Clean Energy, 2024, Vol. 8, No. 3, 34–47
https://doi.org/10.1093/ce/zkae022
Advance access publication 23 April 2024
Research Article

Assessment of energy consumption, environmental effects and fuel costs of the bus rapid transit system in Bogotá (Colombia)

Jhon Jairo Pérez[1,*], Luis Hernando Correa[1], Poul Alberg Østergaard[2] and Pedro Cabrera[3]

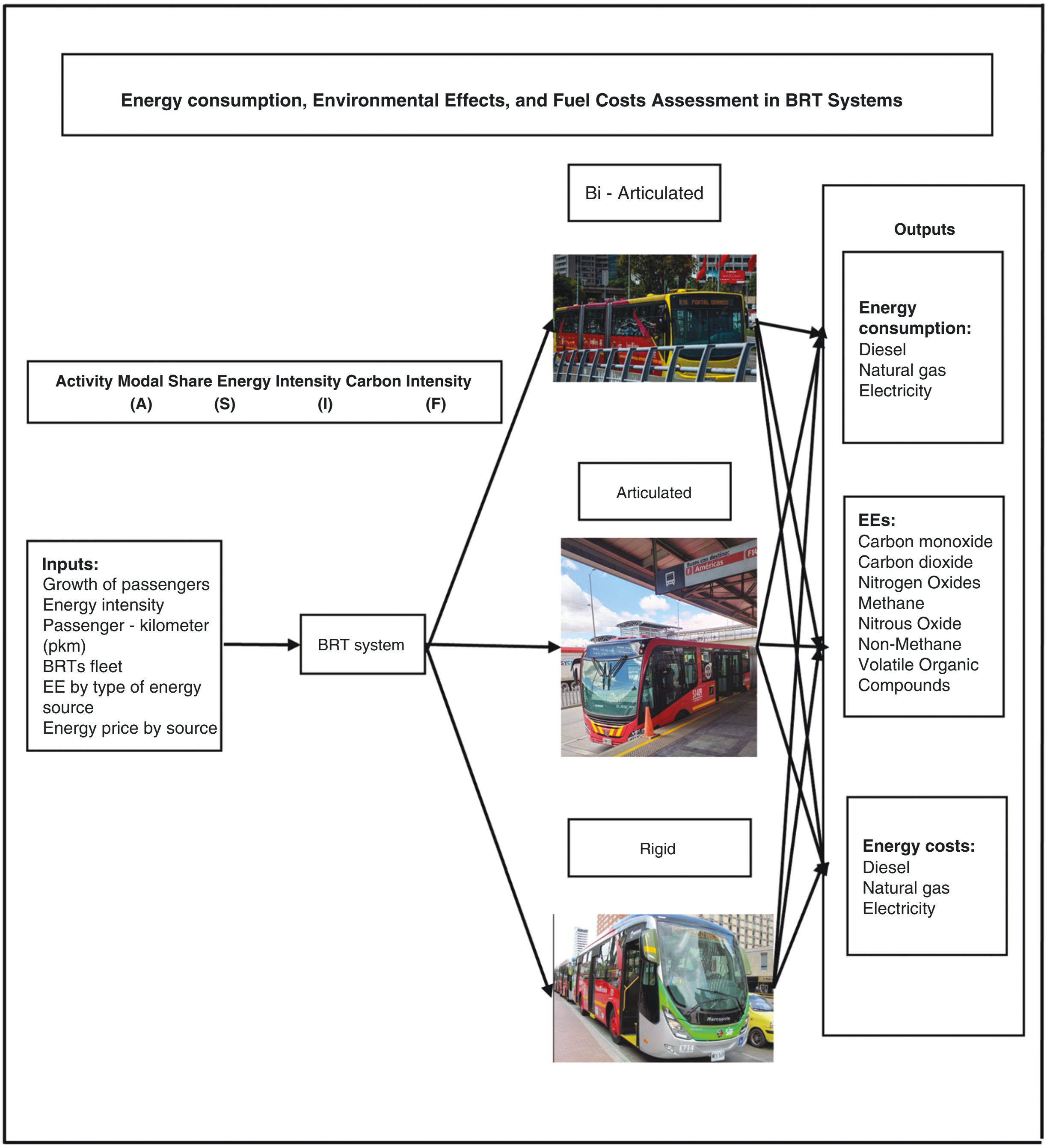
[1]Universidad de La Salle—Engineering Faculty, Electrical Department, Campus La Candelaria, Bogota D.C., Colombia
[2]Aalborg University, Department of Planning, Rendsburggade 14, 9000 Aalborg, Denmark
[3]University of Las Palmas de Gran Canaria, Department of Mechanical Engineering, Campus Universitario de Tafira, Las Palmas de Gran Canaria, Spain
[*]Corresponding author. E-mail: johnj.gelves@gmail.com

Abstract

Colombia aims to boost the utilization of mass transportation systems in its major cities while simultaneously reducing greenhouse gas emissions by 20%, in alignment with the commitments of the COP21 agreement. In 2020, the transport sector in Colombia accounted for 34.4% of the country's energy demand and was responsible for ~49% of its total CO_2 emissions. This article presents an assessment of energy consumption, environmental effects and the fuel costs of Bogotá's bus rapid transit system based on the Activity, Share, Intensity, Fuel methodology. A long-term analysis spanning from 2021 to 2040 was developed using the long-range energy alternatives planning platform. To conduct this assessment, the tool was calibrated using data from 2019 and 2020. Four distinct scenarios based on energy policies implemented in Bogotá were examined: Business as Usual, Fast Transition, High Growth and Low Growth. Regarding energy consumption and environmental effects, the results underscore the pivotal role of diversifying energy sources and reducing reliance on fossil fuels such as oil. Consequently, the analysis emphasizes the urgent need to accelerate the transition to alternative energy sources such as natural gas and electricity.

Received: 20 December 2023. **Accepted:** 13 February 2024

Graphical Abstract



Keywords: ASIF; energy consumption; environmental effects; LEAP long-term energy model; public transport

Introduction

According to the International Energy Agency (IEA), the transport sector accounted for 28.7% of the global energy demand in 2019—dropping to 26.2% in 2020 due to COVID-19 and lockdowns. However, this is still a significant demand, with 94.9% of it being directly met by fossil fuels [1] and, in 2020, global CO_2 emissions reached a level of 31 665.4 Mt [2], very close to the IEA's Business as Usual (BAU) long-term scenario projection of emissions of 33 274 $MtCO_2$ by 2040. In Colombia, the transport sector accounted for 37.2% of energy consumption in 2019. Although this value fell to 34.4% in 2020 due to the lockdowns, it remained higher than the world average [3].

Transport-related emissions in the world are divided into road passenger 45.1%, road freight 29.4%, aviation 11.6%, shipping 10.6% and other 2.2%. Therefore, efforts to reduce emissions from road transportation are a crucial step towards achieving the Sustainable Development Scenario, which aims to decrease total CO_2 emissions to 14 704 Mt by 2040 [1]. In the context of CO_2 emissions, the transport sector accounted for 24.0% [1]. Within this sector, road transport alone contributed 79.7% [4]. In general, emission reductions in the transport sector have an enormous potential for curbing greenhouse gas (GHG) emissions due to technological advances in the use of other energy sources such as electricity, natural gas (NG), biofuels and hydrogen [5, 6].

The objectives of this paper are as follows: (i) to define an assessment approach that is focused on energy consumption, environmental effects (EEs) and fuel costs in bus rapid transport (BRT) systems; (ii) development of an applied case study of mass public transportation in Bogotá based on BRT; and (iii) analyses that allow understanding of the impact of cleaner fuels due to energy transition.

This paper is organized as follows. Section 1 presents a review of the literature with a particular emphasis on public transportation in Latin America and BRT systems. Section 2 presents the assessment approach based on the ASIF (Activity, Share, Intensity, Fuel) methodology. Section 3 presents and discusses the results related to energy consumption, EEs and fuel costs, while Section 4 offers a general discussion, reports the conclusions of the study and describes the limitations of the article.

The TransMilenio BRT system in Bogotá is used as the case in this article. This BRT system has received numerous international awards and recognitions, including from the *New York Times* as a global example of GHG emission reduction in 2009 and the World Bank during the visit of its Executive Directors, also in 2009. In COP15, the Ministry of Environment of Denmark acknowledged TransMilenio as a successful experiment in the transport sector to reduce GHG emissions and mitigate climate change. The British Embassy and the Columbia Planning Foundation awarded it a silver medal in the 2010 Environmental Responsibility Award within the Business Services category. TransMilenio was placed fifth out of the 134 entries in the I Hispanic American and Latin American Contest of Best Practices in Planning and Health by the Pan American Health Organization. The World Health Organization (WHO) presented the project as a successful case of transportation in 2010. Finally, the United Nations Framework Convention on Climate Change listed it as one of the 10 best and most successful projects for its co-social and environmental benefits in 2010, among other recognitions [7].

