



# Inequality in personal exposure to air pollution in transport microenvironments for commuters in Bogotá

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## ABSTRACT

Commuters in Bogotá (Colombia) are exposed to high concentrations of air pollutants, in part, due to their proximity to mobile sources. This paper analyzes current inequalities in the potential daily inhaled dose of particulate matter (PM<sub>2.5</sub>), black carbon (BC), and carbon monoxide (CO) that commuters experience in transport microenvironments according to their socioeconomic background and travel patterns in Bogotá. We use data reported from in-situ measurements of personal exposure to air pollutants in different transport modes and several locations across the city as well as detailed commuter travel time and travel choice data from a city-wide household mobility survey. The personal exposure data together with the mobility survey are then used to estimate the potential inhaled dose of commuters in different transport modes and to investigate the potential associations between the most salient features of commuter exposure. We found larger inequalities in the potential daily inhaled dose of air pollutants between the lowest and the highest quintile of the population distribution. The results also suggest that inequality is largely explained by the transport mode of commuters and travel time. Results are useful for informing further public policies aimed at minimizing air pollution exposure and decreasing the current exposure inequalities, particularly to improve the disadvantaged situation of the low-income population.

## 1. Introduction

Exposure to polluted air has been associated with many negative health impacts, including an increased risk for heart disease, lung cancer, respiratory infections, and mortality (Kingham et al., 2013; Nyhan et al., 2014; Pope et al., 1991). An estimated 4.2 million premature deaths worldwide are associated with ambient air pollution (WHO, 2020). The ambient concentration of air pollutants in the cities of many emerging economies often exceeds the World Health Organization guidelines (WHO, 2006). Nearly 40 % of the cities in Latin America have mean PM<sub>2.5</sub> concentrations above the World Health Organization Air Quality Guidelines (AQG) (Gouveia et al., 2019). Furthermore, commuters are repeatedly exposed to peak concentrations of different air pollutants due to their proximity to traffic-related emissions (Gulliver and Briggs, 2004; Kaur et al., 2007; Li et al., 2015; Morales Betancourt et al., 2017; Pattinson et al., 2018; Suárez et al., 2014; Targino et al., 2021; Velasco et al., 2019). Although commute time is just a fraction of someone's daily activities and varies across regions, the contribution of

transport activities to their daily air pollutant exposure is therefore disproportionately high, exacerbating inequalities among people who use specific transport modes (Hankey and Marshall, 2015; Kingham et al., 2013; Morales Betancourt et al., 2019; Ramos et al., 2015; Suárez et al., 2014). Several studies have analyzed social inequality using in-situ measurements of personal exposure in transport microenvironments (Both et al., 2013; Cepeda et al., 2017; Morales Betancourt et al., 2017). As a result, pollutant exposure in transport microenvironments has been the subject of many studies. For the most part, studies indicate that commuters in motorized vehicles (cars, buses, trains, etc.) are exposed to higher levels of particulates and other pollutants than pedestrians or cyclists (Cole-Hunter et al., 2012; Do et al., 2014; Guo et al., 2012; Int Panis et al., 2010; Ramos et al., 2015; Zurbier et al., 2010).

Unfairness in both transport and the environment are reported in multiple studies that have established that exposure to air pollutants is exacerbated in vulnerable socioeconomic groups, with lower-income populations and minorities often exposed to higher air pollution levels (Pinault et al., 2016; Rowangould, 2013; Samoli et al., 2019).

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Additionally, lower-income communities have often been found to generate fewer emissions due to their higher public transport and active transport use (Tiznado-Aitken et al., 2019). The lack of commuter exposure data has hindered the ability to assess potential environmental inequalities experienced by travelers, especially in Latin American cities.

Accordingly, Boyce (2016) estimated environmental inequality in the US using exposure to pollutants and found high levels of inequality according to ethnicity, and between poor and non-poor individuals. Evans and Kantrowitz (2002) found a correlation between pollutant level, health, and socioeconomic variables. Morello-Frosch et al. (2011) found that socioeconomic status can potentiate the adverse effects of pollutants. Although most of these studies were carried out in the US, they are telling of the likely status of environmental inequality in the Latin American context, a region known to have larger gaps in socioeconomic levels and different vehicle fleet conditions than those in the US. In Latin American cities such as Bogotá, the assessment of the overall sustainability of its transport system should include several aspects often left out, such as its effect on the environment and health. A better understanding of exposure and potential inhaled doses of air pollutants during a commute can help to better design public transport alternatives and close inequality gaps.

In this research, we estimate the potential inhaled dose of fine particulate matter (PM<sub>2.5</sub>), black carbon (BC), and carbon monoxide (CO) in the daily commute according to household income and travel patterns in Bogotá. Transport inequalities in the study area are well known, as the low-income population is disproportionately disadvantaged regarding access to economic opportunities, travel times, and transport affordability (Guzman et al., 2017; Guzman and Oviedo, 2018; Peña et al., 2022). Low-income populations have historically settled at the urban periphery in Bogotá. The location of these residences has a strong effect on travel patterns and travel times (Guzman and Bocarejo, 2017). Previous studies have shown that exposure to pollutants is highest inside Bus Rapid Transit (BRT) buses in Bogotá, compared to other transport modes, including regular buses, private cars, taxis, bicycles, and pedestrians (Morales Betancourt et al., 2017). Exposure within BRT stations and the buses themselves at the time of the study was found to be more than six times higher than that for pedestrians, which are some of the highest levels reported anywhere in the world (Morales Betancourt et al., 2019). These studies also found that vehicle age and emission standards were critical factors determining the exposure concentration inside the BRT buses, with passengers inside the older vehicles (Euro II and Euro III emission standards) experiencing twice as much exposure to PM<sub>2.5</sub> and BC compared to those in the newer (Euro IV and Euro V) buses. Those personal exposure measurements, however, were carried out before the BRT fleet was substantially modernized in 2020 when the share of Euro V and Euro VI buses increased substantially. Similar fleet renewals have taken place more recently when hundreds of older buses with diesel engines have been replaced by fully electric buses and by compressed natural gas.

