Article

Journal of the Brazilian Chemical Society

https://dx.doi.org/10.21577/0103-5053.20230170

J. Braz. Chem. Soc. **2024**, *35*, 7, e-20230170, 1-7

Real-Time Monitoring of Nitrogen Oxides Emission Factors Using Sensors in the Exhaust Pipes of Heavy Vehicles in the Metropolitan Region of Rio de Janeiro

Luis F. M. Silva, [a] ***Alex R. H. De La Cruz,*** [a] ***André H. M. Nunes*** [b] ***and Adriana Gioda*** *,[a]

[a]*Departamento de Química, Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), 22451-900 Rio de Janeiro-RJ, Brazil*

[b]*ZANE-Tecnologia da Informação LTDA, 22451-900 Rio de Janeiro-RJ, Brazil*

The Metropolitan Region of Rio de Janeiro is one of the most populous in Brazil, besides being one of the most important routes for marketing goods through heavy vehicles. This type of vehicle is the main source of nitrogen oxides (NOx) emission into the atmosphere. To assess NOx emission factors, this pilot study used sensors to monitor in real-time the exhaust of 9 trucks from July to September 2022. To the best of our knowledge, this is the first study carried out in the city using low-cost sensors. Although there is legislation to reduce the emission of pollutants from the vehicle fleet, the results showed that 7 out of 9 trucks, exceeded the stipulated limits, reaching 6 g kWh^{-1}. Furthermore, carrying out the maintenance of the engine of one of the vehicles decreased 60% of the NOx emission, even being an old vehicle. Thus, with this data, it was verified that the sensor performed excellently in monitoring NOx, demonstrating robust performance. This pilot study is part of a project that aims to make a long-term study of NOx emissions factors from heavy-duty diesel vehicles using sensors and other parameters.

Keywords: NOx, emission factor, remote sensing, Rio de Janeiro

Introduction

Air pollution is at the top of the list of environmental issues facing humanity today as a result of the world's booming population and industrial activities. Air quality is the reason behind several types of fatal diseases, including respiratory, lung, heart, cerebrovascular, and lung cancer.[1-3] The World Health Organization (WHO) recently reported that about 7 million people die every year from air smoke.[4,5] In the same WHO report,[4,5] it is estimated that 9 out of 10 people breathe with a quality that exceeds WHO recommendations. The main contaminants that increase air pollution are nitrogen oxides (NOx), sulfur oxides (SOx), ozone (O_3) and particulate matter (PM).[1,4,5] During the coronavirus disease 2019 (COVID-19) pandemic, a concerning association has been observed between exposure to atmospheric pollutants, such as NOx, and the increase in morbidity and mortality related to the disease.[6]

Emissions of NOx are a major issue when it comes to air quality and the environment as a whole. These chemicals, which include nitric oxide (NO) and nitrogen dioxide (NO_2), are produced mainly during combustion processes, especially in internal combustion engines present in the vehicle fleet.[7-9] In the diesel engine, NOx is formed from two mechanisms, i.e., from N content of the fuel and combustion conditions and from chemical formation of NO using N_2 and O_2 from the air and high temperatures (exceeding 1400 °C).[10] Furthermore, NOx is one of the main precursors of tropospheric O_3 (a component of photochemical smog), which is highly harmful to human health and can cause respiratory problems, especially in children and the elderly. In addition, NOx also contributes to the formation of fine particles in the air, which are able to penetrate deep into the lungs and cause even more serious respiratory problems.[11-14]

To assess the amount of NOx released into the atmosphere by the vehicle fleet, emission factors are used. Factors are influenced mainly by the age and maintenance status of vehicles, type of fuel used, traffic conditions and driving style of drivers.[15,16] Older, poorly maintained cars tend to emit greater amounts of NOx than newer, and well-maintained vehicles. In addition, fuel type plays a key role, with fossil fuels such as gasoline and diesel generally resulting in higher NOx emissions compared to cleaner

*e-mail: agioda@puc-rio.br
Editor handled this article: Rodrigo A. A. Muñoz (Associate)

fuels such as natural gas vehicle (NGV) or electric vehicle technologies.[8,12,17,18]

In Brazil, the transport of passengers and cargo is carried out mostly by road, having significant dependence on fossil fuels. Thus, this sector has contributed decisively to the increase of emissions of air pollutants.[19] According to the National Energy Balance for 2021,[20] the transport sector consumed 73% of petroleum products in relation to the commercial, agricultural, public, residential, and industrial sectors. Of this percentage, about 94% were used in road transport, with more than 30% of the national greenhouse gas emissions (GEEs) coming from the transport sector.

