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REVIEW

Regulating light-duty vehicle emissions: an overview of US, EU, China and Brazil programs and its effect on air quality

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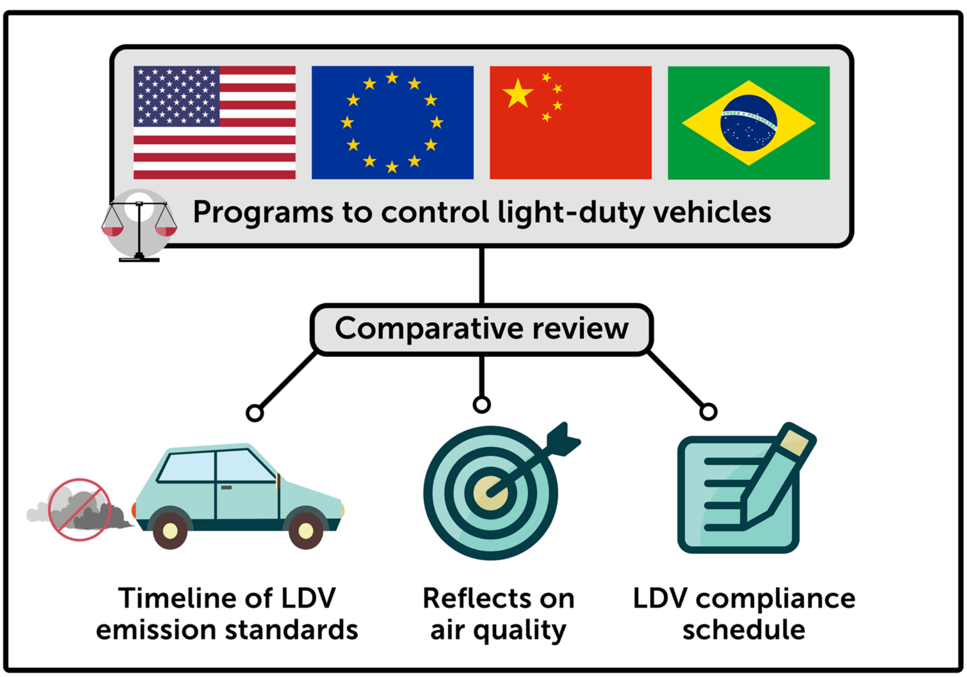
Abstract
This paper reviews the progress and effectiveness of Programs to Control Vehicle Emissions (PCVEs), comparing the experiences in the United States (US), European Union (EU), China, and Brazil. We present a timeline comparison of updates and differences in standards for light-duty vehicle (LDV) compliance. We then review the benefits of controlling LDV emissions on air quality, derived from previous relevant studies. Emission standards have been increasingly restricted in all evaluated PCVEs. However, some technical aspects such as dynamometer test cycles, re-testing structure of environmental protection agency, homogeneity of new and in-use vehicles inspection and maintenance, on-board diagnostics requirements are more consolidated in the US. Previous studies at different scales show the success of PCVEs in reducing vehicle emissions and air pollutant concentrations in the US, EU, China, and Brazil. Despite PCVEs has been achieving relative success, vehicular emissions are still a major threat to air quality around the world, especially in developing countries or ascending economies whose fleet grows dramatically. In places where the air quality standards recommended by the World Health Organization (WHO) are violated, it would be required the implementation of more stringent regulations with a well-designed, and homogeneous compliance policy over regional and national territories. This work contributes to clarifying the current challenges and successful experiences on regulating vehicular emissions worldwide.

Graphical abstract



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Keywords Light-duty vehicles · Policy regulation · Air quality · Vehicular emissions · Emissions control

Introduction

LDV are still considered massive emitters of air pollutants in urban areas (Lyu et al. 2020). Policymakers should be prepared for the challenges of controlling LDV emissions while tackling global warming and air quality issues in the coming future. The US and EU PCVEs are pioneer and guided vehicle emission control worldwide. For instance, the Brazilian PCVE is influenced by the US and EU programs, while China's control policy referenced only the EU PCVE until recently (Dallman and Façanha 2017; Lyu et al. 2020). Even though pioneer and other notable programs may share similarities in imposed emissions standards, all these programs differ in technical structure and procedures, implementation schedule and execution (Rodríguez et al. 2019). Consequently, they reached different effectiveness to reduce vehicle emissions and air pollutant concentrations over the years.

It is imperative for better controlling vehicle emissions in the present and future to have a clear view of the current challenges and profit from past lessons. Understanding pioneers and other notable programs could provide essential information for new proposals and directions for controlling LDV emissions. Among developing countries, Brazil and China have implemented important vehicular emissions restrictions (ICCT 2020a; b, c). China has experienced a massive increase in vehicle registration in recent decades, while Brazil is the fourth largest vehicle producer in the world, representing ~ 48% of the in-use vehicle fleet in Central and South America (OICA 2020). Both Chinese and Brazilian PCVEs can provide valuable information for implementing PCVEs in emerging economies.

Several studies conducted by the International Council on Clean Transportation (ICCT) provide recommendations for PCVEs in the EU (Mock and German 2015), China (Rodriguez et al. 2019) and Brazil (Dallmann and Façanha 2017). Rodriguez et al. (2019) addressed several common and current aspects of PCVEs in the US, EU, and China. The authors showed that the US and China programs (from stage 6 onwards) are more restrictive compared to the EU, mainly due to neutral fuel standards and tighter limits for exhaustive nitrogen oxides (NOx), particulate matter (PM), and organic gases (OG).

