Transportation Research Part D 98 (2021) 102952

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Impact of public transport strikes on traffic and pollution in the city of Barcelona

Lyna González [a], Jordi Perdiguero [b], Àlex Sanz [c,*]

[a] *Universitat Autònoma de Barcelona, Spain*
[b] *Department of Applied Economics, Universitat Autònoma de Barcelona, Campus de la UAB, Edifici B, 08193, Bellaterra. Grup de Recerca en Economia Aplicada (GEAP), and Institut d'Economia de Barcelona (IEB), Spain*
[c] *Universitat Autònoma de Barcelona and Barcelona GSE Post-Doc, Departament d'Economia i d'Història Econòmica, Unitat de Fonaments de l'Anàlisi Econòmica, Spain*

ARTICLE INFO

JEL Codes:
C33 Q53 Q56 Q58

Keywords:
Air pollution
Public transport strike
Public transport use
Public Transport Substitution

ABSTRACT

Many Spanish cities' air contains excessive levels of pollutants caused by traffic. These pollutants are associated with high concentrations of vehicles in urban and surrounding areas, such as Madrid and Barcelona. According to the World Health Organization (WHO), 96.8% of Spain's population breathe polluted air. This paper provides empirical evidence on the effect of public transport strikes on Barcelona's air quality through an econometric analysis. The period analyzed included 147 days of some kind of public transport strike: bus (57), metro (21), trains (71), and tram (4); and also four general strikes. The estimates show that public transport strikes increases the concentration level of SO2, CO, PM_{10}, and NOX throughout the city, especially in the case of metro and RENFE trains. These results also allow us to understand how commuters substitute transport modes and to propose specific policies to increase public transport use.

1. Introduction

According to recent World Health Organization (WHO) reports, air pollution caused an estimated seven million deaths globally in 2016; (WHO, 2016, 2018). In economic terms, the cost of air pollution exceeds 3.7 billion euros per year (Álvarez, et al., 2019); whereas in Spain it represents between 1.7% and 4.7% of the country's Gross Domestic Product (GDP) (Ceballos, et al., 2018). Unsurprisingly, in July 2019 the European Commission announced its decision to refer Spain to the European Court of Justice (CJEU) for exceeding legal air pollutant emission limits – NO_x in particular, in the urban areas of Madrid and Barcelona (European Commission, 2019).

In this regard, some studies have found that urban areas have higher concentrations of chemical pollutants in the air than rural areas, due to the large number of vehicles, reduced road capacity, and poor investment in public transportation (da Silva, et al., 2012; Rahman, et al., 2019). In European cities, about 70% of environmental pollution is caused by motorized transport (Rojas-Rueda, et al., 2012).

In order to address this issue, some large cities have introduced policies to reduce traffic-related pollution by encouraging the use of public transport. One specific problem is that during public transport strikes, services are canceled, or periodicity is reduced and,

* Corresponding autor at: Universitat Autònoma de Barcelona and Barcelona GSE Post-Doc., Departament d'Economia i d'Història Econòmica, Unitat de Fonaments de l'Anàlisi Econòmica, Spain.

E-mail address: Jordi.perdiguero@uab.cat (J. Perdiguero).

https://doi.org/10.1016/j.trd.2021.102952

Available online 16 July 2021

consequently, traffic congestion and air pollution levels grow (Tsapakis, et al., 2012). This means that public transport strikes are a valuable scenario in which to analyze the influence of traffic emissions on urban air quality (Meinardi, et al., 2008). The increase in private traffic flows, congestion, and delays caused by public transport strikes have been confirmed by many studies.

In Los Angeles average road delays increase by 47% when transit services cease due to strike action (Anderson, 2014); while in Rotterdam travel time, traffic, and bicycle use all increase during public transit strikes (Adler and van Ommeren, 2016). Strikes in some German cities have caused the total number of 'car hours' to increase by 11–13% (Bauernschuster, et al., 2017). Taking into account the impact of public transport strikes on air quality, Chaloulakou et al. (2005) identified a fall of approximately 40% in Black Smoke (BM) when taxis and buses went on strike in Athens. Further, in the case of Milan, Meinardi et al. (2008) found that ozone concentrations increased by 11–33% during a public transport strike; in Sao Paulo, da Silva et al. (2012) found that PM_{10} pollution increased during a strike day. In the five largest cities of Germany, transit strikes had a significant impact on air pollution: specifically, PM_{10} emissions increased by 14% and NO_2 concentrations increased by 4% (Bauernschuster, et al., 2017). In the case of Barcelona, during public transportation strikes, Basagaña et al. (2018) found that, in daily means, concentrations of BC, NO, NO_2 and PM_{10} increased by 4%−8%.