Although vehicle emission standards have become increasingly stringent over time around the world, most current road fleets continue to meet the oldest emission standards and ageing engines, as well as emission control devices, contributing significantly to the exacerbation of air quality on the road.[13] For the control of vehicular pollution in Brazil, the National Environmental Council (CONAMA) created the Air Pollution Control Program for Automotive Vehicles (PROCONVE) in 1986 (Resolution 18/1986).[21] In 2022, the last phases of L-7 for light vehicles and P-8 for heavy vehicles took place.[21,22] The P-8 standard specifies maximum emission limits for exhaust, particulate and noise, as well as durability requirements, more stringent on-board diagnostic systems (OBD) and on-road testing, among other requirements. It is equivalent to the Euro VI standard and will align the regulations for heavy vehicles from Brazil to the European Union.[22] The introduction of the P-8 standard in Brazil will bring extensive benefits for the control of harmful emissions by heavy vehicles and the reduction of the associated impacts on air quality and public health. Compared to the P-7 standard, introducing the P-8 standard would bring about \$11 in health benefits for every \$1 invested in more advanced vehicle emission control technologies.[23]

Measurements of NOx emission in vehicles in real conditions of use are very important, since the P-8 phase of PROCONVE, measurements of emissions in real traffic are mandatory. Recently, research projects have been conducted to investigate low-cost sensors that can be deployed in vehicles and effectively monitor pollutant emissions.[24-28] Many companies have used sensors to carry out real-time monitoring of pollutants, based on the internet-of-things (IoT). IoT is a network of devices that can collect and exchange data, allowing devices (sensors and electronic components) to connect and collaborate with other IoT devices.[29]

The Metropolitan Region of Rio de Janeiro (MRRJ) has a population of more than 13 million and 5 million vehicles, of which 38% are light gasoline vehicles (GVs), and 4% are heavy-duty diesel vehicles (HDDVs).[30] The humid and hot climate and the high solar radiation also affect the air quality due to the possibility of chemical/photochemical reactions. Therefore, this scenario is conducive to carrying out studies that include emissions from the transport sector. There is a need for emission factors for HDDVs in the estimation of emission inventories in the city of Rio de Janeiro derived from real-time measurement sensors. This pilot study aimed to measure the NOx emission factors from exhaust pipes of heavy vehicles in the city of Rio de Janeiro using a low-cost sensor. This study is unprecedented in Rio de Janeiro and the university-startup partnership benefits society as a whole.

Experimental

Sensor

The NOx sensor used in this study was developed by Continental Automotive Co. (UniNOx model, Hanover, Germany) (Figure 1). It consists of a probe and a command module, which are securely connected by a cable harness forming a unit. This sensor unit is installed in the exhaust system and is used to detect NOx in the exhaust gas flow.

Figure 1. NOx sensor and control module installed in the vehicles tested for this study.

It is an important component of the treatment system for NOx reduction that is used in diesel vehicles with exhaust gas recirculation (EGR), an emission control technology allowing significant NOx emission reductions from most types of diesel engine. The NOx sensor has a Nernst cell and a second cell called pumping cell. The NOx sensor measuring probe consists of zirconium oxide ceramic and has two chambers, one of which is open to the side of the exhaust, which are located three pairs of electrodes called pumping cells. The operating temperature of the sensor is 800 ºC and to reach this temperature there is a resistance to perform sensor heating.[31,32]

The NOx sensor has its own electronic module that work at voltages of 125 or 250 V (Figure 1). It uses the batteries of vehicles with power source. It works with the J1939 protocol, a network standard used in various vehicles and equipments that are powered by motors with electronic controls. The sensors operate continuously 24 h a day, 7 days a week; however, measurements are taken only when the vehicles are turned on. Specific concentration ranged from 0 to 1,500 ppm with precision of ± 10 ppm. The sensor comes with factory calibration and a self-correction system. It has a lifespan of 36,000 h and was used during the sample period for less than 1,000 h.