Previous studies provided an outlook of US (He et al. 2017), EU (Hooftman et al. 2018), Chinese (Lyu et al. 2020) and Brazilian (Dallman 2020) PCVEs. Other studies evaluated the vehicle emissions and air pollutant concentrations in some periods after PCVEs was implemented in US (Parrish et al. 2009), EU (Winkler et al. 2018), China (Wu et al. 2016) and Brazil (Andrade et al. 2017). Also, the researchers evaluated and revised additional strategies to PCVEs in developed and developing countries, such as the creation of low emission zones, traffic restriction by time and type of vehicle, or even the application of post-emission control measures associated with air quality management programs (Gulia et al. 2015, 2020). In most cases, studies are focused on the current characteristics of each program. However, a timeline comparison of emission standards and the technical structure of environmental agencies to ensure LDV compliance were not explored by previous research. It is imperative to investigate the PCVEs progress in developed and developing countries regarding the effectiveness in reducing vehicular emissions and improving air quality.

In this work, in addition to a timeline comparison of stages and associated emission standards of PCVEs, we address the following questions: (i) what are the basic priority measures of environmental agencies to ensure LDV compliance on a national scale? (ii) what is known of PCVEs effectiveness in controlling vehicular emissions and atmospheric pollutant concentrations in US, EU, China, and Brazil? We highlighting the best practices of PCVEs and some useful instruments to control vehicle emissions in developing countries.

Comparison of US, EU, Chinese, and Brazilian PCVEs

In 1965, the US established the first vehicular emission standards and requirements, based on the federal law Clear Air Act. Five years later, the EU implemented vehicle emission standards and requirements, following the directive 70/220/EEC from 1970 (TransportPolicy 2020a, b). Since the US and EU have started their regulation, most countries worldwide followed their programs. The US PCVE has been using longer periods between two implementation stages, while China, Brazil, and the EU have adopted multiple stages using shorter periods among them. The Tier 2 stage from the US PCVE was the longest stage among all programs, the migration from Tier 2 to Tier 3 took more than 10 years (Fig. 1). The strategy used by the US PCVE intends to ensure the consolidation of all requirements over the territory during the new stage planning.

Since Tier 1 and 2, the US PCVE consolidated the LDV compliance, regulated pollutant types, emission standards without difference for otto and diesel LDV (neutral fuel), and other aspects. Years later, Tier 3 imposed ambitious emission standards for LDV, demanding new monitoring technologies for controlling the exhaust and evaporative emissions (Transport Policy 2020a; He et al. 2017).

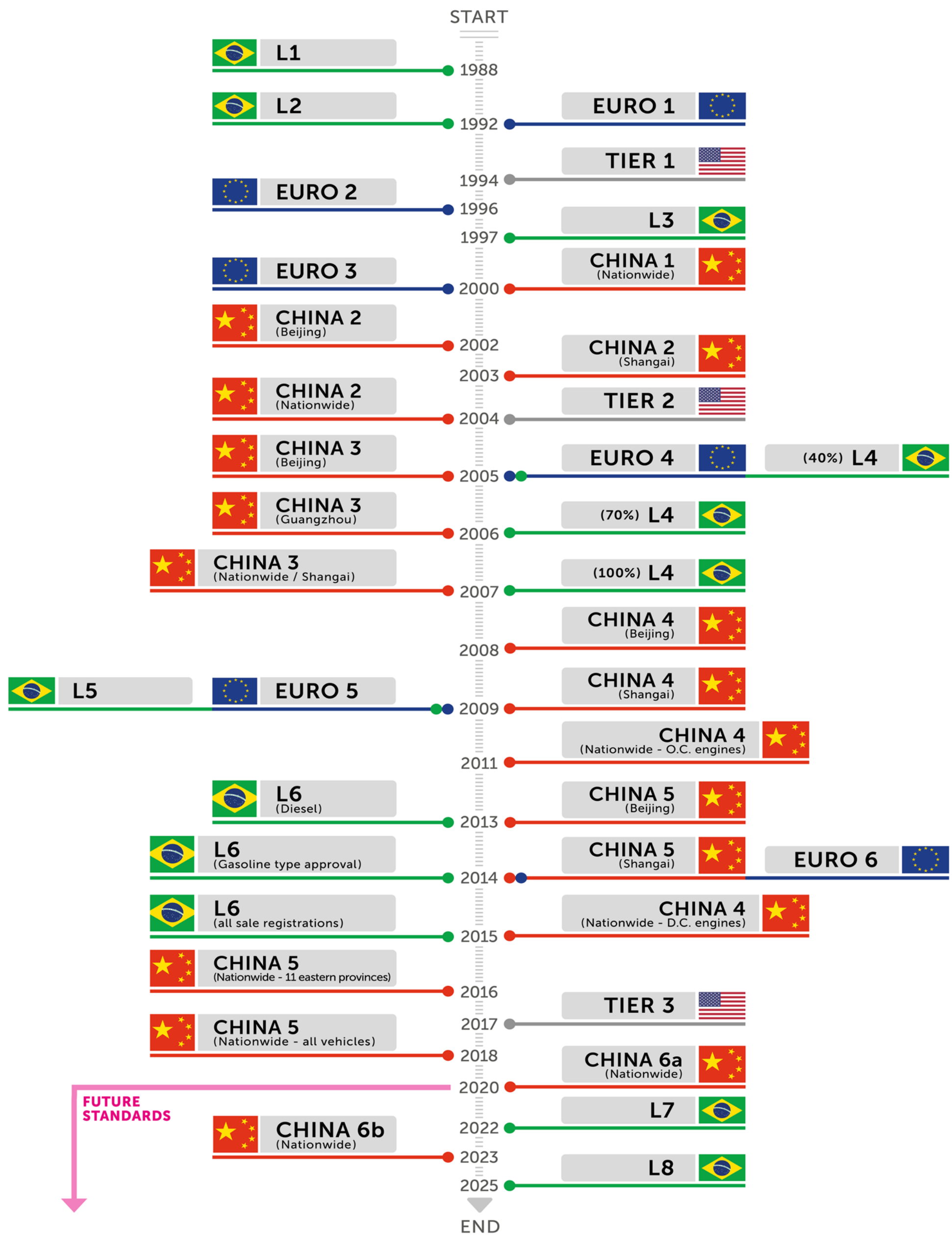

Fig. 1 Timeline (from 1988 to 2025 period) of implemented PCVEs stages and associated emissions standards in the US, EU, China, and Brazil PCVEs for LDV (DieselNet 2020a, b, c, d; TransportPolicy 2020a, b, c, d)