We apply multiple techniques to evaluate measures of inequality in the potential daily dose received by commuters in Bogotá's transport system every day. Our goal is to understand how the potential daily dose of pollutants is distributed among commuters on a typical workday, and whether socioeconomic characteristics and the choice of transport mode explains these differences. This paper contributes to current issues related to lessons, pitfalls, and perspectives of urban transport sustainability in Latin America and their role in air quality and the increased exposure of commuters, with potentially negative effects on their health.

## 2. Study population

The study area is Bogotá and its 17 neighboring municipalities, which had a population of 8.9 million people in 2018, of whom 81 % lived in Bogotá. The evolution of the public transport system in the city has been marked by recurrent challenges, many of which remain

unsolved such as the increase in ownership and use of motorcycles and cars, resulting in increased air pollution, congestion, and traffic accidents (Guzman et al., 2020a). Once the BRT was implemented in early 2000, the next step was to organize the traditional bus system. The local government decided to implement the Integrated Public Transport System (SITP in Spanish), incorporating an integrated fare for the operation of all its public transport sub-systems, such as BRT and traditional buses. The SITP is composed of the BRT system, the feeder buses that connect peripheral zones with the BRT lines, the regular public buses in mixed traffic (Guzman et al., 2018), and recently, a cable car (Guzman et al., 2022; Morales-Betancourt et al., 2023). The SITP only works in Bogotá, and the connection with neighboring municipalities is made through inter-municipal routes not integrated with the SITP.

We used information on household income ranges reported in the 2019 Bogotá Household Travel Survey (HTS) to consider differences in socioeconomic levels. This information is reported in nine ranges, where range 1 corresponds to the poorest households and range 9 to the wealthiest. On the other hand, Colombia's traditional residential area classification by socioeconomic strata (SES), classifies households into six categories. SES 1 households correspond to the worst conditions and SES 6 to the best conditions (Cantillo-García et al., 2019). In SES 1 zones, the average household income is equal to or less than US\$ 250/month (range 1), and in SES 2 the average income is between US\$ 250 and US\$ 500/month (range 2). The wealthiest households have an average income above US\$ 2,750/month and are located in the north-eastern neighborhoods of the city (Fig. 1 left). We used three categories in our analysis, based on income ranges: low (ranges 1 to 3), medium (ranges 4 to 6), and high (ranges 7 to 9), as shown in Fig. 1 (left). According to the most recent HTS, 16 million daily trips are made with a duration greater than 3 min. Although car and motorcycle ownership in the region has increased considerably in the last 10 years, most trips are still made in non-motorized modes and by public transport: walking comprises 24.7 % of the daily trips. The BRT is the second most commonly used mode of transport at 15.6 % and then cars at 14.3 %, although about 60 % of these trips are less than 5 km (Guzman et al., 2021). Bicycle represents 7.4 % of the total trips, the traditional bus system 15.3 %, and motorcycles 5.7 %.

The average travel time for the whole study area is 51 min; however, there are great differences according to the transport mode and trip origin, as shown in Fig. 1 (right). There are differences in travel time according to the socioeconomic level of commuters (household location), where trips are longer for low-income households, as they are located mostly on the urban periphery. This is important because it is directly related to the exposure time of travelers in transport micro-environments. BRT, regular and provisional buses have the longest average travel times, at 96, 86, and 76 min respectively. These transport modes also have the longest trips (Guzman et al., 2020b). Walking and cycling trips are the shortest (22 and 38 min, respectively). There are marked differences in car use in the high-SES, as well as a decrease in walking and public transport trips.

## 3. Data and methods

We collected data on socioeconomic and mobility indicators from the last HTS in Bogotá to characterize socioeconomic and mobility patterns, and personal exposure data from previous in-situ observational studies carried out in Bogotá. In this study, we compare alternative measures of transport exposure inequality, calculated using the data and methods described in this section.

### 3.1. Mobility data

The dataset used in this study was created using diverse sources. A detailed commuter information dataset was extracted from the Bogotá HTS in 2019. A sample of 20,989 households, with 45,324 persons,