1 Literature review

This section presents a brief literature review of energy planning that is focused on the transport sector as well as public transportation in Latin America.

1.1 Energy planning in transportation

Several studies have focused on determining the energy demand in specific countries or regions, including China, Jordan and the European Union [8–11], and evaluating GHG emissions [12–15] through the application of two approaches known as top-down and bottom-up models [16–18]. The top-down approach is based on macroeconomic data, such as the gross domestic product (GDP), population, economy by sector, income, prices or aggregate energy consumption and mainly applies econometric and statistical methods [19–21]. The bottom-up approach uses detailed information, including energy consumption per user, technology information related to end users, useful life and the quantities and characteristics of consumption units [22–25]. The feasibility of carrying out bottom-up analyses can, however, be limited by issues related to data costs or access [26–28].

Most works on the transport sector study gasoline (petrol) and diesel fuels, using information about fuel consumption, prices and income, following a top-down analysis. Ajanovic *et al.* [16] surveyed the methods applied to assess aggregate transport fuel demand. Dahl [29] analysed several works for gasoline and diesel demand in 124 countries and found different relationships between price and income. Sterner [30] studied the link between fuel prices and taxes as a mechanism to fight climate change using data from seven European countries. In a more recent study [31], a review was undertaken of >300 studies on public transport economics and a section was dedicated to analytical techniques that capture the spatial and temporal dynamics of demand. According to the authors [31], one of the most frequently investigated subjects is the optimization of pricing and subsidy policies. However, they concluded that discussions and debates on optimal subsidies are far from over. The studies reviewed by the authors were generally based on econometric techniques.

Bottom-up-based analyses have a broader scope in studies of the transportation sector. Pongthanaisawan *et al.* [32] determined energy demand in the Thai transport sector, where consumption corresponds to ~38% of the total final energy consumption. The study by Solís and Sheinbaum [33] applied a disaggregated model that included passenger and freight road transport in Mexico. In this study, energy consumption in road transportation was divided into private cars (32.6%), gasoline light-duty freight (25%), diesel duty freight (12%) and buses (11.3%), corresponding to 39% of the total CO_2 emissions. Jiao *et al.* [34] assessed GHG emission reductions of the urban transportation system in Guangzhou, China, through energy transition, applying a long-range energy alternatives planning (LEAP) model.

Song *et al.* [35] studied the energy consumption and GHG emissions of a diesel and natural gas-based heavy-duty vehicle fleet on a provincial level in China. Chang *et al.* [36] applied a bottom-up model to determine the energy consumption and environmental emissions of the high-speed rail system in China. Martínez-Jaramillo *et al.* [37] determined the impacts of transport policies in the Medellín (Colombia) metropolitan area. Medellín has been developing a complete public transport structure integrated by train lines, tram lines, a gondola-lift transport system, a BRT system, hybrid buses and bicycle sharing.

1.2 Public transportation in Latin America

Many large cities in Latin American countries such as Brazil, Chile, Colombia and Mexico have changed their modes of mass transportation. In Brazil, there are several successful cases of the implementation of integrated transport systems (ITSs) that combine different modes of transport. Examples include cities such as São Paulo, Curitiba, Porto Alegre, Belo Horizonte and Goiania. Curitiba has had an ITS since the 1980s and has served as a model of inspiration for several cities in Latin America [38]. Rio de Janeiro, the second most-populated city of Brazil, implemented a BRT system known as the ‘corridor Transcarioca’, with a total daily capacity of 1.2 million passengers [39]. In Porto Alegre, private capital has been applied not only to the operation and administration of their BRT system, but also to infrastructure investments [40].

In [41], an extensive study was developed of seven Latin American cities, presenting the benefits of BRT systems. These include public facilities, transportation time, infrastructure and a reduction in total emissions. In 2005, Mexico City launched a BRT network to mitigate its severe pollution problems. The system transported 254 million people in 2014. According to Mexican authorities, CO_2 emissions were reduced by 35 000 Mt per year [42]. Rodriguez *et al.* [43] studied other benefits of BRT systems in cities such as Quito and Bogotá, including building development, use of land and property rights in the corridors. Fig. 1 shows the most significant BRT systems in Latin America.

Fig. 1: BRT systems in large cities in Latin America

The lockdown caused by COVID-19 had various effects on the mass transportation sector, including reductions in international flights and the use of the metro and BRT systems in numerous countries around the world. Total oil demand fell by 57% and road transportation decreased between roughly 50% and 75% [44]. By contrast, new forms of displacement gained importance such as walking and cycling. As result of COVID-19 lockdowns, global energy demand decreased by 4.0% and CO_2 emissions by 5.8% [45]. Recent works have tried to explain the effects of COVID-19 on transport and emissions. Griffiths *et al.* [46] presented various opportunities that arose in the aftermath of COVID-19, including the reduction in unnecessary transportation by using more digital resources, changes in transport habits, decreases in car use and better carbon efficiency in transportation systems with the entry of new technologies. For instance, Bogotá (Colombia), Berlin (Germany) and Mexico City (Mexico) changed traditional vehicle lanes into bicycle lanes, as did Gdansk (Poland), whose inhabitants stated that they were more interested in using public transport in the future [47].

2 Assessment approach

This section presents an assessment approach for BRT urban public transport aimed at determining the long-term energy consumption, EEs and fuel costs. The presentation is divided into methods, BRT system data and scenarios.

2.1 Methods

The assessment approach is based on the ASIF methodology [48] in which GHG emissions or EEs are estimated. The ASIF approach applies decomposition factors to determine EEs from the modal choice of transportation. The parameters used in the method are: (i) activity, which establishes the number of journeys (passenger-kilometres (p-km) total); (ii) modal transportation—such as bi-articulated, articulated or rigid buses; (iii) energy intensity (EI), which presents the use of energy per unit of p-km travelled described by the mode (MJ/p-km); and (iv) carbon intensity, which represents emissions per energy demand (tCO_{2Eq}/MJ). The inputs consist of growth of passengers per year, EI, p-km, BRT fleet, EEs and prices by energy source.

The results are energy outputs (energy consumption), EE outputs and cost outputs. The assessment structure is illustrated in Fig. 2.

The mathematical formulation of the applied method includes three parts: energy consumption, EEs and costs. Energy consumption is determined through Equations (1) and (2), based on p-km and EI (J) [32, 49, 50]:

$$pkm_{s,u,f,t} = \sum_{s,u,f,t} \left(vkm_{s,u,f,t} * AO_{s,u,f,t} \right) \tag{1}$$

$$E_t = \sum_{s,u,f,t} \left(pkm_{s,u,f,t} * EI_{s,u,f,t} \right) \tag{2}$$

where $vkm_{s,u,f,t}$ is the total distance (km) travelled in a period that includes submode (*s*), useful life (*u*), fuel type (*f*) and time (*t*); $AO_{s,u,f,t}$ is the average number of passengers; E_t is energy consumption over time (*t*) in J; $pkm_{s,u,f,t}$ is p-km by submode (*s*), useful life (*u*), fuel type (*f*) and time (*t*); and $EI_{s,u,f,t}$ is the energy consumption per passenger (l/km or J/km) by submode (*s*), useful life (*u*), fuel type (*f*) and time (*t*).

The second part calculates the EEs through Equation (3). Following the ASIF methodology, the outputs are divided into carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), methane (CH_4), non-methane volatile organic compounds (NMVOCs) and nitrous oxide (N_2O):