From 1992 to 2016, the EU implemented 6 new regulation stages, where the emission standards for LDV reduced progressively. However, fuel type distinction, organic pollutants regulated, and LDV compliance program were not modified or included over the years as in the US PCVE. China followed the EU PCVE until China 5 stage. Since stage 6, China has included requirements of the US PCVE, with neutral fuel standards (Lyu et al. 2020). The Chinese PCVE allow municipalities to implement a new stage and associated emissions standards before it has been applied in national scale. The cities of Beijing and Shanghai were the first to implement new LDV emission standards (Fig. 1) (Transport Policy 2020c). Due to coronavirus and lockdown, only 16 provinces implemented China 6 stage, while nationwide implementation is extended for 2021 (TransportPolicy 2020c).

In 1986, the Brazilian National Environment Council (CONAMA) created its PCVE, with eight stages (from L1 to L8) since then. This program was based on federal resolutions CONAMA 18/1986 (L1–L2), CONAMA 8/1993 (L3), CONAMA 315/2002 (L4–L5), CONAMA 415/2009 (L6), and CONAMA 492/2018 (L7–L8) (Transport Policy 2020d; Dallman and Façanha 2017). Despite the US PCVE have had some influence on dynamometer tests and the organic regulated pollutants types, the Brazilian PCVE was mainly based on the EU program, sharing the same issues related to

LDV compliance, and different emission standards for otto and diesel engines.

A comparison of PCVEs exhaust emission standards of carbon monoxide (CO), NOx, PM, hydrocarbons (HC), and OG + NOx for passenger vehicles (PV) is shown in Fig. 2. For the same pollutants, Fig. 3 shows standards for light-duty commercial vehicles (LDCV)/light-duty trucks (LDT). Heavy light-duty trucks (HLDT) on Tier 1, Tier 2 (bin 5), and Tier 3 were considered. Vehicles classified as N_1 class III, LDV type 2 (class III), and class II, respectively in EU, China, and Brazil are also included in Fig. 3. HLDT is a US designation for trucks and vehicles with a gross weight from 3750 to 5750 lb. The LDCV classes selected for EU, China, and Brazil are similar to the HLDT class in the US. This gross weight class commonly includes pickup trucks, sport utility vehicles (SUVs), vans, and minivans (DieselNet 2020a, b, c, d).

For all pollutants, the emission standards for PV (Fig. 2) and LDCV/LDT (Fig. 3) became more restrictive over the successive PCVEs stages. The emission standards for PV and LDCV/LDT follow a similar temporal profile for all evaluated PCVEs. Furthermore, the contrast in the level of restriction between PCVEs is similar for the two vehicle categories. However, for all pollutants and PCVEs, emission standards for PV are generally less restrictive compared to LDCV/LDT standards (Figs. 2 and 3). Since Tier 2, NOx and HC standards from the US PCVE are the most restrictive among the programs. Tier 3 imposed drastic reductions for PM and OG + NOx. CO standards on Tier 3 approached the regulation level proposed by the EU, China, and Brazil programs for diesel cycle LDV engines (Figs. 2 and 3).

Restrictions of CO, NOx, and HC were greatly improved from L2 to L6 stages of Brazilian PCVE. Since L7, the emission standards of HC and NOx were replaced by OG + NOx, moving near to the US program. In L8, the same standards of OG + NOx are used for controlling PV and LDCV. In L7 and L8, PV and LDCV are controlled by the same standard of PM and CO. PM was regulated only for diesel-fueled LDV until the L6 stage (Figs. 2 and 3).

EU and China share similarities on emission standards of all regulated pollutants, from stages 1 to 6 of EU PCVE, and 1–5 of China's program. During these stages, EU and China's PCVEs differ basically on the implementation dates. Both programs present the most restrictive CO and NOx standards for diesel cycle and otto cycle LDV, respectively. Euro 5 and 6 imposed equal restrictions of PM for diesel and otto cycle. HC + NOx emission of otto cycle LDV was regulated until Euro 2. After Euro 3, otto cycle emissions are controlled by individual standards of HC and NOx, while the diesel-fueled LDV are still regulated by the sum of these compounds.

A comparison among PCVEs can be done on CO, PM, NOx, HC, OG + NOx, HC + NOx standards for PV and LDCV/LDT, considering vehicles with the same gross