Data collection

The records were collected using the remote sensing devices provided by Case Zane (Rio de Janeiro, Brazil). The measures are done *per* min. The sensor was installed in the exhaust system and measured the gases that passed through its measurement chambers (Figure 1). The sensor makes a request for all measurements and stores them until it connects to the mobile network and sends it to the Green-IoT cloud. The Green-IoT database is a database in which the data is stored as object. The stored object follows an agreed data format, called Sensor Markup Language (SenML). SenML includes the name of the sensor responsible for the measurements, the time when the measurements are taken, and a nested object that includes all the measurements.

Test trucks

The study was performed in MRRJ, Brazil, from July to September 2022. The sensors were placed in 9 HDDVs with EGR control technique. Vehicles are used in the delivery of large goods daily within MRRJ and all trucks are in a phase of PROCONVE that will soon be discontinued (P-7) and can be compared shortly with P-8 to assess the gains. Table 1 summarizes the main characteristics of the tested vehicles.

Vehicle exhaust emissions are usually measured with a gas analyzer and reported in parts *per* million (ppm). It is crucial to compare these emissions with the vehicle emission standards. A previous research[33] has shown a correlation between vehicle emission concentration and specific fuel consumption, which is typically reported in grams *per* kilowatt-hour (g kWh^{-1}) for heavy-duty vehicles. For the general conversion of the emission gas concentration (ppm) into specific fuel consumption (g kWh^{-1}) for HDDVs, the following formula was used:[8,33]

$$\text{NOx}\left(\frac{\text{g}}{\text{kWh}}\right) = 6.636\times10^{-3}\times\ \text{NOx}/\text{ppm} \tag{1}$$

Empirical constants were obtained and reported in the literature,[33] comprising the molecular mass of the exhaust gases on a wet basis (in g mol^{-1}), the power (in kW), and the molecular mass of the components (in g mol^{-1}).

Table 1. Summary of vehicles tested with NOx sensor

Truck ID	Type	Year	Maximum net power		Measured data
			cv / kW	rpm	
445	toco	2013	186 (137)	2.400	17,318
456	toco	2013	186 (137)	12.400	19,907
160	truck	2014	277 (204)	2.300	24,160
457	truck	2019	277 (204)	2.300	7,932
595	truck	2014	277 (204)	2.300	25,004
905	truck	2013	277 (204)	2.300	29,386
931	truck	2013	277 (204)	2.300	20,633
932	truck	2013	277 (204)	2.300	16,303
951	truck	2013	277 (204)	2.300	12,299

cv: constant velocity; rpm: rotation *per* min.

Results and Discussion

Sensing performance

Table 2 shows the number and percentage of the zero and non-zero measurements. Around 173,000 records were used, including the records retrieved from the backup database when measuring the sensor probe performance.

Table 2. Success rate for the NOx air quality sensors

	NOx
Non-zero measurements	172,942
Percentage / %	96.3
Zero measurements	5,250
Percentage / %	3.7

NOx sensor probe achieved a robust performance since the percentage of zero measurements was low (3.7%).

NOx measurement occurs when the vehicle is both stationary and in motion; however, the NOx emission limit calculation is based only on vehicles in motion. When the vehicle is idle, the standard is low and consistent for all vehicles. The distribution of average NOx emission factors for individual trucks on a g kWh^{-1} basis along the test route is provided in Figure 2. The emission factors were evaluated both with the truck in motion (A) and stationary (P).

Vehicles in motion had a mean and standard deviation of emission factors of 2.9 ± 1.0 g kWh^{-1} during the campaign, with the average emission factors ranging from 1.6 to 6.1 g kWh^{-1}, while at a standstill had a mean and standard deviation of 1.2 ± 0.2 g kWh^{-1} with the average ranging from 0.064 to 1.7 g kWh^{-1}. There was a statistical difference in the emissions in motion and stationary; however, no differences were observed among the monthly emissions, suggesting an emission pattern.

Although the current Brazilian standard, PROCONVE P-8, has been in operation since 2022, the vehicles in this study are in the PROCONVE P-7 phase since 2012. The NOx standard in PROCONVE P-7 legislation is 2 g kWh^{-1}, while in the P-8 is 0.4 g kWh^{-1}. The NOx emission factors from seven out of the nine HDDVs exceeded the maximum permissible emissions in the P-7 and P-8 phases, and emitted very high levels of NOx during operation, even with the EGR system.