These empirical findings tested the hypothesis that public transport strikes increase road-traffic related air pollution. The main aim of this research is to better understand this hypothesis. The focus is on Barcelona, which is considered to be one of the most polluted cities in Europe, and whose main source of atmospheric pollution is motor-vehicle traffic (L'Agència de Salut Pública, 2017).

In general terms, our results coincide with those obtained by Basagaña et al (2018), since they show a greater impact of metro and train strikes. Unlike the results obtained by Basagaña et al. (2018), our results, however, highlight the impact of a greater number of contaminants. The novel element in our work is the analysis of air quality data, for all the air quality stations in the city, monitored hourly through an econometric regression model adjusted by control variables, which may affect pollution levels. Instead of analyzing the impact of strikes on average daily pollution levels, the use of hourly data, including the specific hours when strikes happened, together with the control of meteorological variables, might explain the greater precision in our estimates.

This is the first study to include an analysis of the effect of general strikes on air pollution in Barcelona. Additionally, once the impact of public transportation strikes on pollution is analyzed, we use these results to try to understand how commuters choose between different transportation modes when they cannot choose their preferred mode due to a strike. This analysis could help us to better understand how commuters choose their preferred mode of transport and what their direct substitutes are.

This information may help policymakers improve their decisions related to public transport policies. It's important to closely understand how commuters switch between different transport modes to implement efficient air pollution policies. It's important to remark that with our data, however, we can only infer how commuters substitute between modes; future research should empirically analyze this substitution in order to confirm our results.

The research is structured as follows: Section 2 describes key information about the variables that comprise the panel data used in this case study. Section 3 presents the methodology used; while Section 4 summarizes the results. Section 5 discusses the main findings of the assessment and its policy implications, and Section 6 concludes.

2. Data

The second most populated urban area in Spain is Barcelona. Its metropolitan zone comprises 36 municipalities with 3,247,281 inhabitants, of which 1,620,809 live in Barcelona city. There is a population density of 16,000 inhabitants/km^2 in a space of 101.35 km^2. The dominant mode of transportation is public, which represents 39.8% of daily trips, followed closely by walking, with 32.4%. In third place is the private vehicle, which is used by 25.6%, and lastly, bicycles, which are employed by 2.2% (Àrea d'Ecologia, Urbanisme i Mobilitat, 2018).

The city's collective public transport network predominantly comprises a metro system, a bus network, two different regional railway systems (operated by Ferrocarrils de la Generalitat de Catalunya (FGC), and by Rodalies RENFE[1]) and tram (Table 1).

The data used in the analysis, which provides information on a number of variables from various sources, is a panel data. These sources include the Catalonian government's official newspaper (Diari Oficial de la Generalitat de Catalunya, DOGC), the Spanish government's Home Office, the Catalonian government's Air Quality Monitoring webpage, the Catalonia government's meteorological service, Meteocat and, the newspaper "La Vanguardia". Information about public transport strikes was obtained from the Catalonian government's official newspaper, which publishes governmental decrees and resolutions determining the minimum services to be provided in the event of a strike. Data were collected through the 'advanced search' function on the DOGC website with the thematic descriptor "garanteix el servei essencial de transport"[2] for the period from January 2008 to December 2016.[3] To ensure that strikes were accurately identified, we used a verification procedure in the information-gathering process. Therefore, we only included strikes that, in addition to appearing in the DOGC, were also announced, and confirmed, in the newspaper "La Vanguardia" (https://www.lavanguardia.co/hemeroteca). This validation was necessary because although strikes were often published in the DOGC, in the end, many of these were canceled or postponed by trade unions. By combining the DOGC and newspaper data we obtained high quality

[1] Historically, FGC was managed by the regional Government and Rodalies RENFE was managed by the national government. Since 2010 both have been managed by the regional government, but the infrastructure of FGC is the property of the regional government and the infrastructure of Rodalies RENFE is the property of the national government.