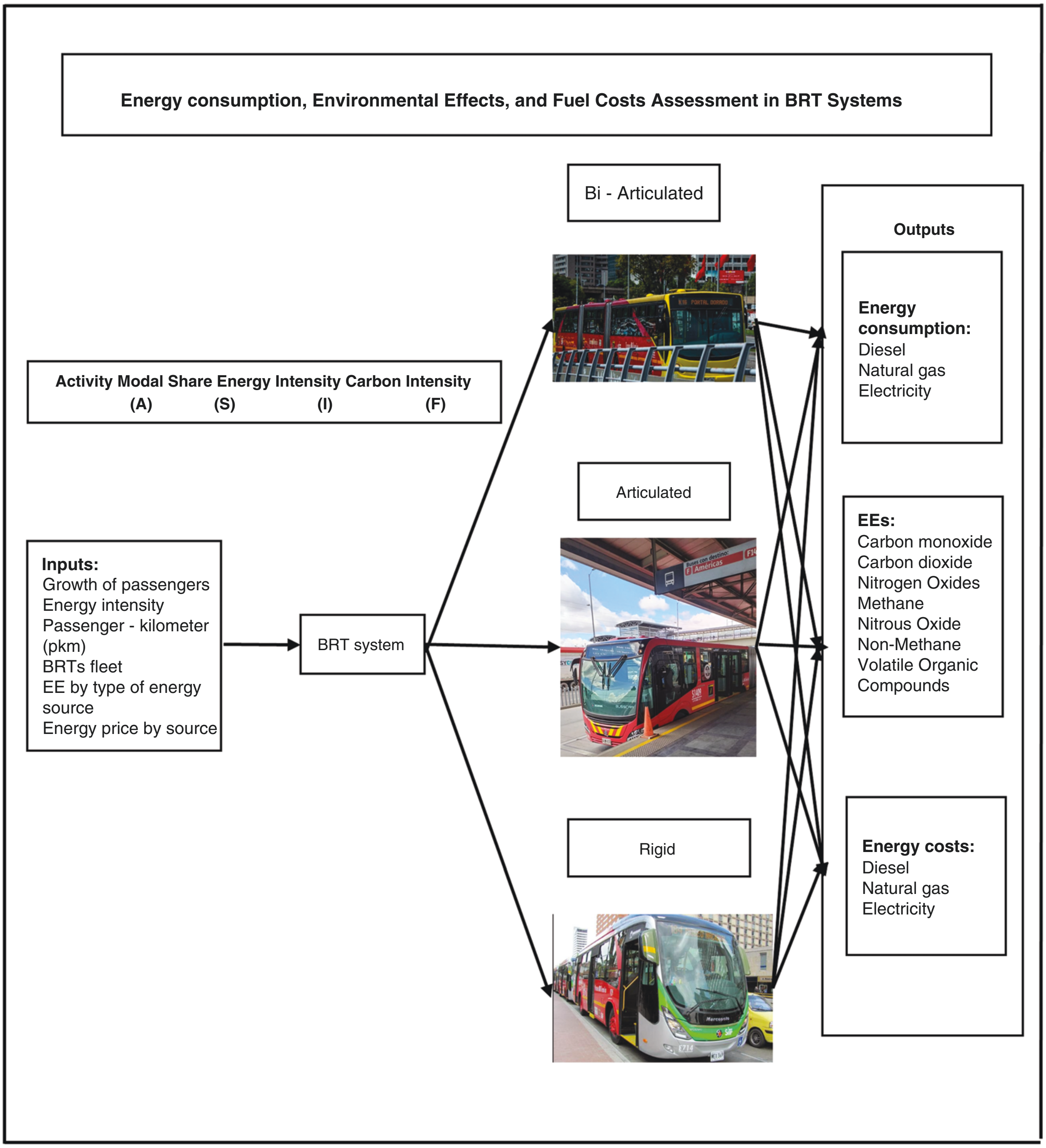


Fig. 2: Energy consumption, EEs and fuel costs in BRT systems

$$EE_t = \sum_{s,u,f,t} \left(FCI_{s,u,f,t} EI_{s,u,f,t} AC_{s,u,f,t} \right) \tag{3}$$

where EE_t are the environmental effects (*E*) over time (*t*); $FCI_{s,u,f,t}$ is the fuel carbon intensity (tCO_{2eq}/MJ); $EI_{s,u,f,t}$ is the energy consumption per passenger; and $AC_{s,u,f,t}$ is the activity based on p-km by submode (*s*), useful life (*u*), fuel type (*f*) and time (*t*). The emission factors were taken from the Emission Factor Database (EFDB) [51].

The third part determines the total costs by fuel according to energy consumption and energy prices through Equation (4):

$$TC_{f,t} = \sum_{s,u,f,t} \left(E_{s,u,f,t} P_{s,u,f,t} \right) \tag{4}$$

where $TC_{f,t}$ is the total cost by energy source (USD current); $E_{s,u,f,t}$ is the energy consumption over time (*t*) in J; and $P_{s,u,f,t}$ is the energy source price by submode transportation (*s*), fuel type (*f*) and time (*t*).

The assessment approach followed in this work was implemented using the LEAP platform [52]. LEAP allows the development of different scenarios of the application of energy policies to determine energy consumption and environmental analyses based on the ASIF methodology. LEAP has been applied in close to 190 countries around the world and there is extensive literature concerning energy planning in the transportation sector based on the LEAP platform [53–56].

2.2 BRT system data

Bogotá is in the centre of Colombia and is the most important economic, industrial and cultural city in the country. Its population in 2021 was 7.8 million [57] and it presented a high population density of ~4310 inhabitants per square kilometre in 2018. Bogotá's GDP was US$83 billion in 2019 [58], equivalent to 25.7% of the country's total, and the city is the seventh-largest by GDP in Latin America.

The ITS of Bogotá is divided into BRT trunk lines (114.4 km of exclusive lanes), feeder buses (between the neighbourhoods) and rigid buses (outside the trunk lines). The BRT system that operates in the trunk lanes is known as TransMilenio and is formed by 1330 bi-articulated, 763 articulated and 273 rigid units. The fleet can be separated into three age groups: >10 years old (7.0%), between 6 and 10 years old (29.0%) and ≤5 years old (64.0%). There are 98 routes and, on average, each BRT unit travels 10 000 km per month [59]. In terms of usage, in February 2023, for instance, there were 92 931 229 boardings in the ITS and, with respect to TransMilenio, there were 41 911 397 BRT boardings, which represented 45.3% of all boardings in the Bogotá ITS. A complete map of the TransMilenio system with its routes, lanes and stations can be seen in online Supplementary Fig. S8).

TransMilenio was inaugurated on 4 December 2001. Table 1 presents the main features of the TransMilenio BRT system applied in the LEAP model, including relevant aspects for each transport mode such as maximum passenger capacity, average number of passengers and energy intensities by source.

The TransMilenio system operates as a concession contract for operators of the BRT. Consequently, there is (i) vertical separation and a fare collection process; (ii) a remuneration scheme for operation of the BRT units based on kilometres travelled and not on passengers carried; and (ii) an auction process for operators. The public costs of the system include studies, real-estate purchase, infrastructure, control-centre operation and management—the total sum of which corresponds to 1216.3 MM (constant 2008 US$) per year. The private costs comprise the entire BRT fleet, BRT operation and operation of the collection system. This amounts to 778.5 MM (constant 2008 US$) per year [63].

2.3 Scenarios

The calibration of the simulations is based on Table 1 using 2019 and 2020 as a reference [64]. The scenarios are developed considering the lockdown as a consequence of COVID-19 and the realistic long-term scenarios are implemented on a main BAU trajectory (i) together with three derived scenarios (ii), (iii) and (iv), as follows:

(i) 'BAU' corresponds to the general trajectory and assumes the transportation policy applied by the Mayor's Office of Bogotá. In this scenario, the fleet includes 700 bi-articulated buses (402 by NG and 298 by diesel) and 741 articulated (562 NG and 197 diesel) [65]. In this scenario, the number of passengers increases at a rate of 1.0% per annum (p.a.) after 2022.

(ii) 'High Growth (High) scenario' considers a rapid economic recovery of the city of Bogotá with an annual rate of increase of 2.0% p.a. in the number of passengers after 2022.

(iii) 'Low Growth (Low) scenario' represents a slow growth of the economy, with passenger demand increasing at a rate of 0.5% p.a. between 2022 and 2029. Subsequently, the modelling adopts the BAU scenario between 2031 and 2040.

(iv) 'Fast Transition (Fast) scenario' includes mainly the reduction in the use of diesel in the BRT system from the year 2030 through a transition towards NG and electricity. The detailed assumptions of the four scenarios are presented in Table 2.