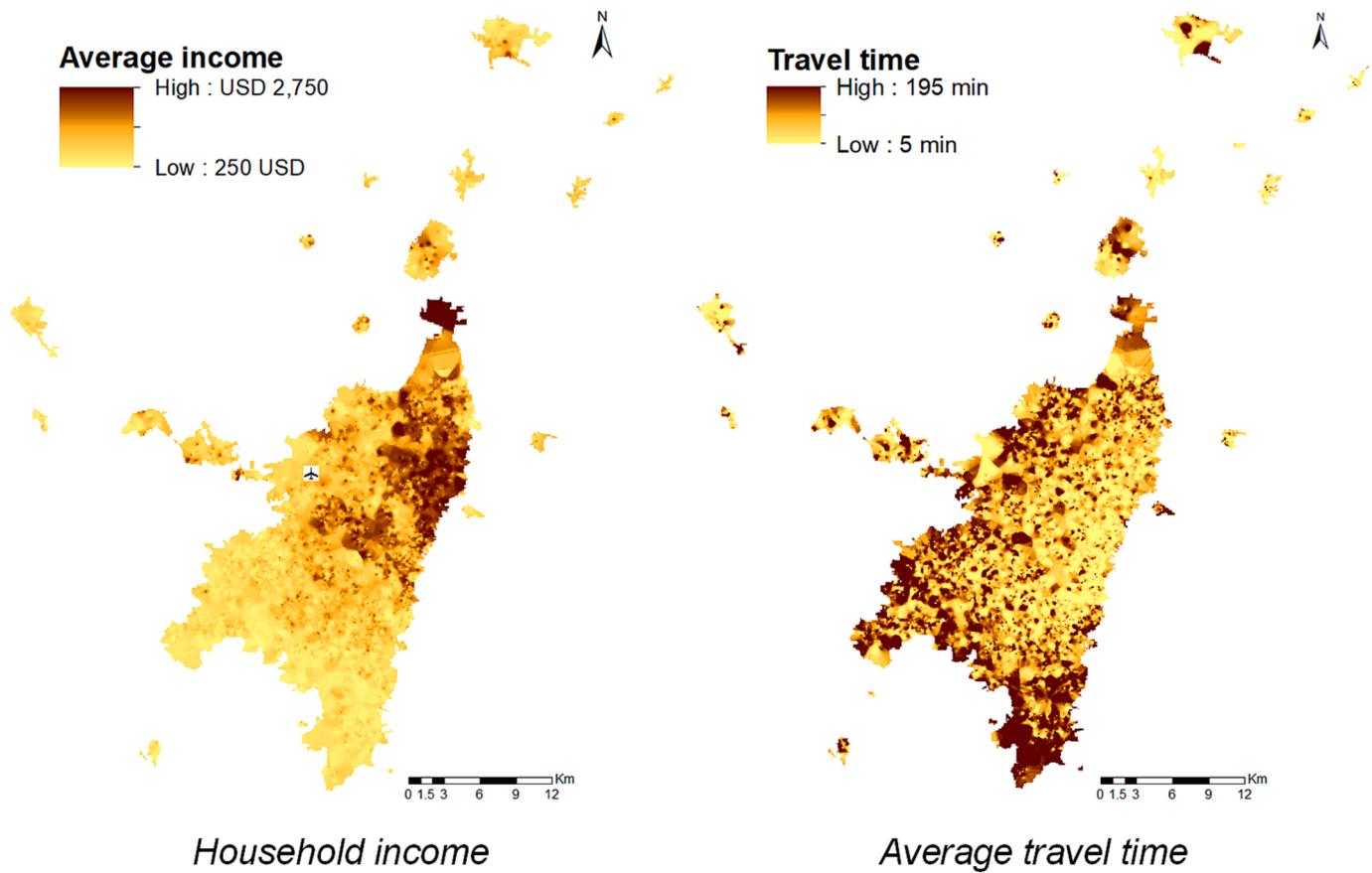


Fig. 1. Average of household income (in USD) and travel time in Bogotá and neighboring municipalities.

included information about the travel patterns and socioeconomic characteristics of respondents. Also, 112,456 trips were gathered from this data. The survey contains cross-sectional travel and socioeconomic data, which includes household, person, and trip identification, location, main transport mode, travel time, and socioeconomic information (income range, educational level, age, and gender). The HTS also includes questions about vehicles and a travel diary for each person. The latter records all trips on a typical day, their duration, and the transport mode used.

According to the sample data, 61.0 % of respondents belong to the low-income group, 25.9 % to medium-income, and 13.1 % to high-income. Walking trips represent 36.4 % of daily trips, public transport 32.1 % (BRT 12.7 % and regular buses 19.4 %), and cars 20.8 %. Each trip is made up of several stages; that is, a traveler may use different transport modes to reach their destination. The HTS prioritizes and assigns a main transport mode per trip. The survey results, therefore, prioritize travel modes, assigning the main transport mode for each trip. This main transport mode is used to estimate potential personal exposure. Table 1 presents the variables used from the HTS sample, with their respective descriptive statistics. These variables were chosen from the

**Table 1**  
Descriptive statistics of the (sample) mobility characteristics of Bogotá and neighboring municipalities.

Variable	N	Mean	Dev. St.	Min	Max
Travel time/traveler	52,069	46.6	41.1	5	240
Trips/person	52,069	2.5	1.09	1	14
Men age	24,971	35.7	20.0	5	99
Women age	27,098	37.6	19.9	5	99
Travel time low-income/trip	17,069	44.4	35.6	5	240
Travel time medium-income/trip	30,670	47.1	39.7	5	240
Travel time high-income/trip	66,209	46.9	43.1	5	240

available data, following the reviewed literature.

### 3.2. Potential inhaled dose of pollutants

The second dataset was obtained from personal exposure and physical activity measurements reported in studies carried out in Bogotá (Morales Betancourt et al., 2017, 2019). Those studies collected in-situ measurements of personal exposure for commuters in different transport modes of three traffic-related air pollutants: PM<sub>2.5</sub>, BC, and CO in different places in the city. The average exposure concentration in each transport mode from those studies is compiled in Table 2. In this study, we used the mean air pollutant concentration per each transport mode as input for the calculation of the potential inhaled dose. The data collected for pedestrians and cyclists spanned diverse types of roads. Including heavy traffic highways, urban canyons, and local roads.

As it is difficult to directly compare the short-term exposure experienced by commuters in different transport modes and across different

**Table 2**  
The concentration of air pollutants in transport microenvironments in Bogotá.

Transport microenvironment	Concentration [ $\mu\text{g}\cdot\text{m}^{-3}$ ]		
	PM <sub>2.5</sub>	BC	CO
Pedestrian	41.1	22.8	1,929.6
Bicycle	39.3	21.2	2,442.1
BRT	164.6	85.5	4,305.8
Bus: Feeder	70.2	28.5	2,671.2
Bus: Regular line	77.5	35.9	4,258.2
Bus: Provisional	77.5	35.9	4,258.2
Informal	77.5	35.9	4,258.2
Motorcycle	43.4	28.5	2,435.6
Car	96.7	41.0	1,605.9

Source: Morales Betancourt et al. (2017) and own elaboration.

places, we estimate the potential inhaled dose of each pollutant for a given commuter according to modal choice and travel times from HTS 2019. We thus constructed a new data set that contained the variable  $D_{ik}$ , which is the potential dose of pollutant  $k$  inhaled during daily travel ( $\mu\text{g}/\text{day}$ ) for a person  $i$ . This variable can be calculated by the following equation:

$$D_{ik} = \sum_{m=1}^m C_{i,k,m} \cdot IR_{i,m} \times t_{i,m} \quad (1)$$

where  $C_{i,k,m}$  in  $\mu\text{g}/\text{m}^3$  is the concentration of pollutant  $k$  in the transport microenvironment  $m$  from reported data (Table 2),  $IR_m$  is the inhalation rate at microenvironment  $m$ , which depends on the age and gender of the traveler, and  $t_{i,m}$  is the time of the exposure (travel time reported) in the corresponding microenvironment  $m$  of a person  $i$  due to daily trips, which can include several transport modes. The microenvironments in our dataset correspond to the transport modes in the HTS dataset, so we now have the potential dose of pollutant  $k$  for each unit of all daily trips. The next step was to tag each individual observation with the latitude and longitude of the origin of that specific trip. This procedure assumes that trips originate at the location of the individual's household. In this case, the duration of exposure equals the travel time from all trips made by a person. The inhalation rate associated with each activity level was selected from the EPA's Exposure Factor Handbook - Table 6.17 (US-EPA, 2011).