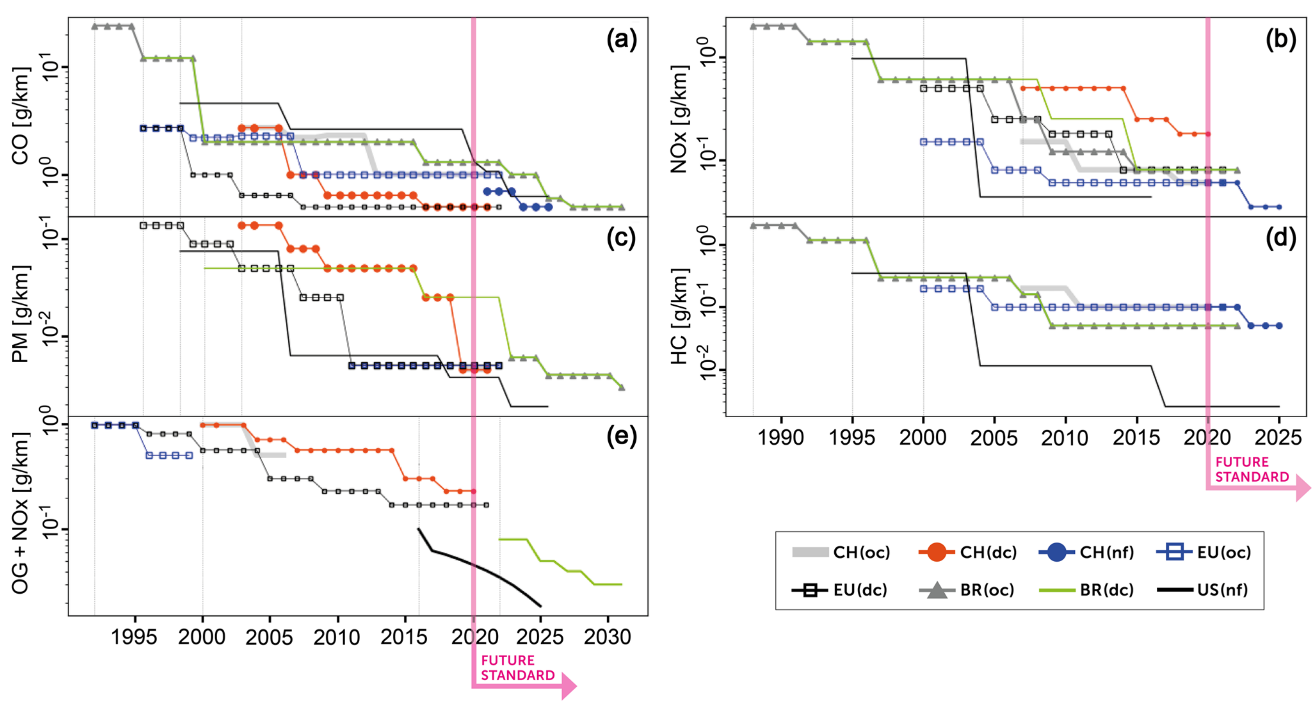

Fig. 2 Exhaust emissions standards (log scale) of (**a**) CO, (**b**) NOx, (**c**) PM, (**d**) HC, and (**e**) OG + NOx for PV otto cycle (oc), diesel cycle (dc), and neutral fuel (nf) in the US, EU, China, and Brazil PCVEs (TransportPolicy 2020a, b, c, d)

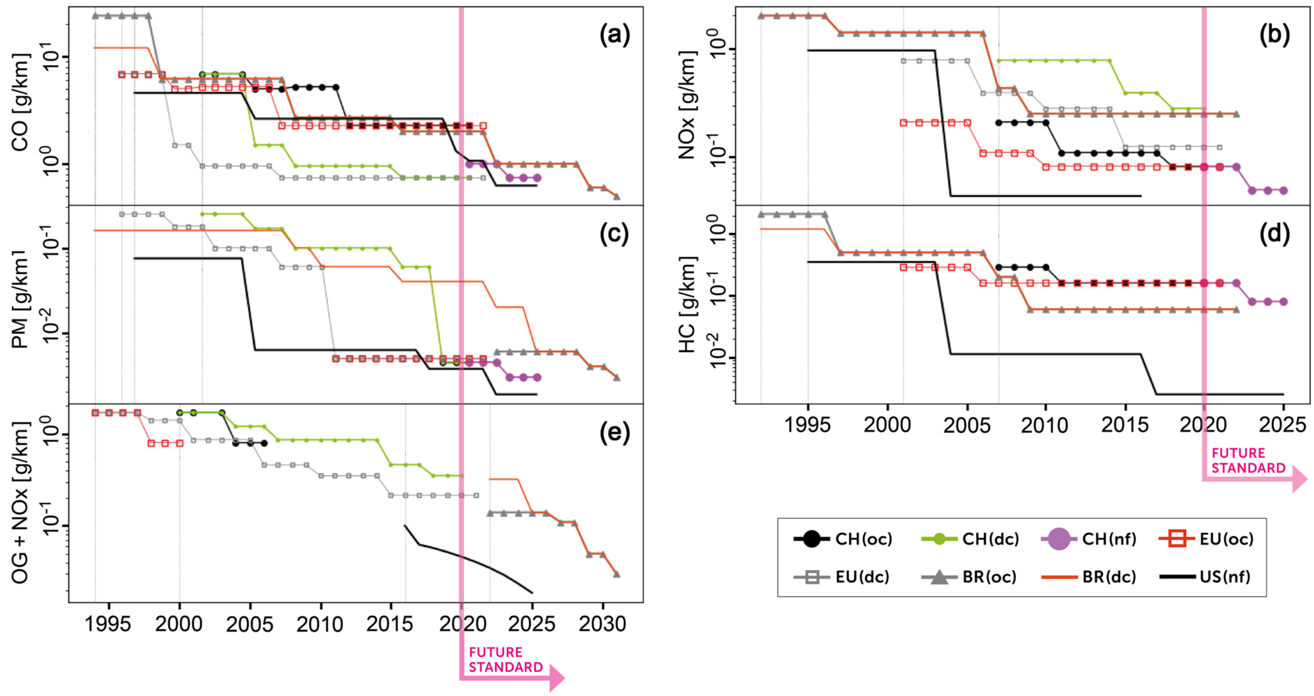

Fig. 3 Exhaust emissions standards (log scale) of (**a**) CO, (**b**) NOx, (**c**) PM, (**d**) HC, and (**e**) OG + NOx for LDCV/LDT (oc, dc, and nf) in the US, EU, China, and Brazil PCVEs (TransportPolicy 2020a, b, c, d)

weight, regardless of dynamometer tests operational conditions. China 6a and 6b present the most restrictive standards of CO and NOx, and slightly more permissive values than the US PCVE for PM and HC emissions (Fig. 4) (Dallmann e Façanha 2017). Euro 6 is the most restrictive stage for HC + NOx emissions, while the Brazilian PCVE enforces the lowest control level of these pollutants (Fig. 4).