Table 1: Transportation data of vehicles in the TransMilenio BRT system

Characteristic	Bi-articulated	Articulated	Rigid
Maximum passenger capacity	250	160	80
Average number of passengers	121	77	39
Annual distance travelled (calculated) (km)	50 000–60 000	70 000–80 000	60 000–70 000
Energy intensity of diesel use (MJ/km) [60]	16.06	14.7	11.8
Energy intensity of natural gas use (MJ/km) [61]	12.92	8.012	–
Energy intensity of electricity use (MJ/km) [62]	14.3	13.5	10.8
Main applications	Widely separated stations	Intermediate stations	Short distances

Table 2: Detailed BAU and transition assumptions in the long-term scenarios

BAU (year)	**2019–20 Calibration model**			**2020–30**			**2030–40**		
Type of fuel	**Diesel (%)**	**NG (%)**	**Electric or hybrid (%)**	**Diesel (%)**	**NG (%)**	**Electric or hybrid (%)**	**Diesel (%)**	**NG (%)**	**Electric or hybrid (%)**
Bi-articulated	100	0	0	58	42	0	23	60	17
Articulated	100	0	0	26	74	0	20	70	10
Modal	4	0	96 (Hybrid)	4	0	96 (Hybrid)	0	0	100 (Electric)
Transition (years)	**2019**			**2020–29**			**2030–40**		
Bi-articulated	100	0	0	58	42	0	20	60	20
Articulated	4	0	0	26	74	0	10	60	30
Modal	4	0	96 (hybrid)	4	0	96 (hybrid)	0	0	100 (electric)

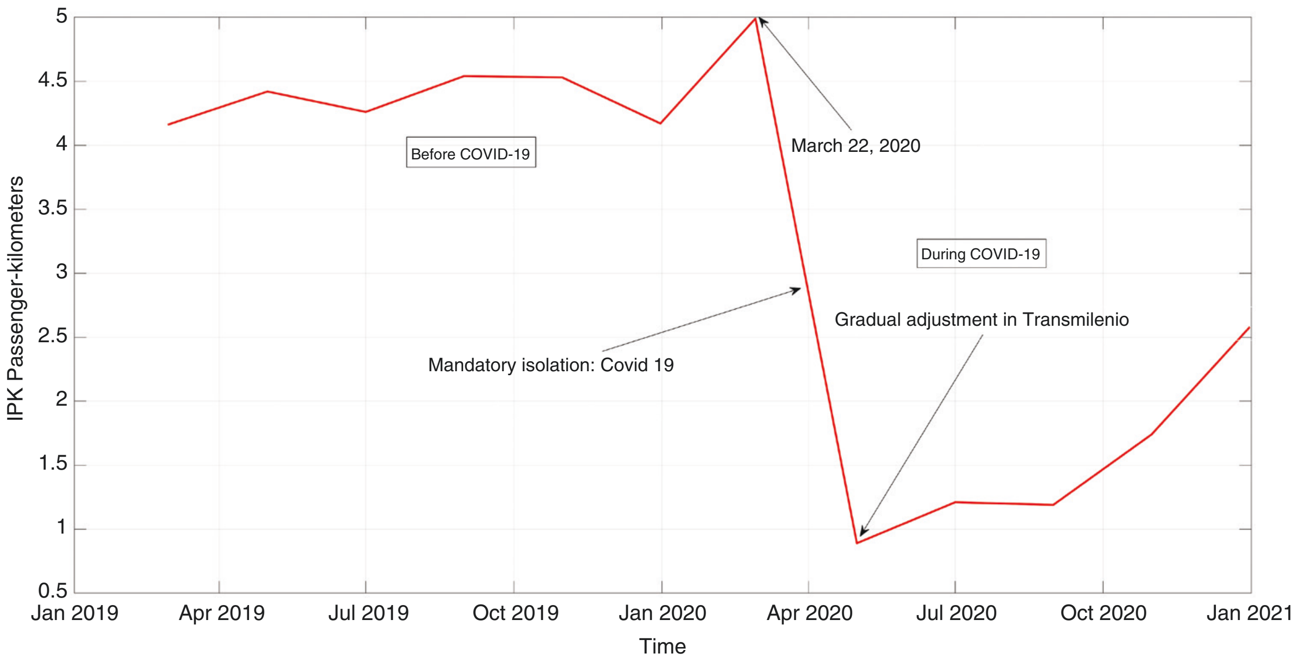


Fig. 3: Overall p-km index before and during COVID-19 in the TransMilenio system [59]

Table 3: Detailed energy demand in the BAU scenario for the Bogotá BRT system

Year	**Bi-articulated**			**Articulated**			**Modal**		
Fuel	**Diesel (TJ)**	**NG (TJ)**	**Electricity (TJ)**	**Diesel (TJ)**	**NG (TJ)**	**Electricity (TJ)**	**Diesel (TJ)**	**NG (TJ)**	**Electricity (TJ)**
2019 (before fleet renewal)	608.4 (100%)	–	–	1344.3 (100%)	–	–	18.2 (5.6%)	–	305.0 (94.4%)
2020 (new fleet and COVID-19)	225.6 (97.2%)	10.3 (2.8%)	–	80.4 (84.7%)	14.5 (15.2%)	–	7.1 (5.6%)	–	118.4 (94.4%)
2022 (post-COVID-19)	641.9 (95.6%)	29.4 (4.4%)	–	228.8 (84.7%)	41.2 (15.2%)	–	20.1 (5.6%)	–	336.9 (94.4%)
2030 (next partial new fleet)	319.7 (85.8%)	52.8 (13.8%)	9.4 (0.4%)	175.8 (80.6%)	38.9 (17.8%)	3.3 (1.6%)	–	–	66.38 (100%)
2040 (long-term model)	346.1 (83.6%)	57.2 (13.8%)	10.4 (2.6%)	190.3 (80.6%)	42.2 (17.8%)	3.6 (1.6%)	–	–	72.0 (100%)

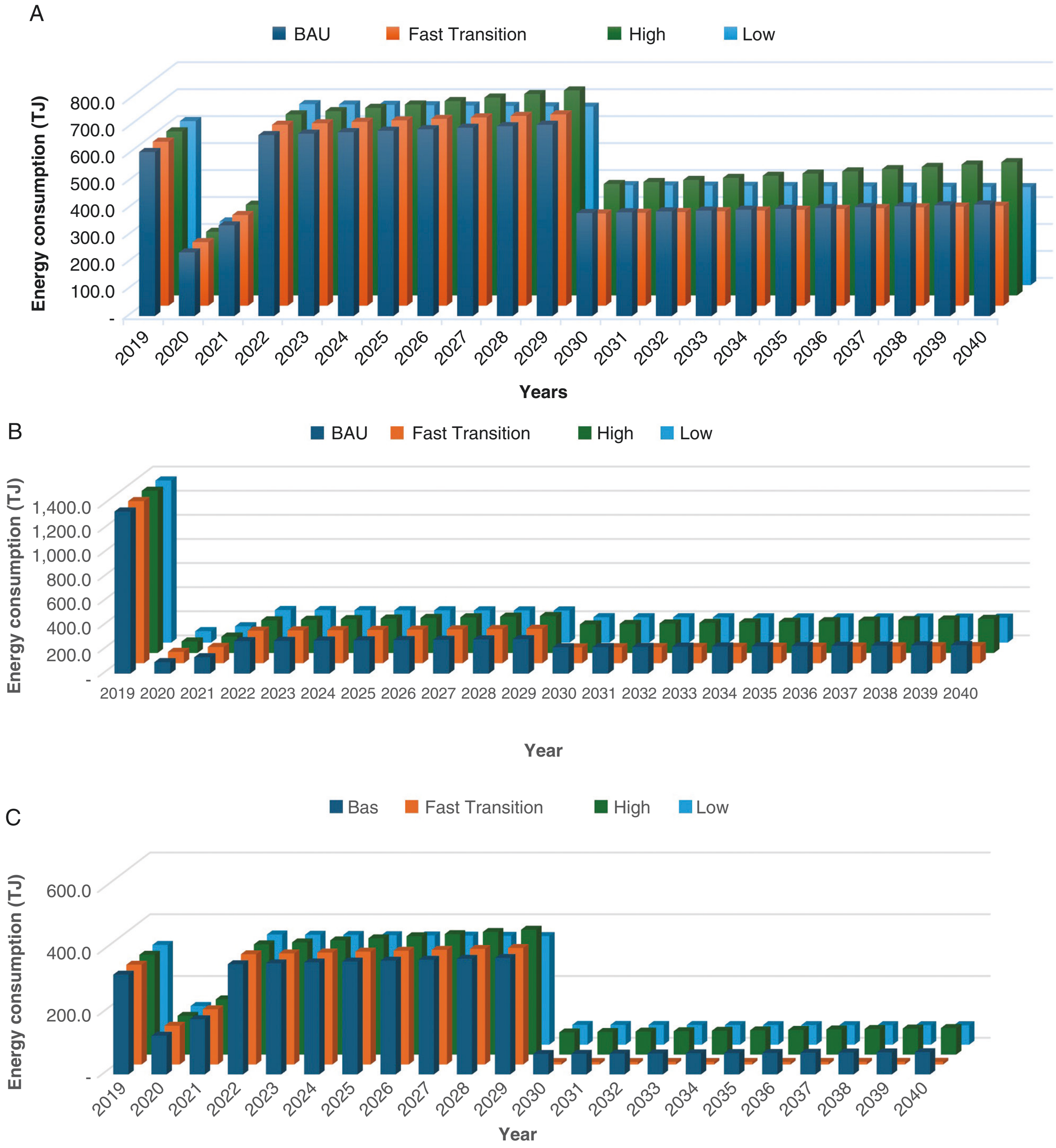


Fig. 4: Energy consumption scenarios for type of BRT unit. (a) Bi-articulated, (b) articulated and (c) rigid.