Despite the best technologies and cleaner fuels, high emissions of pollutants are still observed, indicating that lack of maintenance may be the reason.[34] Figure 3 shows a 60% reduction in NOx emissions after changing the pressure control valve in the 456A vehicle. The average emission factors decreased from 3.76 to 1.48 g kWh^{-1} after maintenance.

Emission measurement techniques for HDDVs usually encompass tests conducted on engine and chassis dynamometers, and tunnel investigations.[35-38] However, numerous engine dynamometer test cycles rely on steady-state modal profiles that might not accurately mirror actual vehicle activity patterns. Chassis dynamometer tests come at a significant cost, and the availability of such dynamometers is limited. Tunnel studies have limitations

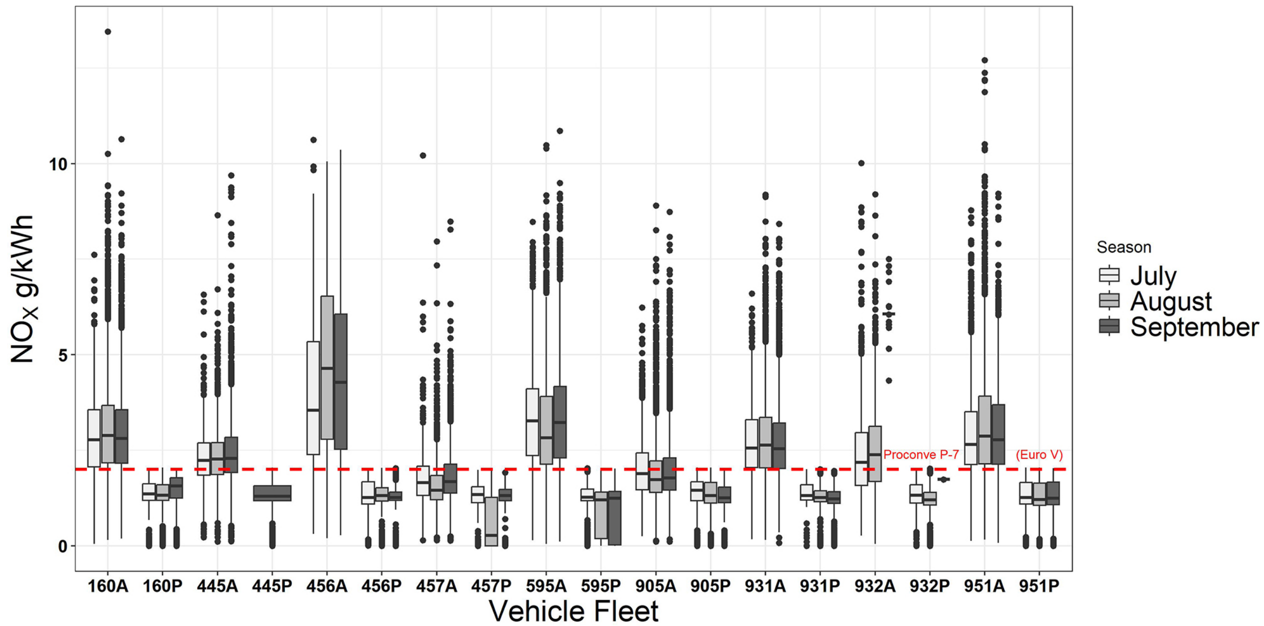

Figure 2. Monthly NOx emission factors in nine heavy vehicles monitored with sensor during 2022. Vehicles are identified using a letter to designate the vehicle (P = stationary, A = in motion), a number to identify the engine model.