[2] Guarantees the essential transport service.

[3] http://dogc.gencat.cat/ca/pdogc_canals_interns/pdogc_cercador_de_normativa/?destParam=cercaAdv

Table 1
Characteristics of Collective Public Transport in Barcelona.

System of public transport	Trips in millions/2017	Contribution (%)
Metro	390.4	39.6
Bus	369	37.5
Train RENFE	113.4	11.5
Train FGC	84.3	8.5
Tram	28	2.9

Source: Own elaboration, from Àrea d'Ecologia, Urbanisme i Mobilitat, 2018

information for our study, that is, the mode of transport affected (bus, metro, train RENFE, train FGC or tram), the time and date of the strike, and the minimal services provided. In addition to the public transport strikes, we also included the general strikes that affected Barcelona city in the same period of study. This data was collected from the Spanish government's Home Office. Table 2 lists the number of days and hours affected, by strike type. In our database, there were 147 days impacted by some type of public transport strike; against four general strikes. The bus and train systems (RENFE and FGC) recorded the highest number of days with a strike, 57 and 71 (51 from RENFE and 20 from FGC), respectively. This was followed by the metro, with 21 days, and the tram, with four days. Note that strikes on different transportation networks overlapped on only sixteen days. During the study period, the year most affected by strikes in Barcelona was 2012, followed by 2013 and 2016.

Regarding the hourly distribution of the public transport strikes, we can see in graph 1 that the strikes are concentrated in the hours of greatest mobility, from 8 to 10 in the morning, and at night. We can also see how there are no strikes in the early morning hours where the demand for mobility is very low.

The public transport system in Spain is considered an essential service for the community, who have a right to free circulation (Article 19 of the Constitution); therefore interruptions to public transport services must be regulated by a government entity, which guarantees a minimum service that generally covers between 20% and 65% of the usual service.(See Fig. 1)

Air pollution data were collected from the Catalonian government's Air Quality Monitoring webpage. We gathered hourly average data for five types of pollutants (CO, SO_2, O_3, PM_{10}, and NO_x) from 14 air quality stations located in the Barcelona metropolitan area. Additionally, weather condition data was collected from the Catalonia government's meteorological service, Meteocat. We also gathered hourly mean data about the main weather conditions that can affect air pollution; that is, atmospheric pressure, rain, relative humidity, temperature, and wind direction and force. Fig. 2 shows the location of the meteorological (in green) and air quality stations (in yellow). The whole city of Barcelona, and adjacent municipalities, are covered by these stations.(See Fig. 3)

The current WHO guideline value of 40 $\mu g/m^3$ (annual mean) was established at NO_2, 20 $\mu g/m^3$ (24-hour mean) to SO_2, 20 $\mu g/m^3$ (annual mean) to PM_{10}, and 100 $\mu g/m^3$ (an eight-hour daily average) to O_3 (WHO, 2005). The city-wide average level is shown in Table 3. When these guide values were compared with this work data, it was found that particulate matter (28.818 $\mu g/m^3$) and nitrogen dioxide (41.126 $\mu g/m^3$) exceeded the limits; as mentioned above, the latter causing the European Commission to refer Spain to the EU's Court of Justice over poor air quality (European Commission, 2019).

Obviously the levels of pollution vary over the days of the week, and the hours of the day. As can be seen in graph 3, pollution levels are significantly lower during the weekend, and relatively stable during the five working days.

Likewise, it can be seen how pollution levels increase in the hours of greatest mobility (between 8 and 10 in the morning, and at night). Specifically these are the periods of the day when there are the greatest number of strike hours on public transport. The exception is SO_2, which, as can be seen in Fig. 4, has its pollution peak at 11 in the morning.

Table 4 below presents information on levels of transit contamination and background air quality stations, differentiated by strike and non-strike periods. As can be seen, the transit stations present higher levels of contamination than the background stations, both for strikes and non-strikes, with the exception of O3, which always shows an inverse relationship. We can also see how the difference between strike and non-strike days is greater in the case of transit stations than those of the background. It therefore seems that the strikes generated an increase in pollution, especially in transit stations. This evidence is common for all pollutants with the exception of PM_{10}, which does not show a clear relationship between the increase in pollution on strike days and the type of air quality station.