Finally, we calculate information on air pollutant concentration for nine specific transport modes (Table 2). Taking into account all the calculations described above, our final database includes 45,324 observations and 15 variables.

### 3.3. Equality exposure measures

To establish how exposure varies across income groups and transport modes, we analyzed the potential level of exposure for travelers in Bogotá according to socioeconomic characteristics. Sustainable Development Goals prioritize and address the health impacts of all types of pollution. As noted, commuting behavior was captured from the 2019 HTS, with routine transport by BRT, bus, motorcycle, car, bicycle, and foot. We used all trip purposes reported in HTS.

By joining the exposure measurements in transport microenvironments and the travel pattern data, we estimate statistically significant mean differences in the potential inhaled dose of  $\text{PM}_{2.5}$ , BC, and CO in people's daily trips through a statistical  $t$ -test to compare the means of two groups. I.e., we use this inferential statistic to study if there is a statistical difference between groups. This methodology is used in hypothesis testing, assuming that the means of the two distributions are equal. If the  $t$ -test accepts the null hypothesis, it indicates that the groups are highly probably equal. The  $t$ -test analysis was used to examine the relationships between the expected potential inhaled dose of pollutants according to the income group and transport mode used. Considering the methodology followed to estimate the potential dose, the differences in the mean inhaled dose per trip and income group are driven by the correlation between income, travel time, and modal choice. This exercise aims to make evident those expected differences in exposure to pollutants, and thus serves as an equality indicator.

In addition to the mean difference analysis, four alternative measures of exposure inequality were therefore calculated using the following methods. First, we wanted to determine whether potential inhaled doses were shared equally by each commuter or group. We calculated a first horizontal inequality measure as the ratio of percentiles to compare the exposure of the low-income to that of the high-income population. We can thus compare the potential dose absorbed at different ends of the distribution between groups, giving an accurate interpretation of the results. We used the 90th percentile ratios in our analysis because exposure between-group ratios varies across the distributions. Second, we used Lorenz curves (Guzman et al., 2017; Lucas et al., 2016) to

compare the distribution of pollution exposure dose across the sampled population. These curves are a graphical representation of equality. The Gini coefficient is an indicator used to determine the overall degree of inequality.

Nevertheless, these results do not allow for comparisons across income groups in their aggregate form; however, and therefore, we propose the Palma ratio (Guzman and Oviedo, 2018; Palma, 2011) as a third measure to consider differences in the average distribution of income across the sample. In this case, we compared the ratio of inhaled doses in the top 10 % of households (richest) to the bottom 40 % (poorest). The larger the ratio, the greater the inequality. As a fourth measure, we propose a vertical equality measure to estimate how disadvantaged the vulnerable groups are (i.e., low-income groups). This could be useful for designing specific policies in their favor to improve their current transport exposure conditions. We thus compare the percentile-wise exposures for the three pollutants by income group. This approach allows us to compare the exposure from each income group by plotting exposure doses against the percentile of travelers across the study area.

Finally, to show the distribution of the potential inhaled dose information, we built maps showing the aggregated daily inhaled doses per household using deterministic methods of spatial interpolation. Inverse Distance Weighting (IDW) spatial interpolation was performed using ArcGIS software 10.7. This methodology calculates values for a pixel using a weighted combination of a set of sample points. We set the pixel size to  $100 \text{ m} \times 100 \text{ m}$ , and household locations represented the sample points, as the total pollutant per household was the figure to interpolate. The weight of each point in the calculation of a cell value is a function of distance and the number of points considered. We used a search radius of 12 neighboring points.

## 4. Results and analysis

The  $t$ -tests performed showed significant statistical differences at 5 % of statistical confidence, in the mean inhaled dose of  $\text{PM}_{2.5}$ , BC, and CO per trip between high-income commuters and medium- and low-income commuters, where the wealthy had lower exposures to the previous pollutants during their commutes, as is shown in Fig. 2. Comparing medium- and low-income commuters,  $t$ -test results showed non-statistical differences in the mean inhaled dose of BC per trip (Fig. 2b). In contrast, compared to low-income commuters, medium-income commuters showed statistical differences in the mean inhaled dose of  $\text{PM}_{2.5}$  and CO per trip of about + 3.2 % and -7.9 %, respectively. Compared with the mean inhaled dose per trip of low-income commuters, high-income commuters inhaled 3.5 % less  $\text{PM}_{2.5}$ , 8.8 % less BC, and 20.8 % less CO.

The previous analysis of the mean inhaled dose of pollutants revealed a negative relationship between the income group and the inhaled dose during a trip. That is, as income increases, the inhaled dose of BC and CO of commuters is, on average, lower in their daily trips. Regarding  $\text{PM}_{2.5}$ , the major differences are between high- and medium-income commuters, where high-income commuters inhaled on average 6.5 % less during a trip.

In addition to the significant differences reported in Fig. 2, we compare the incidence of choosing a particular transport mode with the mean potential dose of a given pollutant. Therefore, analyzing the mean inhaled dose of pollutants per trip and transport mode shown in Table 3, Fig. 3 shows that commuters inhale, on average, more of the three pollutants when traveling by BRT. Conversely, commuters are less exposed to  $\text{PM}_{2.5}$  and BC when traveling by motorcycle or by active modes (pedestrian or cycling), and to less CO when traveling by car. Aside from feeder and informal transport, commuters that use public transport are exposed, on average, to higher concentrations of pollutants. These results are consistent with expectations based on travel times when commuting using these transport modes.