All PCVEs have a compliance schedule to ensure that vehicles comply with emissions and fuel economy requirements. The PCVEs compliance is based on actions to be done by regulators and manufacturers. These actions occur during the prototype (pre-production), while they are in production and post-production. (Fig. 5). In the US and, recently, in China, the programs require that all vehicles should be covered by a certificate of conformity during their lifetime. The conformity is re-monitored when the vehicle reaches 10,000 km in China, and 16,000 km in the US. In the EU, a new certificate of conformity is required for LDV after running 80,000 km. No re-certification is needed in Brazil once the vehicle has entered commerce.

While in the US and China regulators have the autonomy to re-evaluate and re-certificate LDV in low and medium-mileage conditions, in the EU and Brazil the compliance is more vulnerable to failures (Fig. 5) (Mock and German 2015). Some difficulties in evaluating LDV compliance and fraud susceptibility in emissions tests are shared by the EU, China, and Brazil. It can be associated with the heterogeneity of technical and political structure over the territories (Lyu et al. 2020). The compliance evaluation of in-use LDV is a hard task without technical and financial support in many municipalities (Ventura et al. 2020), especially those in some regions of developing countries (Dallman 2020).

Many studies have demonstrated the discrepancies between LDV real emissions and PCVEs regulation standards in the EU (Bishop et al. 2019; Kousoulidou et al. 2013), in China (Huang et al. 2013; Zheng et al. 2018), and Brazil (Pérez-Martínez et al. 2014). It seems that in the US the PCVE is more effective, due to the consolidated US Environmental Protection Agency (EPA) technical structure and legal authority for ensuring its execution (Bandivadekar et al. 2015). Moreover, the US EPA has the technical ability to evaluate and confirm the results presented by the manufacturers (~ 15% of LDV pass through the EPA laboratories) (He et al. 2017). In the US program, the inspection results are transparent to the public, include punishments, recalls (voluntary or with the legal process), tax sanctions and compensation (Maxwell and Hannon 2017). Besides being more efficient in new LDV compliance, the testing structure of US PCVE allows in use LDV to remain subject to EPA inspection, maintenance and durability requirements (Mock and German 2015).

In the EU and China (except some regions), environmental regulators do not still have their established re-testing programs (Mock and German 2015; Rodríguez et al. 2019).