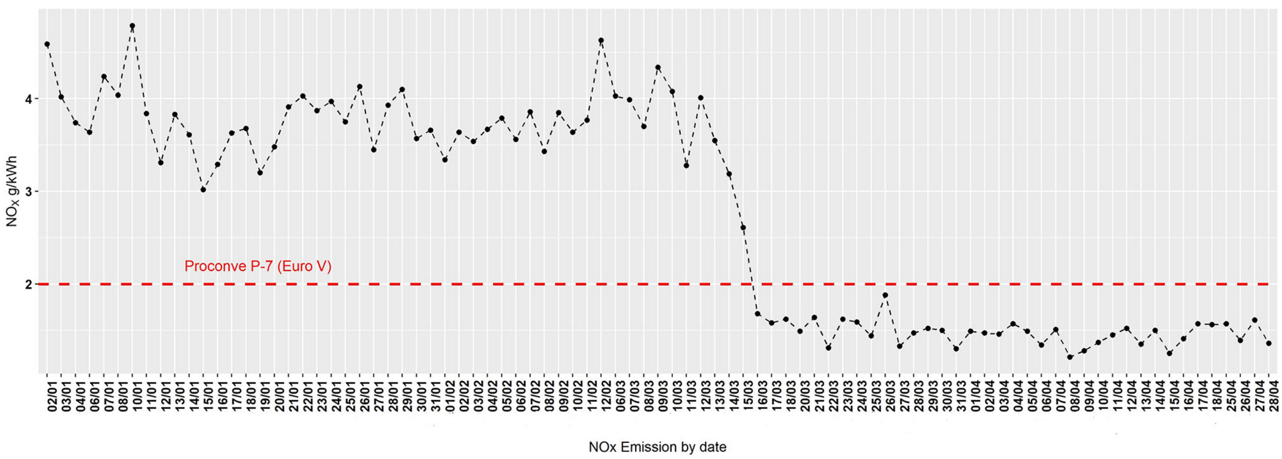

Figure 3. NOx emission factor before and after maintenance of the 456A vehicle engine.

in their capacity to distinguish between distinct vehicle types.[38-41] Thus, real-time measure NOx emission factors using a low-cost sensor is an alternative. The use of sensors can help reduce vehicle issues related to NOx emissions and ensure compliance with PROCONVE legislation.

Pollutant and air quality monitoring is conducted at monitoring stations, which have high installation and monitoring costs. Conventional air monitoring stations are large, expensive, and non-scalable, which limits data access. Researchers are exploring other solutions for air pollution monitoring, dubbed the future air pollution monitoring system.[24,42] The sensor, together with the IoT module, is only $350, making it a cost-effective alternative.

In recent years, significant efforts have been devoted to monitoring air pollution. However, existing and proposed systems lack the capability to provide sufficient spatial and temporal resolutions of pollution information accurately and economically.[4,43] Therefore, it is necessary to explore more cost-effective ways of conducting such monitoring. This pilot study represents the initial step in this direction.

Conclusions

The first results aim to evaluate the behavior of the sensor and present the first data. The sensor achieved its goal, with 96.3% of the non-zero measurements, demonstrating robust performance. Regarding the values for NOx emission factor, seven out of nine monitored vehicles (80%) presented averages above the stipulated by the Brazilian legislation (2 g kWh^{-1} PROCONVE, P-7), reaching up to 6 g kWh^{-1}.

If the MRRJ vehicle fleet follows this behavior, with emissions up to three times higher than the P-7 standard, the levels of NOx in the atmosphere can be considered high and cause an increase in O_3 levels. Fleet monitoring is essential to know which vehicles meet the legislation and which ones must be replaced or repaired.

In general, better emission control or the adoption of zero and almost zero emission technologies for professional vehicles is required to achieve significant NOx reductions in urban areas, considering their high NOx emissions in use observed in this study. In addition, the performance of engine maintenance promoted a decrease in the NOx emission rate, lower than that stipulated in phase P-7. This pilot study is part of a project that aims to make a long-term study of NOx emissions from heavy-duty diesel vehicles using sensors and other parameters.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - Brazil (finance code 001). The authors thanks to CNPq, and FAPERJ for financial support. ZANE Tecnologia da Informação Ltda thanks to Prof Paulo Santos (TECGRAF PUC/RIO).

Author Contributions

Luis F. M. Silva was responsible for conceptualization, data curation, writing-original draft preparation; Alex H. De La Cruz for visualization; André H M. Nunes for writing-reviewing, and project administration; Adriana Gioda for supervision, writing-reviewing, and editing.

References

1. Ajmal, Z.; Haq, M.; Naciri, Y.; Djellabi, R.; Hassan, N.; Zaman, S.; Murtaza, A.; Kumar, A.; Al-Sehemi, A. G.; Algarni, H.; Al-Hartomy, O. A.; Dong, R.; Hayat, A.; Qadeer, A.; *Chemosphere* **2022**, *308*, 136358. [Crossref]