Fig. 4 shows the low/high-income group exposure ratios, which vary

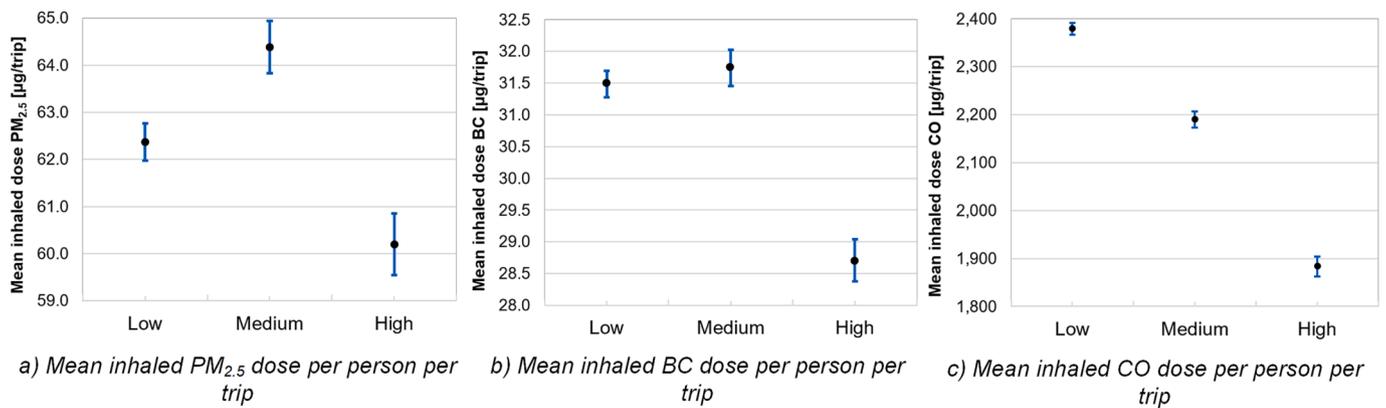


Fig. 2. Mean inhaled dose of pollutants per trip and income group (with confidence intervals).

Table 3  
Mean inhaled dose of pollutants per trip and transport mode [µg/trip].

Mode	PM <sub>2.5</sub>		BC		CO	
	Mean	Std. err.	Mean	Std. err.	Mean	Std. err.
BRT	183.7	0.69	95.4	0.36	4,805	17.93
Regular bus	75.3	0.41	34.9	0.19	4,141	22.72
Provisional bus	60.2	0.33	27.9	0.15	3,309	18.15
Car	56.8	0.31	24.1	0.13	943	5.08
Informal	48.9	0.58	22.6	0.27	2,687	31.97
Feeder bus	46.2	0.76	18.8	0.31	1,759	28.90
Motorcycle	25.4	0.25	16.7	0.16	1,424	13.92
Active	24.0	0.11	13.2	0.06	1,207	5.87

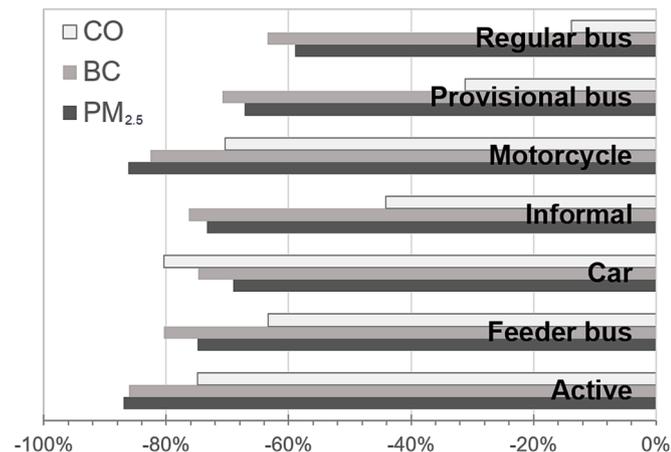


Fig. 3. Relative difference of inhaled dose [µg/trip] in transport microenvironments by transport mode (BRT as the base).

across the distributions, as a first horizontal equality measure, to better understand the personal exposure would have on the potential pollutant inhaled doses.

Fig. 4 shows the difference in the potential dose between low- and high-income groups at every point of the travelers' distribution. In an evenly distributed scenario, this ratio should be approximately equal to 1 at each point in the distribution. This would indicate relative equality in air pollution exposure while commuting. The graph, however, shows peaks at the right upper end of the distribution. The low/high-income ratio rises with the exposure percentiles. At the lower end of the distribution, the low-income group faces less exposure than the wealthiest because most of their trips involve walking, a bicycle, or a motorcycle (60 %), resulting in lower levels of exposure in transport. At the upper end, however, the exposure of the low-income population is roughly 2 % to 100 % higher than for the high-income. This is mainly due to long

trips on public transport.

Because the distribution of potential inhaled doses of air pollutants during daily travel is skewed to the urban periphery (see Fig. 7) where the low-income population usually resides, inequality at the upper end of the distribution is of particular interest (the top decile accounts around 27 % of the total pollution load). The ratio is above 1.0, particularly in the 90th percentile and beyond. This measure of inequality confirms that there is a high inequality of dose inhaled across income groups. Comparisons at the 90th percentiles yield a low/high-income exposure ratio of 1.02, 1.08, and 1.24 for PM<sub>2.5</sub>, BC, and CO, respectively (Fig. 4). Two transport modes (active and motorcycle) have low/high-income p90 ratios below 1.0, and public transport has p90 ratios above 2.0.

We then apply a Gini index to air pollution exposure using concentration curves per pollutant, as shown in Fig. 5a. These curves plot the cumulative percentage of total pollutants inhaled (y-axis) against the cumulative percentage of the population. If every person, irrespective of their income group, has the same value of potential inhaled doses, the concentration curve will be a 45-degree line (grey line). We use these curves to report Gini coefficients for income calculated and traveler-level data.

The results show degrees of exposure inequality in transport. The Gini index is between 0.44 and 0.46, depending on the inhaled pollutant dose. This exposure calculation accounts for travel times and transport modes. For instance, about 20 % of the population, regardless of their income group, is exposed to high pollutants during their daily trips (44 % of total pollution). This suggests horizontal equity, as higher exposure levels are inhaled by a large proportion of the population. This highlights another equality gap in transport justice in Bogotá. The situation is similar as regards accessibility to work and study opportunities in the study area (Guzman et al., 2017) and street space distribution (Guzman et al., 2021). We can also safely confirm, based on this evidence, that exposure to pollutants in transport microenvironments is more unequally distributed than accessibility, and slightly better distributed than income (0.504). A significant share of the population in Bogotá is thus more exposed to air pollution in the transport system, has lower accessibility to work and study, and is also poor or very poor.

