3 regulation provides the most comprehensive approach to LD vehicle emissions control. Brazilian regulators should develop a road map to achieve Tier 3 level emission standards through updates to PROCONVE. While the full scope of these changes may not be achievable in the L7 phase, important advances toward this goal can be made through modernization of certification test procedures and adoption of more stringent emission limits.

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Appendix. ABNT technical norms related to regulatory motor vehicle testing in Brazil.

Norm	Description
NBR 6601:2012	Light-duty vehicles: Determination of hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide and particulate matter in exhaust gas
NBR 1176:2006	Road vehicles: Masses - vocabulary and codes
NBR 7024:2010	Light-duty vehicles: Fuel consumption determination
NBR 8689:2012	Light-duty vehicles: Test fuel requirements
NBR 10312:2014	Light-duty vehicles: Road load measurement and dynamometer simulation using coastdown techniques
NBR 11481:2010	Light-duty vehicles: Evaporative emission measurement
NBR 12026:2009	Light-duty vehicles: Determination of aldehydes and ketones in exhaust gas by liquid chromatography - DNPH method
NBR 12857:2016	Requirements for calibration gas mixtures for use in vehicular emission laboratories
NBR 14008:2007	Light-duty vehicles: Determination of emission deterioration factor through mileage accumulation
NBR 15598:2008	Light-duty vehicles: Test method for determination of unburned ethanol in exhaust gas by gas chromatography
NBR 10972:2010	Light-duty vehicles: Measurement of carbon monoxide concentration in exhaust gas operating at idle