2. Kamarehie, B.; Ghaderpoori, M.; Jafari, A.; Karami, M.; Mohammadi, A.; Azarshab, K.; Ghaderpoury, A.; Alinejad, A.; Noorizadeh, N.; *J. Adv. Environ. Health Res.* **2017**, *5*, 44. [Crossref]
3. Gull, N.; Nawaz, Y.; Ali, M.; Hussain, N.; Nawaz, R.; Mushtaq, S. K.; *Acad. J. Interdiscip. Stud.* **2013**, *2*, 535. [Crossref]
4. Han, Y.; Park, B.; Jeong, J.; *Procedia Comput. Sci.* **2019**, *155*, 728. [Crossref]
5. World Health Organization (WHO); *Ambient (outdoor) Air Pollution*; https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health, accessed in October 2023.
6. Barnett-Itzhaki, Z.; Levi, A.; *Environ. Res.* **2021**, *195*, 110723. [Crossref]
7. da Silva Jr., R. S.; Andrade, M. D. F.; *Rev. Bras. Meteorol.* **2013**, *28*, 105. [Crossref]
8. Pilusa, T. J.; Mollagee, M. M.; Muzenda, E.; *Aerosol Air Qual. Res.* **2012**, *12*, 994. [Crossref]
9. Ravina, M.; Caramitti, G.; Panepinto, D.; Zanetti, M.; *Air Qual., Atmos. Health* **2022**, *15*, 541. [Crossref]
10. Guardiola, C.; Martín, J.; Pla, B.; Bares, P.; *Appl. Therm. Eng.* **2017**, *110*, 1011. [Crossref]
11. Slezakova, K.; Castro, D.; Begonha, A.; Delerue-Matos, C.; Alvim-Ferraz, M. C.; Morais, S.; Pereira, M. C.; *Microchem. J.* **2011**, *99*, 51. [Crossref]
12. Mendoza-Villafuerte, P.; Suarez-Bertoa, R.; Giechaskiel, B.; Riccobono, F.; Bulgheroni, C.; Astorga, C.; Perujo, A.; *Sci. Total Environ.* **2017**, *609*, 546. [Crossref]
13. Ning, Z.; Wubulihairen, M.; Yang, F.; *Atmos. Environ.* **2012**, *61*, 265. [Crossref]
14. Pardo, L. H.; Fenn, M. E.; Goodale, C. L.; Geiser, L. H.; Driscoll, C. T.; Allen, E. B.; Baron, J. S.; Bobbink, R.; Bowman, W. D.; Clark, C. M.; Emmett, B.; Gilliam, F. S.; Greaver, T. L.; Hall, S. J.; Lilleskov, E. A.; Liu, L.; Lynch, J. A.; Nadelhoffer, K. J.; Perakis, S. S.; Robin-Abbott, M. J.; Stoddard, J. L.; Weathers, K. C.; Dennis, R. L.; *Ecol. Appl.* **2011**, *21*, 3049. [Crossref]
15. Aguiar, S. O.; Araújo, R. S.; Cavalcante, F. S. Á.; de Lima, R. K. C.; Bertoncini, B. V.; Oliveira, M. L.; *TRANSPORTES* **2015**, *23*, 35. [Crossref]
16. Companhia Ambiental do Estado de São Paulo (CETESB); *Emissão Veicular*, 2022, https://cetesb.sp.gov.br/veicular/relatorios-e-publicacoes/, accessed in October 2023.
17. McCaffery, C.; Zhu, H.; Tang, T.; Li, C.; Karavalakis, G.; Cao, S.; Oshinuga, A.; Burnette, A.; Johnson, K. C.; Durbin, T. D.; *Sci. Total Environ.* **2021**, *784*, 147224. [Crossref]
18. Buruiana, D. L.; Sachelarie, A.; Butnaru, C.; Ghisman, V.; *Int. J. Environ. Res. Public Health* **2021**, *18*, 9075. [Crossref]
19. Lopes, T. F. A.; Policarpo, N. A.; Vasconcelos, V. M. R.; de Oliveira, M. L. M.; *Eng. Sanit. Ambient.* **2018**, 1013. [Crossref]
20. Ministério de Minas e Energia; *Balanço Energético Nacional 2022*, https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2022, accessed in October 2023.
21. Conselho Nacional do Meio Ambiente (CONAMA); Resolução CONAMA No. 18, de 6 de maio de 1986, Dispõe sobre *A Criação do Programa de Controle de Poluição do Ar por Veículos Automotores-PROCONVE*; Brasília, 1986. [Link] accessed in October 2023