PM<sub>2.5</sub> and BC have a similar Gini index and relatively equal low/high-income 90th ratios, while CO has a lower Gini but a higher ratio in low/high-income 90th percentile ratios. This contrast implies that multiple metrics of air pollution exposure inequality are necessary to capture its different dimensions according to socioeconomic characteristics, travel times, and modal choice. Several studies have defined a metric for potential PM<sub>2.5</sub> dose (e.g., de Nazelle et al. (2012) and Morales Betancourt et al. (2019) by computing the 24-hour dose that a person exposed to amounts matching the WHO guidelines (i.e., 25 µg/m<sup>3</sup>) would inhale. This value is estimated to be 226 µg/day. Fig. 5b shows that around 70 % of commuters in the city experience a dose

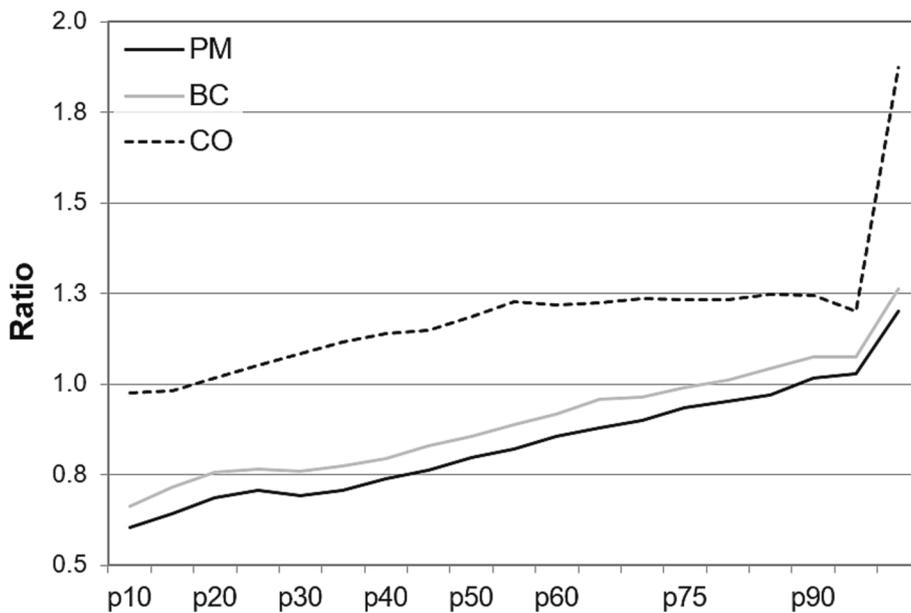


Fig. 4. Percentiles of inequality ratios by the inhaled dose of pollutants in transport environments.

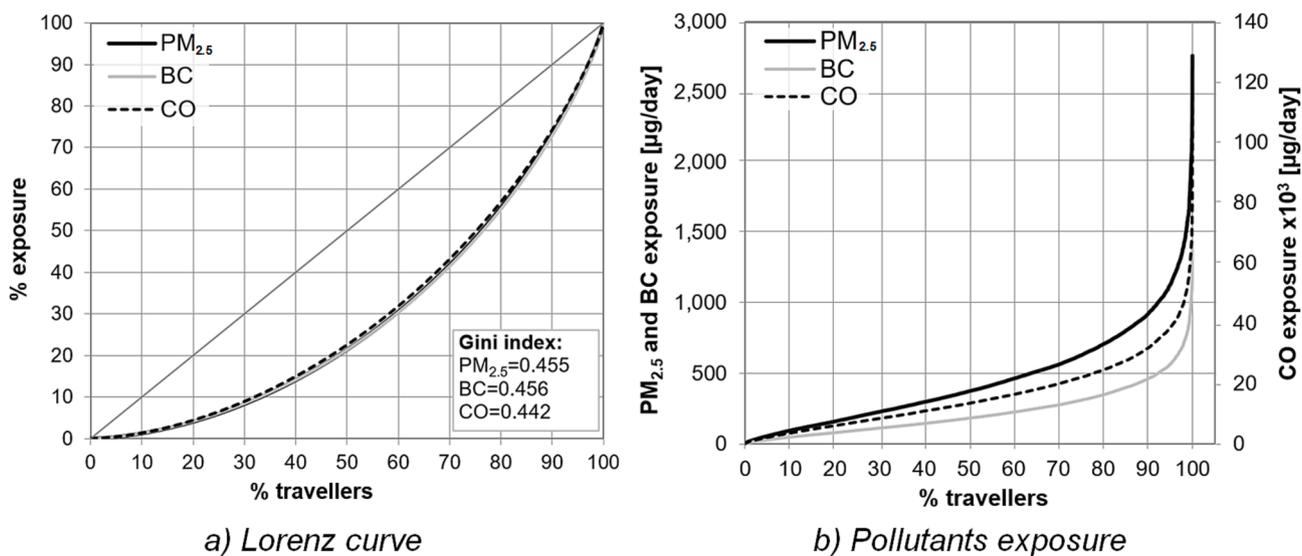


Fig. 5. Inhaled doses of pollutants in transport microenvironments [ $\mu\text{g}/\text{day}$ ] concentration curve.