Passenger demand behaviour before and during COVID-19 (2019–21) is shown in Fig. 3 and has been included in the four scenarios. The figure shows the most relevant aspects, including the start of lockdown and the gradual adjustment to normal TransMilenio operation.

3 Results

In this section, the results are presented of the assessment of energy consumption, EEs and fuel costs applied in the four scenarios defined in Section 2.3 in the BRT system of Bogotá.

3.1 Energy consumption

In the BAU scenario, the major energy consumption stems from bi-articulated (56%), followed by articulated (32%) and rigid (12%) BRT units. In this scenario, in 2019, consumption comprises 1970.8 TJ of diesel and 305 TJ of electricity for a total energy consumption of 2275.8 TJ. In 2020, with the COVID-19 restrictions, energy demand drops to 313.1 TJ of diesel, 24.8 TJ of NG and 118.4 TJ of electricity 456.3 TJ in total. Thus, in this scenario, in 2030, energy consumption is 495.5 TJ of diesel, 92.5 TJ of NG and 79.1 TJ of electricity. In addition, in 2040, the use of diesel is reduced from 1970.8 to 536.5 TJ compared with the 2019 baseline and NG

Table 4: Energy demand obtained for the four scenarios analysed

Year	BAU (TJ)	Fast (TJ)	High (TJ)	Low (TJ)
2020	456.2	456.2	456.2	456.2
2022	1298.3	1298.3	1298,3	1298.3
2030	666.4	481.2	721.2	646.2
2040	721.9	521.7	862.0	633.7
Total accumulated (2020–40)	19 419.6	17 301.0	20 855.6	18 459.5

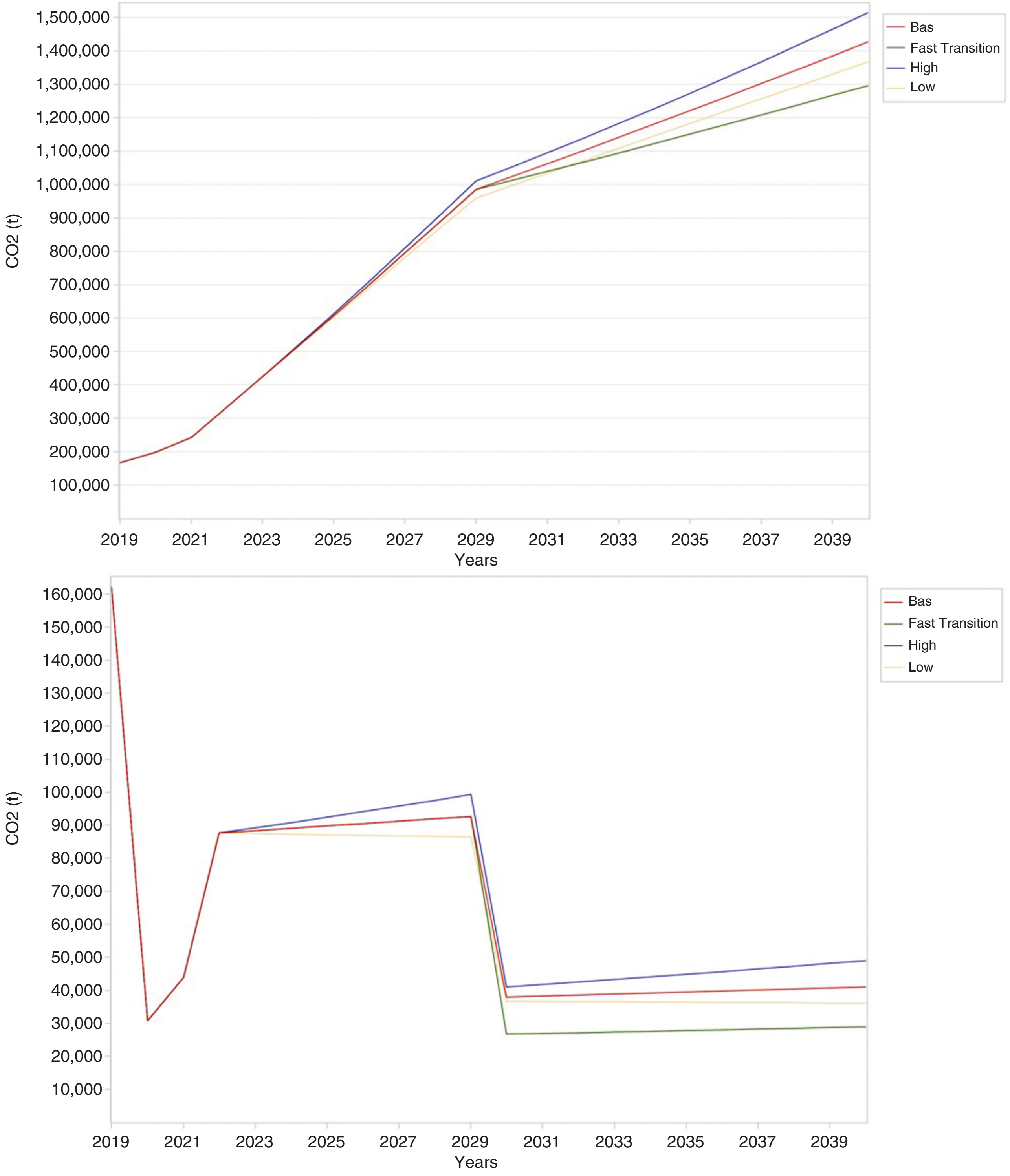


Fig. 5: CO_2 emissions. The upper panel (a) presents the long-term emissions in all scenarios and the lower panel (b) presents the cumulative emissions in all scenarios.

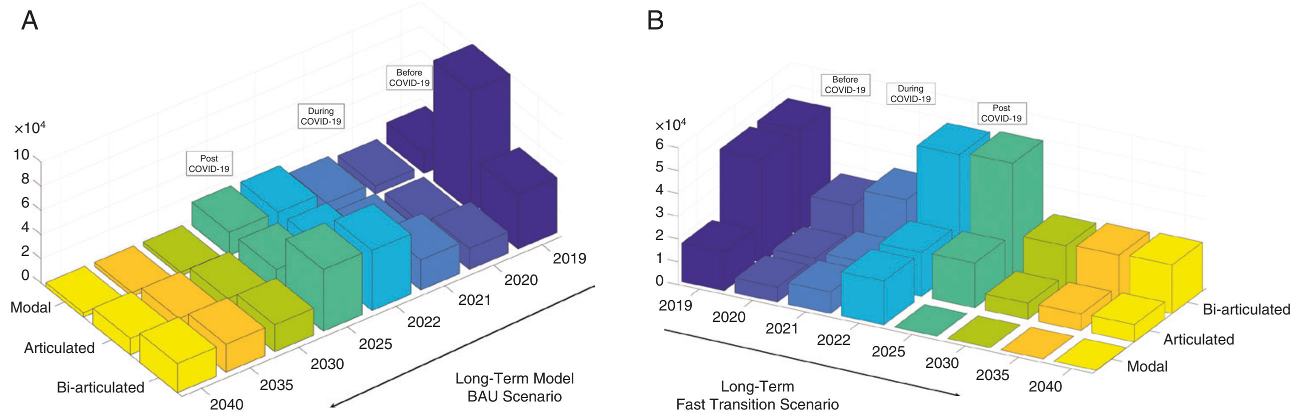


Fig. 6: CO_2 emissions in BAU and Fast scenarios by type of vehicle in the BRT system. The upper panel shows the BAU scenario and the lower panel shows the Fast scenario.

Table 5: EEs in BAU, Transition and High scenarios [51]

Years	2019	2020			2030			2040		
Scenario	BAU (t)	BAU (t)	Fast (t)	High (t)	BAU (t)	Fast (t)	High (t)	BAU (t)	Fast (t)	High (t)
CO_2	162 104	30 812	30 812	30 812	37 946	41 058	26 738	41 085	49 057	28 950
CO	1966	359	359	359	227	246	141	246	294	153
CH_4	13.1	9.6	9.6	9.6	28.9	31.2	26.5	31.2	37.3	28.7
NMVOCs	437	79.7	79.7	79.7	50.7	54.9	31.4	54.9	65.5	34.0
NOx	2184	401	401	401	344	372	226	372	444	244
N_2O	6.6	1.2	1.2	1.2	1.1	1.2	0.7	1.2	1.5	0.8

increases to 99.4 TJ. Table 3 gives a detailed summary of the energy demand for each type of vehicle in the simulation horizon.