22. Conselho Nacional Do Meio Ambiente (CONAMA); Resolução No. 492, de 20 de dezembro de 2018, *Estabelece as Fases PROCONVE L7 e PROCONVE L8 de Exigências do Programa de Controle da Poluição do Ar por Veículos Automotores-PROCONVE para Veículos Automotores Leves Novos de Uso Rodoviário, Altera a Resolução CONAMA No. 15/1995 e Dá Outras Providências*; Brasília, 2018. [Link] accessed in October 2023
23. Miller, J.; Façanha, C.; *Análise de Custo-Benefício da Norma P-8 de emissões de Veículos Pesados no Brasil*; ICCT, 2016, [Link] accessed in October 2023
24. Kaivonen, S.; Ngai, E. C.-H.; *Digit. Commun. Networks* **2020**, *6*, 23. [Crossref]
25. Gonzalez, A.; Boies, A.; Swanson, J.; Kittelson, D.; *Int. J. Environ. Res. Public Health* **2022**, *19*, 15223. [Crossref]
26. Liu, B.; Zimmerman, N.; *Transp. Res., Part D* **2021**, *91*, 102635. [Crossref]
27. Castell, N.; Dauge, F. R.; Schneider, P.; Vogt, M.; Lerner, U.; Fishbain, B.; Broday, D.; Bartonova, A.; *Environ. Int.* **2017**, *99*, 293. [Crossref]
28. Karagulian, F.; Barbiere, M.; Kotsev, A.; Spinelle, L.; Gerboles, M.; Lagler, F.; Redon, N.; Crunaire, S.; Borowiak, A.; *Atmosphere* **2019**, *10*, 506. [Crossref]
29. Kopetz, H.; *Real-Time Systems*, 2nd ed.; Springer: Boston, 2011, p. 307. [Crossref]
30. DETRAN-RJ; *Anuário Estatístico 2022*, Rio de Janeiro, 2022, https://www.detran.rj.gov.br/_include/geral/anuario_estatistico_detran_rj_2022.pdf, accessed in October 2023.
31. Wang, Z.; Deng, Z.; Zhu, R.; Zhou, Y.; Li, X.; *Sens. Actuators, B* **2022**, *359*, 132658. [Crossref]
32. Wang, Z.; Deng, Z.; Wang, J.; Lin, W.; Fu, X.; Li, X.; *Sens. Actuators, B* **2022**, *373*, 131622. [Crossref]
33. Vergel-Ortega, M.; Valencia-Ochoa, G.; Duarte-Forero, J.; *Case Stud. Thermal Eng.* **2021**, *26*, 101190. [Crossref]
34. Ventura, L. M. B.; Pinto, F. O.; Gioda, A.; D'Agosto, M. A.; *Sustainable Cities Soc.* **2020**, *53*, 101956. [Crossref]
35. Gajendran, P.; Clark, N. N.; *Environ. Sci. Technol.* **2003**, *37*, 4309. [Crossref]
36. Yanowitz, J.; Graboski, M. S.; Ryan, L. B. A.; Alleman, T. L.; McCormick, R. L.; *Environ. Sci. Technol.* **1999**, *33*, 209. [Crossref]
37. Burgard, D. A.; Bishop, G. A.; Stedman, D. H.; Gessner, V. H.; Daeschlein, C.; *Environ. Sci. Technol.* **2006**, *40*, 6938. [Crossref]

38. Frey, H. C.; Rouphail, N. M.; Zhai, H.; *Transp. Res. Rec.* **2008**, 23. [Crossref]
39. Kirchstetter, T. W.; Harley, R. A.; Kreisberg, N. M.; Stolzenburg, M. R.; Hering, S. V.; *Atmos. Environ.* **1999**, *33*, 2955. [Crossref]
40. Miller, T. L.; Davis, W. T.; Reed, G. D.; Doraiswamy, P.; Fu, J. S.; *Transp. Res. Rec.* **2003**, *1842*, 99. [Crossref]
41. Li, C.; Ma, T.; Karavalakis, G.; Johnson, K. C.; Durbin, T. D.; *Emiss. Control Sci. Technol.* **2023**, *9*, 12. [Crossref]
42. Idrees, Z.; Zheng, L.; *J. Ind. Inf. Integr.* **2020**, *17*, 100123. [Crossref]
43. Chiang, M.; Zhang, T.; *IEEE Internet Things J.* **2016**, *3*, 854. [Crossref]

Submitted: August 20, 2023
Published online: October 24, 2023