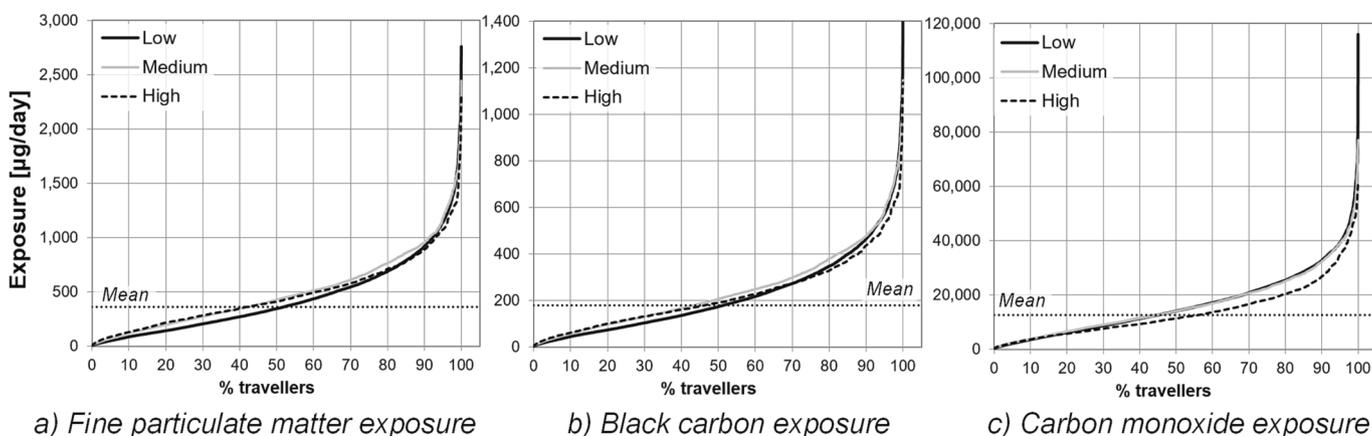


Fig. 6. Income groups inhaled dose [ $\mu\text{g}/\text{day}$ ] by pollutant and percentile.

larger than this in their daily commute alone.

Turning to vertical inequality, the goal of this analysis is to identify differences in exposure doses in each income group. This will allow us to identify disadvantaged groups, seeking to support the development of actions that better accommodate their needs, such as improving the technology of the public transport fleet. Fig. 6 shows the vertical equality results, where exposure doses are included on the vertical axis, and the percentiles of the travelers on the horizontal axis, thus comparing the three income groups by pollutant. At the start, there are no differences between income groups.

In all cases, the Gini index is higher in the low-income group, indicating higher vertical inequality between the poor populations. The results also indicate greater exposure differences at the upper range of the distribution, beyond the 50th percentile, where all income groups are exposed to much higher doses than the average for the study area. The low-income group is slightly less exposed to  $PM_{2.5}$  and BC, because, as we saw, many of their trips are made by motorcycle or walking and cycling. The wealthy population is also exposed to lower doses of CO also due to their transport preferences.

As a fourth equality measure, we calculated the total potential inhaled doses for people from income ranges 1 to 3 (deciles 0 to 4) and 7 to 9 (deciles 9 to 10) (bottom 40 % and top 10 %, respectively), in line with previous studies applying a similar overall logic to that of the Palma ratio (PR) to income. We then calculate the ratio for each pollutant dose. The general results show that people belonging to the top 10 % in the study area inhaled a similar dose of  $PM_{2.5}$  as the bottom 40 % (PR = 0.98) on average, for every minute they travel. The gap increases to 1.05 and 1.28, respectively for BC and CO. Note that the low-income group is almost five times larger than the wealthy group. Considering the total potential dose inhaled by the whole study population, we find that the high-income group would inhale 4.3 times less  $PM_{2.5}$ , 4.6 times less BC, and 5.4 times less CO than the bottom 40 %. This shows the potential negative effects of modal choice and travel times for the most socially vulnerable populations as regards equality. A transport policy, such as bus fleet renewal, should target the bottom tier of the income pyramid in the city, decreasing levels of inhaled doses for the poorest in the study area.

Finally, Fig. 7 shows a proxy of the total amount of pollutants inhaled at the household level (from travelers belonging to the same home). The maps show the potential inhaled dose by pollutant per each sampled household (of the people who traveled) according to its location. Individual trips were aggregated and linked to the corresponding household

location of the traveler. Sampled households were distributed evenly over the study area, allowing us to perform an IDW spatial interpolation to better visualize the zones where households report high or low pollutant inhalation. Darker zones represent higher pollutant inhalation doses and are mainly located in the south and northwest of Bogotá. In these areas, on average, inhaled doses are up to three times higher than the average dose in the study area. It is important to note that low-SES households are also located in those zones. This demonstrates that economically vulnerable populations are also reporting high exposure to pollutants.

Our results further suggest ways in which transport planning and policy decisions could efficiently reduce the potential inhaled dose of pollutants. For instance, a reduction in exposure in the public transport system, given its high exposure concentration, long travel times, and share of trips, could imply a reduction in exposure for commuters. To further test this hypothesis, we performed a simple sensitivity analysis in which a reduction in average dose is calculated according to a given percentage reduction in exposure concentration in the BRT and buses. The results imply that each 10 % reduction in BRT and regular-line bus exposure translates into a 5 % reduction in the potential inhaled dose per commuter, which is equivalent to approximately 8  $\mu\text{g}/\text{day}$  less per person. This suggests that a fleet renewal will have important effects in reducing the inhaled dose for the millions of users of the system. This reduction could also affect positively reduces the inequalities between income groups.

## 5. Discussion and sustainability implications

This work suggests that the distribution of potential inhaled doses per trip is mainly controlled by travel time (the longer the trip, the higher the potential inhaled dose). The results suggest that travel time can account for substantial differences in  $PM_{2.5}$  and BC across income groups. The average motorized travel time is 81 min for the low-income population, 69 min for medium-income, and 58 min for the high-income group. The strong association between travel times and income group means that, on average, the lower-income population is exposed to more air pollutants during travel activities and that travel time alone controls up to two-thirds of the inhaled dose. The inhaled dose of CO is explained mostly by the choice of transport mode. This means that prolonged air pollution exposure during a commute further exacerbates other inequalities related to accessibility in Bogotá. The evidence presented in this work should be interpreted within decision-making channels in the