Fig. 4 shows the energy consumed each year from 2019 to 2040 for the four scenarios and for each BRT type. The following is an analysis of the cumulative consumption. Cumulative bi-articulated consumption in the BAU scenario is 11 078 TJ. With the Fast scenario, this is reduced by 4.1%. Compared with the BAU scenario, consumption is 7.2% higher in the High scenario and 4.8% lower in the Low scenario. With respect to articulated vehicles, cumulative consumption in the BAU scenario is 6292 TJ. Consumption in the Fast scenario is 15.8% lower, 6.7% higher in the High scenario and 4.3% lower in the Low scenario. In rigid BRT units, cumulative consumption is 4324 TJ. Compared with the BAU scenario, consumption is 15.4% lower in the Fast scenario, 4.9% higher in the High scenario and 3.7% lower in the Low scenario. Table 4 shows energy consumption in the years 2020, 2022, 2030 and 2040, and the total cumulative consumption for each scenario. The total cumulative consumption for the BAU scenario is 19 419 TJ. Compared with the BAU scenario, it is 10.9% lower in the Fast scenario, 7.4% higher in the High scenario and 4.9% lower in the Low scenario.

3.2 EEs

The EEs in the long-term model are measured in terms of emissions of CO, CO_2, NO_x, CH_4, NMVOCs and N_2O. Fig. 5a shows the CO_2 emissions for all scenarios from 2019 to 2040, while Fig. 5b presents the cumulative CO_2 emissions by scenario. This cumulative Fig. 5b is a sensitivity analysis that includes the variation between scenarios after COVID-19. The results under the BAU scenario in 2019 indicate a total of 162 104 t of CO_2. This value is close to that reported by the Mayor's Office of Bogotá in 2018. In 2020, CO_2 emissions were drastically reduced due to lockdown and the introduction of the new fleet of BRT units. CO_2 emissions were reduced to 30 812 t and, in the post-COVID-19 period, the total emissions are expected to amount in 2022 to 87 683 t, in 2030 to 37 946 t and in 2040 to 41 086 t. These results are possible with a reduction in the use of diesel in BRT units. As expected, under the High scenario, CO_2 emissions increased in 2030 by ~14.1% and in 2040 by 19.4% compared with the Fast scenario, which includes elimination of the use of diesel in the BRT system. The results show that, in 2030 and 2040, the reduction in CO_2 emissions corresponds to ~29.5%.

Fig. 6 shows a comparison of CO_2 emissions in the BAU and Fast scenarios by type of BRT unit. Whilst, in the BAU scenario in 2030, bi-articulated CO_2 emissions are 22 211 t, in the Fast scenario, they are only 19 715 t, which means a reduction of 12.6%. With respect to articulated units, in the BAU scenario in 2030, emissions amounted to 12 536 t in comparison with 7023 t in the Fast scenario. This result represents a reduction of 43.9%. In the case of modal transport, in the BAU scenario, CO_2 emissions reached 3199 t in comparison with the Fast scenario, in which this is reduced to zero. In 2040, bi-articulated CO_2 emissions amounted to 24 048 t in the BAU scenario and 21 346 t in the Fast scenario, representing a decrease of 11.2%. With respect to articulated units, CO_2 emissions were 13 573 t in the BAU scenario and 7604 t in the Fast scenario, representing a reduction of 44.0%. These results demonstrate the remarkable impact of the Fast Transition scenario in the reduction of CO_2 emissions.

Table 5 presents a complete summary of the EEs found, comparing the BAU, Fast and High scenarios as the most important

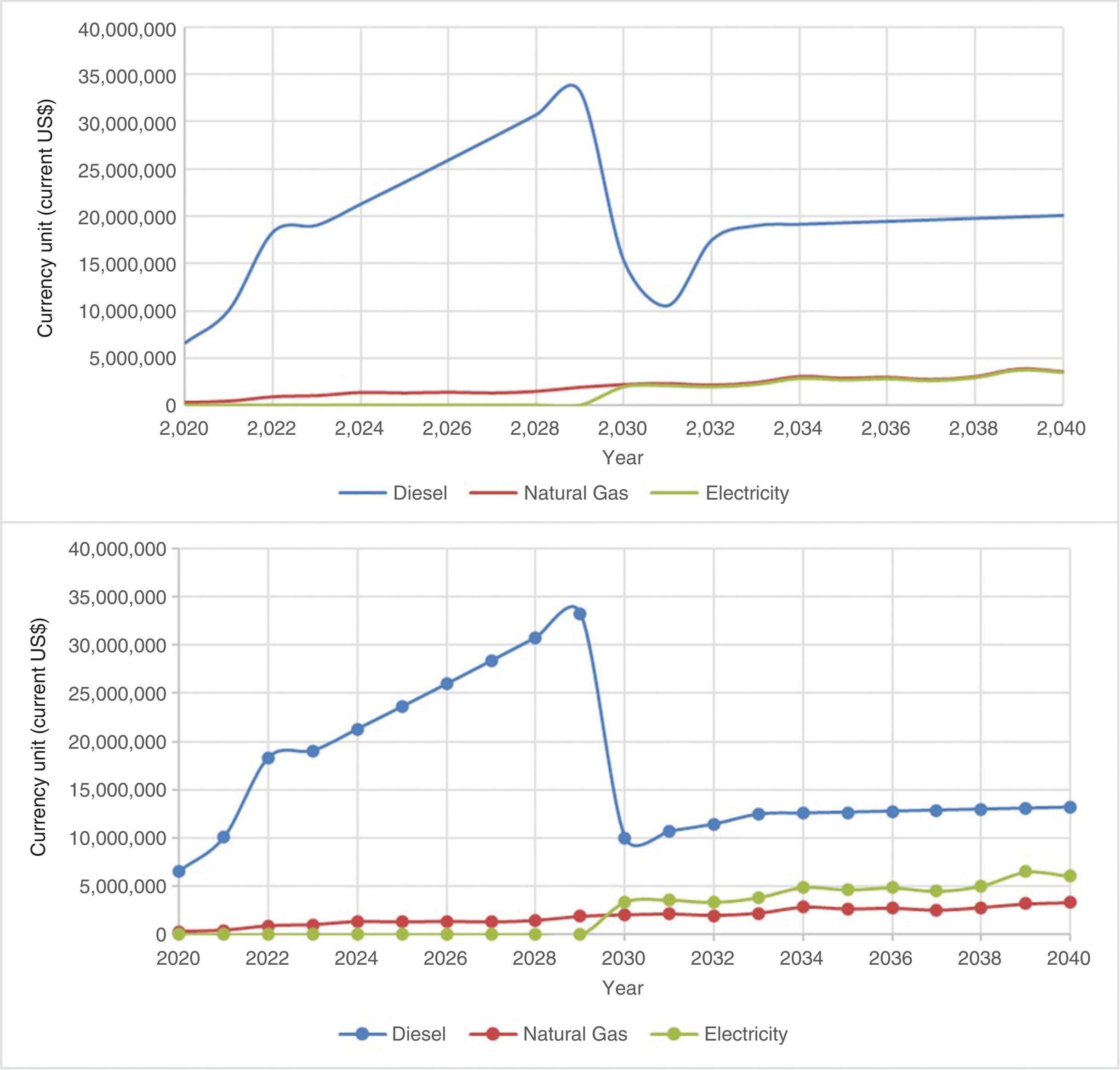


Fig. 7: Energy costs. (a) BAU scenario (upper panel) and (b) Fast Transition scenario (lower panel).

ones in this study. The results are shown for 2019 before COVID-19, 2020 during COVID-19, 2022–30 post-COVID-19 and 2040 (long-term). In 2040, CO_2 emissions were 41 085 t in the BAU scenario and 28 950 t in the Fast scenario, which represents a reduction of 29.5%. By contrast, CO_2 emissions were 49 057 t in the High scenario, which represents an increase of 16.2% compared with the BAU scenario.

3.3 Energy costs

Energy costs were calculated on the basis of the BAU and Fast Transition scenarios. Fig. 7 in the upper panel illustrates all energy costs from 2020 to 2040. Diesel presents a higher cost than electricity and NG as an energy source in US dollars. The results are based only on energy costs and do not include fleet costs or financial analyses. In the results, long-term projected international energy prices are applied. As shown in the comparison of the BAU scenario with the Fast Transition scenario in the lower panel, the costs are reduced to a large extent due to the participation of electricity as an energy source.

4 Discussion and conclusions

This paper presents an assessment approach related to energy consumption, EEs and fuel costs in the BRT urban public transport system of Bogotá that operates in exclusive lanes and is known as TransMilenio. The assessment is based on the ASIF methodology applied by the Intergovernmental Panel on Climate Change (IPCC) and simulations considering four scenarios: BAU, Fast Transition, High Growth and Low Growth. The analysis was carried out on the LEAP platform using a long-term model from 2020 to 2040.