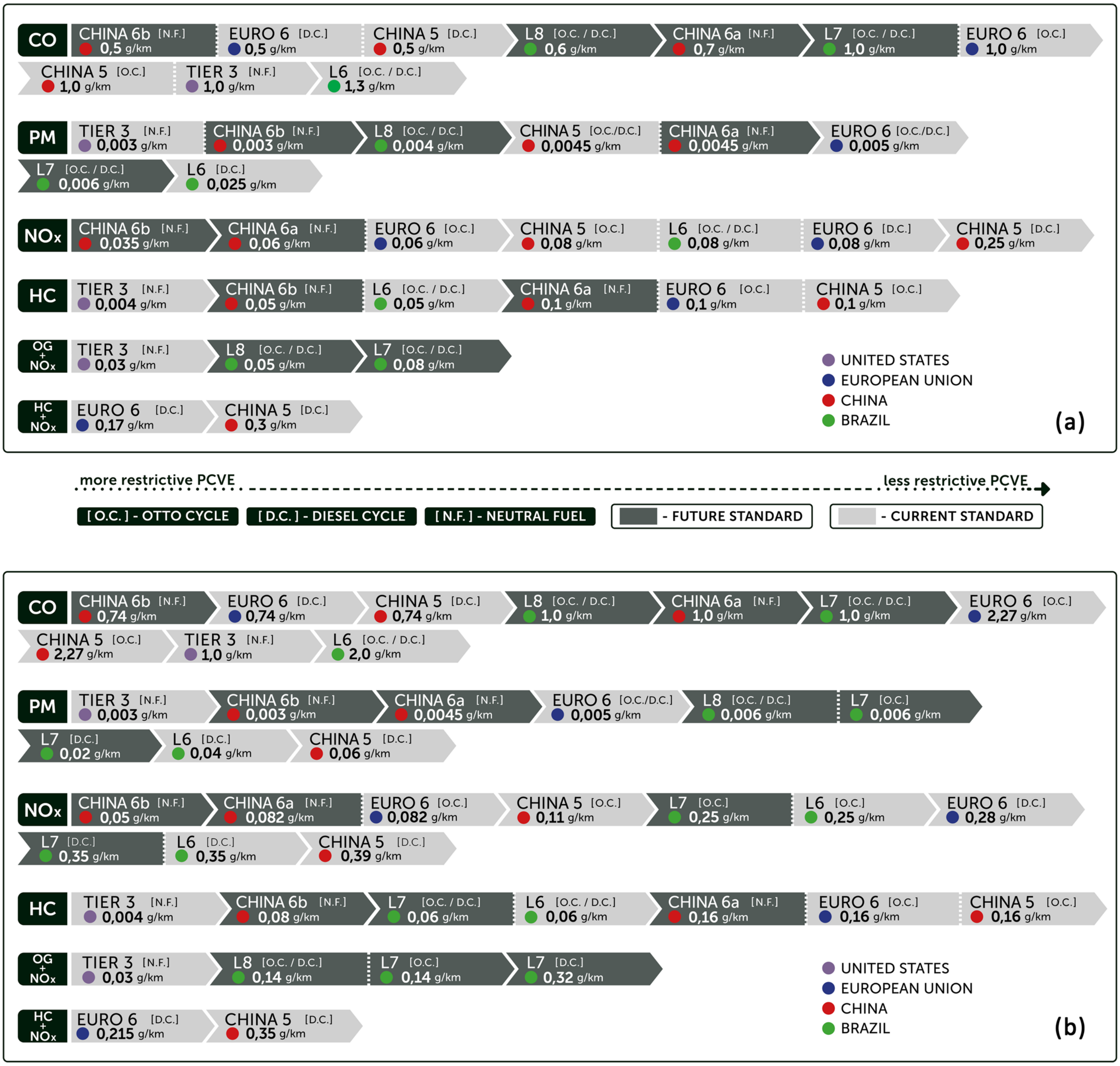

Fig. 4 Comparison of the current and future emissions standards for (**a**) PV and (**b**) PDCV/LDT (otto cycle, diesel cycle, and neutral fuel) in US, EU, China, and Brazil PCVEs (DieselNet 2020abcd; TransportPolicy 2020abcd)

In the EU, the discrepancies in NOx emissions rates of diesel cycle LDV are directly associated with the failures of compliance programs (Yang et al. 2017). Looking for controlling the poor air quality in China, a new compliance framework, based on EPA's federal and state compliance experience was implemented on China 6a. The Chinese government is also implementing an in-use vehicle inspection and maintenance system to eliminate old vehicles (Lyu et al. 2020). In Brazil, regulators have demonstrated strong limitations in compliance programs of in-use LDV (Dallman 2020).

The example of the US PCVE with neutral fuel standards is considered the most effective in ensuring LDV compliance, regardless of engine mechanic system (Rodríguez et al. 2019). Evaporative emission limits in US PCVE were implemented earlier with more restrictive standards, compared to the EU, China, and Brazil. China 6 and Brazilian's L7 will adopt stricter evaporative emissions limits, reaching the level of the US PCVE (Dallman 2020). Evaporative emission standards from China 6a and L7 are more stringent than Euro 6 (Rodríguez et al. 2019).

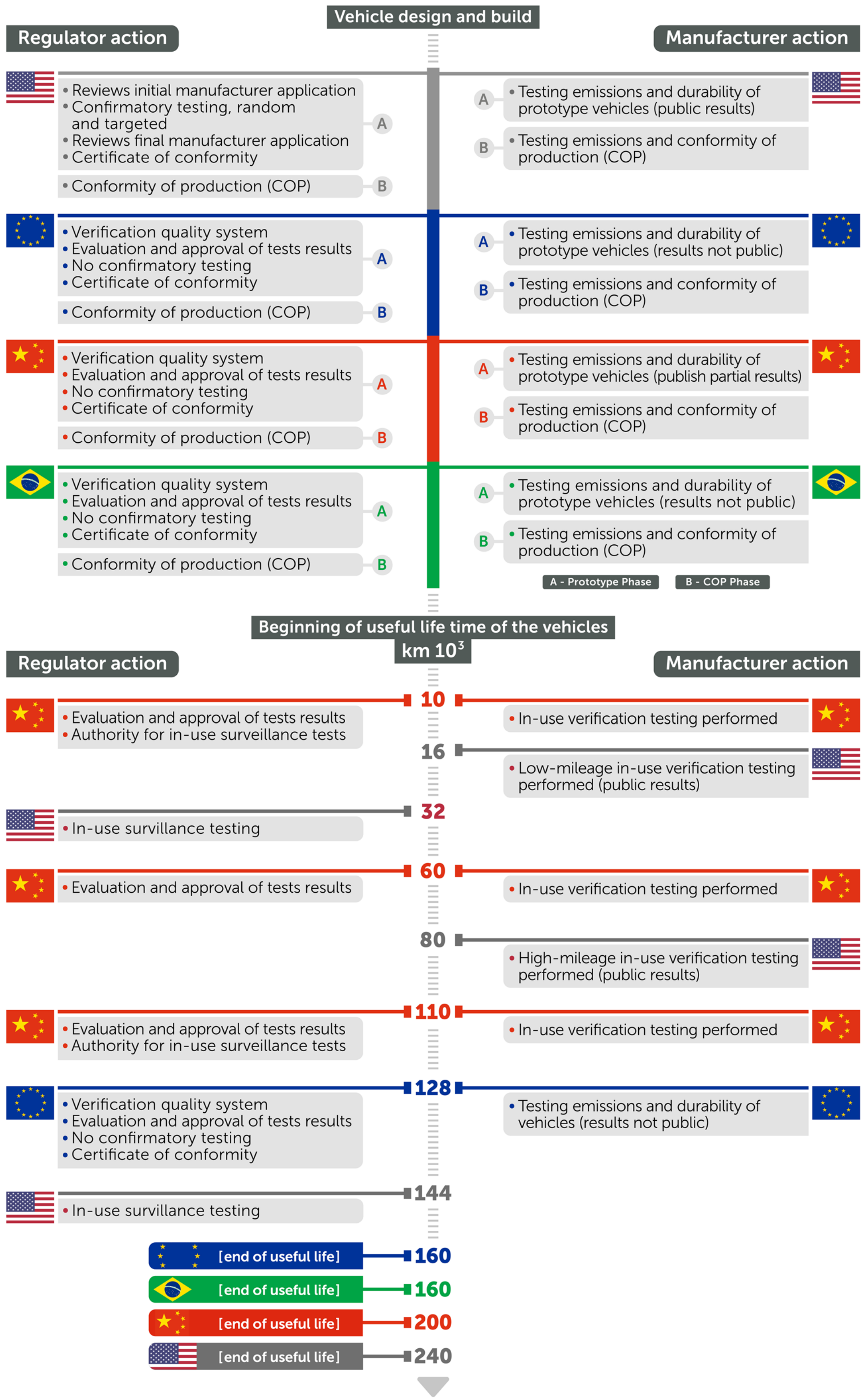

Fig. 5 Compliance schedule in US (Tier 3) (He et al. 2017), EU (Euro 6) (Mock and German, 2015), China (6a–6b) (He and Yang, 2017) and Brazil (L7–L8) (Dallman 2020) PCVEs