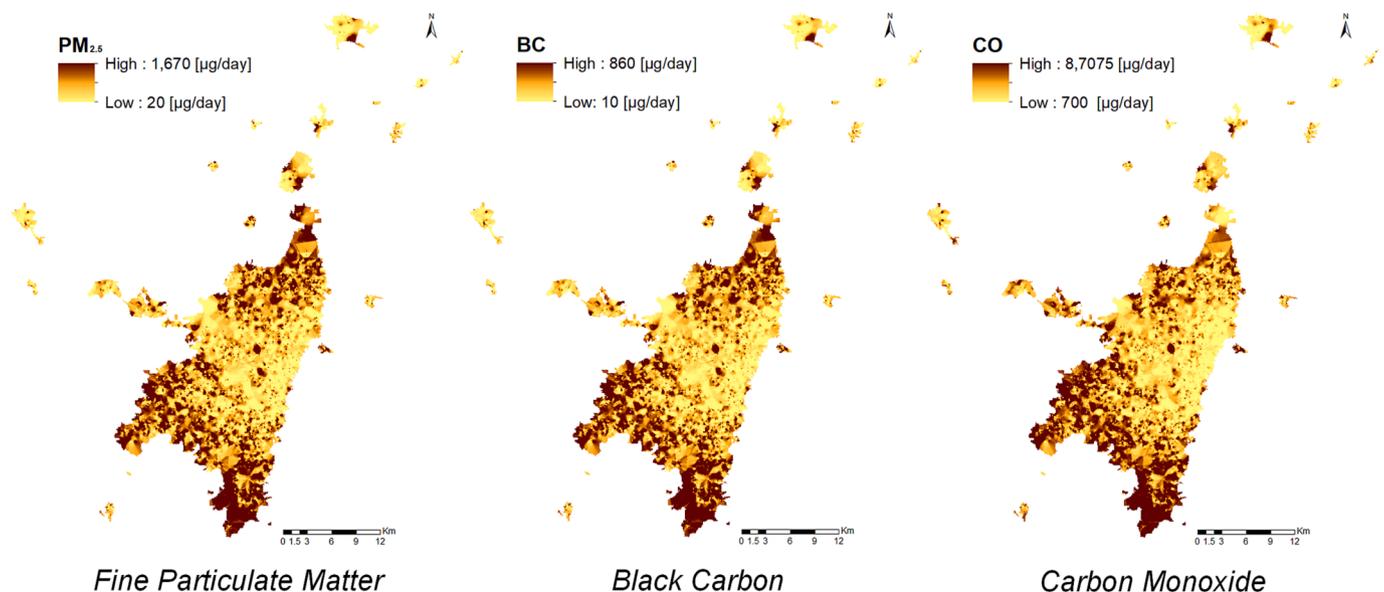


Fig. 7. Spatial distribution of inhaled doses of pollutant [ $\mu\text{g}/\text{day}$ ] during daily trips.

transport sector, highlighting the policy action necessary in the transport agenda to close gaps in a context such as Bogotá. Transport development policies have historically given priority to infrastructure, and not often to clean vehicles in public transport.

Having a clean transport fleet is crucial because the specific transport mode was also found to be a significant factor in determining the level of exposure, with commuters whose main transport mode is the BRT experiencing significantly higher air pollution exposure than users of other modes. In mid-2019, a process of renewal of the BRT fleet started, in which the oldest portion of the bus fleet, 1,152 buses with Euro II and III standards, were replaced by 741 natural gas-powered vehicles and 700 DPF-equipped diesel buses. The technological upgrade of such a large proportion of the complete BRT fleet is expected to significantly reduce emissions of air pollutants. A recent study demonstrated that personal exposure to PM<sub>2.5</sub> and BC decreased by nearly 50 % due to the BRT fleet renewal (Morales Betancourt et al., 2022). The fleet of regular-line buses is currently undergoing a rapid transformation, where the oldest buses are gradually being replaced by lower and even zero-emission technologies. Given the relevance of transport mode choice in driving exposure and exacerbating inequality, these ongoing transformations in public transport are likely to decrease both, exposure and inequality exposure for commuters in Bogotá.

The concept of environmental justice in sustainable transport encompasses a concern for reducing the systematic discrimination and marginalization related to potential health impacts. This research addressed traditional and applied metrics involving a non-income outcome variable such as personal exposure in urban transport, to estimate the contribution of travel time, modal choice, and socioeconomic factors to the reduction of systemic inequalities between different social groups and transport modes. The analysis using several metrics allowed us to visualize and examine the distribution of personal exposure according to location, gender, age, and income, which in Latin American cities tend to be correlated. These results allow the identification of barriers to creating just and inclusive societies and analyze the distribution of inequalities in a transport system at the city level beyond arithmetical imbalances. Such imbalances are a reflection, sometimes unintended, of the levels of marginalization experienced by some groups who become disproportionately worse off than others concerning elements of social disadvantage such as income, age, or gender.

## 6. Conclusions

This study revealed the main factors controlling exposure and inequality to air pollutants during daily travel activities in Bogotá. The analysis shows that, at the time of the analysis, 70 % of travelers in the city experienced a potential dose of inhaled PM<sub>2.5</sub> higher than 226 µg/day during their commute. This is the dose a person would experience if exposed for 24 h to the dose in the WHO PM<sub>2.5</sub> concentration guidelines. Similarly, when the analysis is performed for BC, our results suggest that 38 % of commuters experience a potential BC dose larger than the 226 µg/day threshold. Since then, significant modernization of the public transport fleet has taken place, both for the BRT component and the regular-line buses, with high penetration of low- and zero-emission technologies.

We applied inequality metrics to analyze the population share experiencing high doses of air pollutants during the commute. Inequality metrics applied to air pollution exposure may inform decision-makers on how to allocate resources more effectively to reduce exposure. We show that implementing low- or zero-emission public transport vehicles may have significant potential to redress structural environmental inequalities by reducing their exposure to air pollutants. This work shows that combining in-situ personal exposure measurements in transport microenvironments with inequality measures is a valuable approach for starting discussions between different stakeholders and enables a holistic understanding of sustainable transport.

This paper demonstrates that household location, vehicle fleet

technology, modal choice, and travel patterns must all be considered when planning public investments in urban transport to improve citizen welfare. Our research highlights some of the social and environmental constraints faced by different population segments when considering the benefits of a clean transport system. Personal exposure in transport microenvironments and its implications for equality are issues that need addressing in cities where active and public transport use is crucial for sustainable development.

Finally, the limitations of the dataset involving spatial representativeness and socioeconomic information mean that the survey sample was analyzed without considering expansion factors. Another key limitation of the in-situ measurements of air pollution exposure is the assumption of the main transport mode since every trip is composed of several stages. Exposure may thus be overestimated, particularly in public transport, where access and egress times may make up a proportion of total travel time. Unfortunately, there is no available data regarding travel times by trip stage. Also, the study did not consider the temporal variation of air pollution concentration, which can vary greatly at different time scales. Further research is needed in the area of sustainable transport policies and the implications of personal exposure on health, to better-inform urban transport policy outcomes.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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