Road transport plays an important role in the energy transition and on the path to neutral emissions. In addition, the change in the use of fuels based on petroleum derivatives to fuels or sources such as NG, electricity, biodiesel and hydrogen allows the reduction of GHG emissions from road transport especially. The results of the assessment employed show that scenarios involving a rapid energy transition based on cleaner fuels, such as NG and electricity, yield major benefits that include reductions in GHG emissions, energy consumption, dependency on liquid fuels and variable costs in the operation of BRT systems. Rapid action in energy transition has the potential to mitigate the effects that may occur because of a fast economic recovery, which may increase emissions and energy consumption.

The results found in this work allow ratification of the empirical evidence about the benefits of energy transition in public transport in developing countries that run BRT systems [65–67]. According to the WHO, ambient air pollution causes ~4.2 million deaths per year [68] due to chronic respiratory diseases such as lung cancer, chronic obstructive pulmonary disease and ischaemic heart disease [69]. In September of 2020, Greenpeace Colombia [70] disclosed that, in Bogotá, there were ~3900 deaths due to air pollution involving a cost of ~US$1300 MM. The Secretary of the Environment of the Mayor's Office of Bogotá reported average annual pollution levels of 13.9 $PM_{2.5}$ $\mu gr/m^3$ [71] and, although this value is low compared with countries of South-East Asia, it is high in comparison with Latin American cities. In general, large cities have traffic difficulties, population growth and pollution problems.

Regarding energy demand, the results obtained in this study suggest that it is possible to obtain a 10.9% lower consumption for the scenario analysed that supposes a Fast Transition scenario. Additionally, the results obtained in CO_2 emissions demonstrate the remarkable impact of the Fast Transition scenario in reducing CO_2 emissions. In 2040, CO_2 emissions were 41 085 t in the BAU scenario and 28 950 t in the Fast scenario, which represents a reduction of 29.5%. The energy cost is also largely reduced due to the participation of electricity as an energy source in the Fast Transition scenario. Specifically, the diesel cost is US$20 075 189 for the 2040 BAU scenario whereas it is US$13 168 045 for the 2040 Fast Transition scenario. This is thus a decrease of 34.4%.

BRT-based transportation systems have proven to be a rapid solution to these difficulties at moderate costs [39, 41, 72]. Nonetheless, in large cities, there is no magic solution and it is imperative to implement a set of complementary actions aimed at improving transportation, including train lines, light rails, bicycles, taxis, light BRTs and pedestrian areas.

The study presents several limitations related to modelling as well as measurements. In the modelling, a better approximation could have been achieved with a daily passenger demand profile. With respect to EEs, particulate matter and sulphur oxides (SO_x) were not considered. Another relevant limitation in the work corresponds to the lack of a financial analysis of the cost of fuels in the long term, which can be very useful for decision makers.

Supplementary data

Supplementary data is available at *Clean Energy* online.

Conflict of interest statement

None declared.

Author contributions

J.J.P.: conceptualization, methodology, formal analysis, investigation, funding acquisition, and writing – original draft. L.H.C.: investigation, and writing—review & editing. P.A.Ø.: methodology, formal analysis, validation, and review & editing. P.C.: supervision, writing—review & editing.

Acknowledgements

The authors would like to acknowledge internal funding from Universidad de La Salle financial support project CUAC19106. We would like to acknowledge the reviewers for valuable comments, which we believe have benefitted the manuscript.

References

[1] International Energy Agency. *Key World Energy Statistics*. https://www.iea.org/reports/key-world-energy-statistics-2021 (1 August 2022, date last accessed).

[2] International Energy Agency. *Energy Statistics Data Browser in 2021*. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data (9 October 2023, date last accessed).

[3] Unidad de Planeación Minero Energética. *Balance Energético Colombiano*. https://www1.upme.gov.co/DemandayEficiencia/Paginas/BECO.aspx (1 October 2022, date last accessed).

[4] International Energy Agency. *Global CO_2 Emissions from Transport by Subsector, 2000–2030*. https://www.iea.org/data-and-statistics/charts (1 August 2022, date last accessed).

[5] Sandaka BP, Kumar J. Alternative vehicular fuels for environmental decarbonization: a critical review of challenges in using electricity, hydrogen, and biofuels as a sustainable vehicular fuel. *Chem Eng J Adv*, 2023, 14:100442.

[6] Yang M, Hunger R, Berrettoni S, *et al*. A review of hydrogen storage and transport technologies. *Clean Energy*, 2023, 7:190–216.

[7] TransMilenio. *Estadísticas de oferta y demanda del Sistema Integrado de Transporte Público SITP*. 2023. https://www.transmilenio.gov.co/publicaciones/146908/awards-recognition-for-environmental transmilenio-system/ (10 December 2022, date last accessed).

[8] Al-Ghandoor A. An approach to energy savings and improved environmental impact through restructuring Jordan's transport sector. *Renew Sustain Energy Rev*, 2013, 18:31–42.

[9] Dominković D, Bačeković I, Pedersen A, *et al*. The future of transportation in sustainable energy systems: opportunities and barriers in a clean energy transition. *Renew Sustain Energy Rev*, 2018, 82:1823–1838.

[10] Vergel K, Marcelo K, Salison A, *et al*. Estimation of transportation energy demand of the Philippines using a bottom-up approach. *Asian Transp Stud*, 2022, 8:100058.

[11] De Carvalho E, Junior A, de Mendonça Brasil A. Energy impact assessment of electric vehicle insertion in the Brazilian scenario, 2020–2050: a machine learning approach to fleet projection. *e-Prime-Adv Electr Electron Eng*, 2023, 4:100184.

[12] Seo Y, Kim S. Estimation of greenhouse gas emissions from road traffic: a case study in Korea. *Renew Sustain Energy Rev*, 2013, 28:777–787.

[13] Rahman S, Khondaker A, Hasan M, *et al*. Greenhouse gas emissions from road transportation in Saudi Arabia: a challenging frontier. *Renew Sustain Energy Rev*, 2017, 69:812–821.

[14] Kazancoglu Y, Ozbiltekin-Pala M, Ozkan-Ozen Y. Prediction and evaluation of greenhouse gas emissions for sustainable road transport within Europe. *Sustain Cities Soc*, 2021, 70:102924.

[15] Huang Y, Wolfram P, Miller R, *et al*. Mitigating life cycle GHG emissions of roads to be built through 2030: case study of a Chinese province. *J Environ Manage*, 2022, 319:115512.

[16] Ajanovic A, Dahl C, Schipper L. Modelling transport (energy) demand and policies: an introduction. *Energy Policy*, 2012, 4:3–16.

[17] Hache E, Seck G, Simoen M, *et al*. Critical raw materials and transportation sector electrification: a detailed bottom-up analysis in world transport. *Appl Energy*, 2019, 240:6–25.