US (Tier 2 and 3), EU (Euro 6), China (China 5 and 6), and Brazilian program (L6) required on-board diagnostic systems (Dallmann and Façanha 2017). In Brazilian PCVE, catalyst efficiency parameter, upstream oxygen sensor, misfire detection, and electrical diagnosis are required, while the US, EU, and China demands more parameters for being monitored. According to Dallmann and Façanha (2017), the Brazilian on-board diagnostic system is more susceptible to failures while reporting the emissions control components. We highlight some differences between PCVEs in table SM1 in the supplementary material.

PCVEs effectiveness on LDV emissions and air quality

Previous studies at different scales show the success of PCVEs in controlling LDV emissions and air pollutant concentrations in some regions of US (Hasheminassab et al. 2014; Parrish et al. 2009), EU (Winkler et al. 2018), China (Wu et al. 2016), and Brazil (Andrade et al. 2017; Pacheco et al. 2017). However, in the EU, China, and Brazil, its control could be enhanced by the compliance programs consolidation. Consolidating the technical structure for LDV compliance can reduce discrepancies between imposed standards and real-world emissions (Yang et al. 2017).

In the US, vehicular emissions of non-methane hydrocarbons decreased from 1980 to 2000, even with the increase in the total kilometers traveled by vehicles in the same locations (Parrish et al. 2009). Pang et al. (2014) reported a reduction up to 80% from 1995 to 2003 on volatile organic compounds emissions rates of LDV, which was associated with the scrappage policy for old vehicles (without catalytic converter), and the implementation of US PCVE. These reductions were associated with the effectiveness of emission standards and requirements in Tier 1 stage of US PCVE. Hasheminassab et al. (2014) associated the US PCVE a reduction of 24% and 21% on PM concentration, in Los Angeles and Rubidoux, respectively, comparing the periods of 2002–2006 and 2008–2012. From 2014 to 2017, annual mean concentrations of $PM_{2.5}$ and PM_{10} in the US decreased from 9.20 to 7.94, and 19.54 to 19.03, respectively (Yang et al. 2018). Therefore, concentrations for both air pollutants in the US met the WHO Interim Target 4 (IT-4) standards, demonstrating air quality improvement throughout the country before the Tier 3 stage of the PCVE.

In the EU, there is a consensus about PCVE effectiveness to reduce vehicle emissions of PM, NOx, CO, and HC since Euro 1 stage (EEA 2019; Winkler et al. 2018). During Euro 4 and Euro 6 implementation, annual mean concentrations of PM_{10}, $PM_{2.5}$, and NO_2 reduced in the EU. From 2006 to 2015, $PM_{2.5}$, PM_{10} and NO_2 concentrations in the EU decreased from 18.4 to 14.8, from 50.2 to 40.5, from 27.7 to 22.9, respectively (EEA 2021). In this same period, annual mean concentrations of these pollutants did not exceed WHO IT-2 standards. However, after 2014 only $PM_{2.5}$ concentration met the WHO-IT-3, which is more restrictive than IT-2. Since 2000, tropospheric ozone (O_3) average concentration has been stable in the EU and above WHO standards (EEA 2021). Kurtenbach et al. (2012) verified a nonlinear dependency between road traffic NOx emissions and nitrogen dioxide (NO_2) concentrations in Germany, due to the increase in NO_2/NOx emission ratio. According to the authors, the reductions of NOx primary emissions alone were not enough to reduce the NO_2 concentrations significantly. After the Dieselgate scandal in 2015, EU PCVE has been the target of criticism, due to the discrepancies between real-word emission, and manufacturer tests results evaluated by regulatory agents (Skeete 2017). Hooftman et al. (2018) reported some EU PCVE failures to control PV emissions (mainly diesel vehicles), and air quality impacts in the EU. According to the authors, despite efforts to improving tests of in-use LDV compliance, the gap between EU PCVE standards and real-world emissions was not closed; therefore, the EU PCVE update after 2021 will need to take this into account.

In China, the implementation of PVCE reversed the trend of increasing the total vehicle emissions of HC and CO after China 3 stage (Wu et al. 2017, 2016). According to Zhang et al. (2019), between 2013 and 2017, $PM_{2.5}$ concentrations decreased by 39.6, 34.3, and 27.7%, respectively in Beijing–Tianjin–Hebei, Yangtze River Delta, and Pearl River Delta, China. However, between 2014 and 2017, annual average concentrations of $PM_{2.5}$ and PM_{10} in China exceeded WHO IT-1 standards. From 2014 to 2015, $PM_{2.5}$ and PM_{10} concentrations in China increased by 5.33 and 6.19%, respectively (Yang et al. 2018). These concentrations decreased from 2015 to 2017, coinciding with the China 4 and China 5 stages, and the Chinese Air Pollution Prevention Action Plan. In 2017, annual concentrations of $PM_{2.5}$ and PM_{10} in China were still higher than WHO IT-1 standards, and 4–6 times higher than in the US. The Chinese air pollution control policy has shown effectiveness to reduce short-term concentrations (daily averages), reducing the violation of the WHO IT-1 standard. The conformity increased from 30% in 2014 to 46% in 2017 (Yang et al. 2018).

Despite these achievements, controlling vehicle emissions and their impacts on air quality is still a major challenge. In developing countries where the vehicle population increases dramatically, the implementation and execution of PCVEs may be delayed in real-world cases, especially with the disorganized growth of cities (Lyu et al. 2020; Sun et al. 2020).

Between 2005 and 2015, vehicular annual growth rates in the US, EU, and Brazil were 10.7, 12.2, and 85.5%, respectively; while in China, the number of vehicles rose ~415% (OICA 2020). In addition to the lower vehicle registration rates, the US and EU have the most efficient technologies for LDV over the years. LDV in Brazil and China are lighter, less powerful, and high fuel consumption due to low efficiency and manual transmission used in most emerging countries (Posada and Façanha 2015; Yang and Bandivadekar 2017). It probably can contribute to air quality improvement in the US and EU. For controlling vehicular emissions and their effect on air quality in Chinese's developed provinces, it seems is necessary to restrict the vehicle population besides the implementation of more stringent emission standards, improving fuel and technology, and scrapping old vehicles (Sun et al. 2020). Due to Coronavirus, some emission standards implementation was delayed, as in case of China (TransportPolicy 2020c). However, in developed and developing countries, a clear down trend of atmospheric pollutants concentrations was observed during the lockdown, often associated with low vehicular traffic during this period (Albayati et al. 2021). This is strong evidence that vehicular traffic restriction can be an effective measure for PCVEs, in addition to implementing stricter emission standards and requirements.

According to Carvalho et al. (2015), even though the vehicular fleet has risen rapidly, the average annual concentration of all pollutants monitored by Metropolitan Area of São Paulo (MASP) in Brazil decreased from 1996 to 2009, except for O_3. The authors associate these reductions with the Brazilian PCVE, which reduced 90% the LDV emissions in MASP between L2 and L5 stages implementation. Pacheco et al. (2017) also observed a reduction of CO, NOx, and PM concentrations at monitoring stations located in São Paulo, Rio de Janeiro, and Belo Horizonte; these improvements were associated with Brazilian PCVE effectiveness, including the successive stages L4, L5, and beginning of L6. Due to the implementation of PCVE, between 2000 and 2018, annual concentrations of PM_{10} in MASP decreased from 54 to 29ug/m^3. In this Brazilian metropolitan region, since 2016, annual mean concentrations of PM_{10} have not exceeded the WHO IT-3 standards (CETESB 2018). However, Andrade et al. (2017) reported that, despite the success of PCVE in reducing emissions of primary pollutants, the concentrations of secondary pollutants such as O_3 and fine particles increased over time in São Paulo. Besides restricted inspection and maintenance, scrapping old vehicles (more than 10 years old), and controlling evaporative emissions would be the first in line with new Brazilian PCVE standards (Pacheco et al. 2017; Andrade et al. 2017). In Brazil, studies at MASP are essential to show the effectiveness of Brazilian PCVE, however, in other states (except for some large capitals), these effects are still unknown due to lack of vehicle emissions inventories and air quality data. While high-resolution vehicle emission inventories and air quality monitoring data represent the most consistent tools to evaluate the effectiveness of PCVEs, detailed data are limited to large economies and developed countries.

Although air quality improvements have been reported in the US, EU, China, and Brazil, local air pollutant concentrations in many regions can still exceed air quality standards (Winkler et al. 2018). Not all countries and economic sectors have satisfactory progress in reducing atmospheric emissions. Air pollutants from agriculture, biomass burn, fuel combustion from the industrial and energy sector are increasingly contributing to air quality degradation (Guerreiro et al. 2014). There are evident differences in air quality levels and compliance with WHO guidelines in the US, EU, and China. However, this cannot be attributed only to the success or failure of the PCVEs. Other emission sources, long-range transport of air pollutants, and photochemical processes that control pollutants also contribute to the deterioration of the air quality.

Conclusions

We compared the PCVEs from the US, EU, China, Brazil, emphasizing the progress of emissions standards and LDV compliance structures. An overview derived from previous studies, demonstrates the effectiveness in controlling vehicular emissions and air pollutant concentrations.

All PCVEs have been imposing more restrictive emissions standards from LDV over the implemented stages. Compared to other programs, the US PCVE presents additional features such as: efforts to improve the representativeness of monitored emissions (dynamometer test cycles), consolidated vehicle inspection and maintenance, emission control methods (exhaustive and evaporative), and strong the technical structure for compliance re-tests. These are basic priority measures to structure an environmental agency and ensure LDV compliance on a national scale.

Since Tier 2 from US PCVE in 2004, concentrations of PM in the US have not exceeded the WHO IT-4 standard. In the EU, IT-3 standards, which are less restrictive than IT-4, had not yet been fully met before Euro 6 implementation in 2014. Despite some improvements, in China, pollutant concentrations are far above the US, EU, and Brazil, commonly exceeding WHO IT-1 standards. In Brazil, PCVE significantly contributed to air quality improvement, such as MASP, which stopped exceeding WHO IT-3 PM_{10} standards after 2016. However, the lack of air quality monitoring data limits the evaluation of air quality trends in other Brazilian regions.

Control the disorganized growth of LDV fleets, restrict emission standards, reinforce the technical structure of environmental agencies, invest in fuel quality and vehicular technology, brought benefits to air quality in developed countries. In Chinese and Brazilian regions, where the fleet is growing dramatically, it would be required the implementation of more stringent regulations with a well-designed and homogeneous compliance policy over the national territories. Restricting the vehicle population is also envisioned as an alternative. These conclusions contribute to clarify the current challenges and profit from past lessons of PCVE around the world.

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