[18] Besagni G, Borgarello M. A bottom-up study on the relationships between transportation expenditures and socio-demographic variables: evidences from the Italian case study. *Travel Behav Soc*, 2020, 19:151–161.
[19] Bajay S. Long-term electricity demand forecasting models: a review of methodologies. *Electr Power Syst Res*, 1983, 6:243–257.
[20] Sharma D, Chandramohanan Nair P, Balasubramanian R. Demand for commercial energy in the state of Kerala, India: an econometric analysis with medium-range projections. *Energy Policy*, 2002, 30:781–791.
[21] Soares L, Medeiros M. Modeling and forecasting short-term electricity load: a comparison of methods with an application to Brazilian data. *Int J Forecast*, 2008, 24:630–644.
[22] Firth S, Lomas K, Wright A, *et al*. Identifying trends in the use of domestic appliances from household electricity consumption measurements. *Energy Build*, 2008, 40:926–936.
[23] Richardson I, Hodgson G, Thomson M, *et al*. Simulation of high-resolution domestic electricity demand based on a building occupancy model and its applicability to the study of demand side management. In: *Proceedings of the 5th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'09)*, Berlin, Germany, 16–18 June 2009, 1:97–105.
[24] Borg S, Kelly N. The effect of appliance energy efficiency improvements on domestic electric loads in European households. *Energy Build*, 2011, 43:2240–2250.
[25] Hiller C. Influence of residents on energy use in 57 Swedish houses measured during four winter days. *Energy Build*, 2012, 54:376–385.
[26] Winyuchakrit P, Limmeechokchai B, Matsuoka Y, *et al*. Thailand's low-carbon scenario 2030: analyses of demand side CO_2 mitigation options. *Energy for Sustain Dev*, 2011, 15:460–466.
[27] Greene D. Rebound 2007: analysis of U.S. light-duty vehicle travel statistics. *Energy Policy*, 2012, 41:14–28.
[28] Gelves J, Florez G. Methodology to assess the implementation of solar power projects in rural areas using AHP: a case study of Colombia. *Int J Sustain Energy Plan Manag*, 2020, 29:69–78.
[29] Dahl C. Measuring global gasoline and diesel price and income elasticities. *Energy Policy*, 2012, 41:2–13.
[30] Sterner T. Distributional effects of taxing transport fuel. *Energy Policy*, 2012, 41:75–83.
[31] Hörcher D, Tirachini A. A review of public transport economics. *Econ Transp*, 2021, 25:100196.
[32] Pongthanaisawan J, Sorapipatana C, Limmeechokchai B. Road transport energy demand analysis and energy saving potentials in Thailand. *Asian J Energy Environ*, 2007, 8:49–72.
[33] Solís J, Sheinbaum C. Energy consumption and greenhouse gas emission trends in Mexican road transport. *Energy Sustain Dev*, 2013, 17:280–287.
[34] Jiao J, Huang Y, Liao C. Co-benefits of reducing CO_2 and air pollutant emissions in the urban transport sector: a case of Guangzhou. *Energy Sustain Dev*, 2020, 59:131–143.
[35] Song H, Ou X, Yuan J, *et al*. Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. *Energy*, 2017, 140:966–978.
[36] Chang Y, Lei S, Teng J, *et al*. The energy use and environmental emissions of high-speed rail transportation in China: a bottom-up modeling. *Energy*, 2019, 182:1193–1201.
[37] Martínez-Jaramillo J, Arango-Aramburo S, Alvarez Uribe K, *et al*. Assessing the impacts of transport policies through energy system simulation: the case of the Medellin metropolitan area, Colombia. *Energy Policy*, 2017, 101:101–108.
[38] Lu H. *Eco-Cities and Green Transport*. Beijing, P. R. China: Elsevier, 2020.
[39] Silva D. P21 reducing accident rates with the implementation of a bus rapid transit (BRT) system: case study of Rio de Janeiro, Brazil. *J Transp Health*, 2015, 2:S74.
[40] Lindau L, dos Santos Senna L, Strambi O, *et al*. Alternative financing for bus rapid transit (BRT): the case of Porto Alegre, Brazil. *Res Transp Econ*, 2008, 22:54–60.
[41] Vergel C, Rodriguez D. The ridership performance of the built environment for BRT systems: evidence from Latin America. *J Transp Geogr*, 2018, 73:172–184.
[42] Bel G, Holst M. Evaluation of the impact of bus rapid transit on air pollution in Mexico City. *Transp Policy*, 2018, 63:209–220.
[43] Rodriguez D, Vergel-Tovar E, Camargo W. Land development impacts of BRT in a sample of stops in Quito and Bogota. *Transp Policy*, 2016, 51:4–14.
[44] International Energy Agency. *The COVID-19 Crisis and Clean Energy Progress*. https://www.iea.org/reports/the-covid-19-crisis-and-clean-energy-progress (1 October 2021, date last accessed).
[45] International Energy Agency. *Global Energy Review: CO_2 Emissions in 2020*. https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020 (1 October 2021, date last accessed).
[46] Griffiths S, Furszyfer Del Rio D, Sovacool B. Policy mixes to achieve sustainable mobility after the COVID-19 crisis. *Renew Sustain Energy Rev*, 2021, 143:110919.
[47] Nundy S, Ghosh A, Mesloub A, *et al*. Impact of COVID-19 pandemic on socio-economic, energy-environment and transport sector globally and sustainable development goal (SDG). *J Clean Prod*, 2021, 312:127705.
[48] Schipper L, Marie-Lilliu C, Gorham R. Flexing the link between transport and greenhouse gas emissions: a path for the world bank. https://trid.trb.org/view/851906 (1 October 2021, date last accessed).
[49] Schipper L, Meyers S. *Energy Efficiency and Human Activity: Past Trends, Future, Prospects*. Cambridge, UK: Cambridge University Press, 1992.
[50] Schipper L, Scholl L, Price L. Energy use and carbon emissions from freight in 10 industrialized countries: an analysis of trends from 1973 to 1992. *Transp Res D Transp Environ*, 1997, 2:57–76.
[51] Intergovernmental Panel on Climate Change (IPCC). *Emission Factor Database*. https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php?ipcc_code=1.A.3.b&ipcc_level=3. (1 January 2023, date last accessed).
[52] Heaps C. *LEAP: The Low Emissions Analysis Platform*. [Software version: 2020.1.103] Somerville, MA, USA: Stockholm Environment Institute, 2022. https://leap.sei.org (1 October 2021, date last accessed).
[53] Huang Y, Bor Y, Peng C. The long-term forecast of Taiwan's energy supply and demand: leap model application. *Energy Policy*, 2011, 39:6790–6803.
[54] Ahanchian M, Biona J. Energy demand, emissions forecasts and mitigation strategies modeled over a medium-range horizon: the case of the land transportation sector in metro Manila. *Energy Policy*, 2014, 66:615–629.
[55] Nieves J, Aristizabal A, Dyner I, *et al*. Energy demand and greenhouse gas emissions analysis in Colombia: a leap model application. *Energy*, 2019, 169:380–397.
[56] Castro P, Vidoza J, Gallo W. Analysis and projection of energy consumption in Ecuador: energy efficiency policies in the transportation sector. *Energy Policy*, 2019, 134:110948.

[57] Departamento Administrativo Nacional de Estadística (DANE)—Colombia. *Encuesta Multipróposito Bogotá*. 2021. https://www.dane.gov.co/files/investigaciones/multi/Boletin_EM_2021.pdf (1 October 2023, date last accessed).

[58] International Trade Administration (ITA). *U.S. Commercial Service. Bogotá Profile*. 2021. https://www.trade.gov/sites/default/files/2021-03/Bogota%20Profile.pdf (9 October 2023, date last accessed).

[59] TransMilenio. *Estadísticas de oferta y demanda del Sistema Integrado de Transporte Público SITP—February*. 2023. https://www.transmilenio.gov.co/publicaciones/146908/awards-recognition-for-environmental transmilenio-system/ (10 February 2022, date last accessed).

[60] UPME, C., IREES, T. *Primer balance de Energía Útil para Colombia y Cuantificación de las Pérdidas energéticas relacionadas y la brecha de eficiencia energética*. Bogotá: UPME, 2019 *Resumen Ejecutivo BEU Sector Residencial y Terciario*.

[61] Mahmoud M, Garnett R, Ferguson M, *et al*. Electric buses: a review of alternative powertrains. *Renew Sustain Energy Rev*, 2016, 62:673–684.

[62] Portafolio. *Mas energıa electrica en el transporte para el transporte en Bogota*. 2014. https://www.portafolio.co/economia/finanzas/%20energia-electrica-transporte-bogota-53624. (1 June2022, date last accessed).

[63] Hidalgo D, Pereira L, Estupiñán N, *et al*. Transmilenio BRT system in Bogotá, high performance and positive impact: main results of an ex-post evaluation. *Res Transp Econ*, 2013, 39:133–138.

[64] TransMilenio. *Estadísticas de oferta y demanda del Sistema Integrado de Transporte Público SITP—October*. 2022. https://www.transmilenio.gov.co/publicaciones/146908/awards-recognition-for-environmental transmilenio-system/ (10 December 2022, date last accessed).

[65] Church A, Frost M, Sullivan K. Transport and social exclusion in London. *Transp Policy*, 2000, 7:195–205.

[66] Kabia E, Mbau R, Muraya K, *et al*. How do gender and disability influence the ability of the poor to benefit from pro-poor health financing policies in Kenya? An intersectional analysis. *Int J Equity Health*, 2018, 17:149.

[67] Benevenuto R, Caulfield B. Poverty and transport in the global south: an overview. *Transp Policy*, 2019, 79:115–124.

[68] WHO. *Ambient (Outdoor) Air Pollution*. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health#:~:text=Ambient%20(outdoor)%20air%20pollution%20is,Asia%20and%20Western%20Pacific%20Regions (1 June 2023, date last accessed).

[69] Rodrıguez-Urrego D, Rodrıguez-Urrego L. Air quality during the COVID-19: Pm2.5 analysis in the 50 most polluted capital cities in the world. *Environ Pollut*, 2020, 266:115042.

[70] Tiempo. *Contaminacion del air en Bogota*. 2020. https://www.eltiempo.com/vida/medio-ambiente/muertes-en-bogota-por-la-contaminacion-del-aire-segun-ultimo-reporte-de-greenpeace (1 June 2021, date last accessed).

[71] Ambiente. *Datos abiertos—secretaria del medio ambiente*. 2020. http://www.ambientebogota.gov.co/web/transparencia/datos-abiertos (1 June 2021, date last accessed).

[72] Abbasi M, Hadji M, JafarzadehFadaki S. An investigation of bus rapid transit system (BRT) based on economic and air pollution analysis (Tehran, Iran). *Case Stud Transp Policy*, 2020, 8:553–563.