Average data from Barcelona's meteorological stations are summarized in Table 5:

3. Empirical analysis

Our econometric regression model aims to isolate the effect of strikes once controlling for the other factors that can affect pollution levels. Therefore, the model assumes that once controlling for other factors that influence the city's pollution levels, any difference between the strike periods and those not affected by it are due to the strike. This approach is similar to that used by Bel and Rosell (2013), Gong (2017), Basagaña et al (2018), Perdiguero and Sanz (2020) and Rivers et al (2020), to measure the impact of different events on air quality levels. Both the articles by Bel and Rosell (2013) and Gongs (2017) analyze the impact on pollution levels of reducing cars' speed to 80 km/h in specific areas of the Barcelona Metropolitan Area. Both studies use a differences-in-differences estimator where they control for the same control variables as in our study. In fact, the papers by Basagaña et al (2018) and Rivers et al (2020) analyze the effect of public transport strikes on the levels of pollution in the Metropolitan Area of Barcelona and in 18 cities in Canada respectively, using a methodology very similar to that presented in this study. Both studies measure the impact of strikes econometrically through a dummy variable and seek to control for the remaining factors that can affect pollution levels, and which are

Table 2
Description of Strikes (2008–2016).

Duration	Strikes						
	General	All PTS*	Bus	Metro	Train RENFE	Train FGC	Tram
Day	4	147	57	21	51	20	4
Hour	96		449	184	597	191	76
2008	0	14	14	0	0	0	0
2009	0	6	2	0	0	0	4
2010	1	17	0	0	8	9	0
2011	1	10	0	0	3	7	0
2012	2	30	19	6	4	1	0
2013	0	26	9	0	17	0	0
2014	0	9	3	0	3	3	0
2015	0	12	1	0	11	0	0
2016	0	29	9	15	5	0	0

Source: Own elaboration.
* All PTS: All Public Transport Strikes.

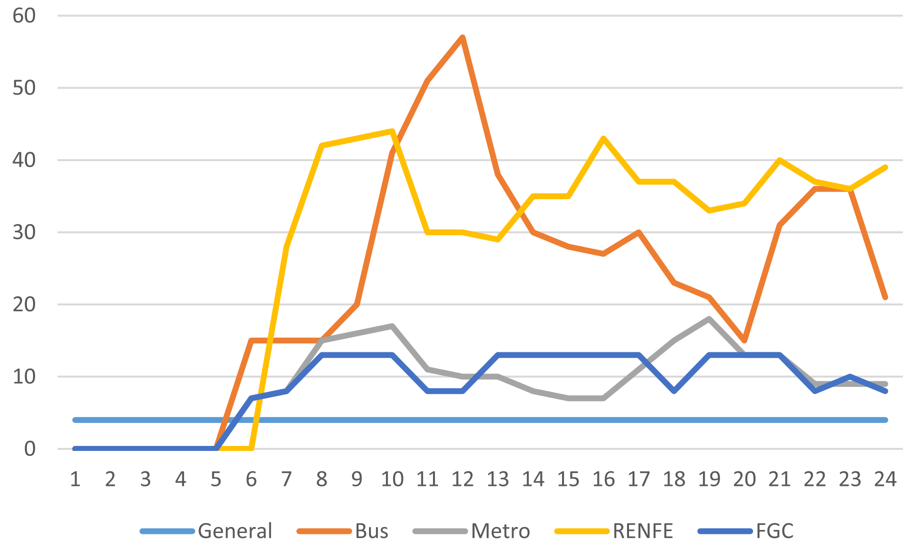

Fig. 1. Distribution of strikes by hours of the day. Source: Own elaboration.

very similar to those used in this study. In fact, exactly the same methodology was used by Perdiguero and Sanz (2020) to evaluate the impact of cruise activity on pollution levels in the city of Barcelona.

To assess the impact of a public transport strike on pollution, we apply this simplified model:

$$Y_{it} = \beta_0 + \beta_i Strike_t + \beta_r X_{it} + \beta_j \mu_i + \varepsilon_{it}$$

As a dependent variable (Y_{it}) we use the hourly mean of each pollutant analyzed (CO, NO_x, O_3, PM_{10}, and SO_2), in the air quality station i, at hour t, which are explained by the following endogenous variables. It is important to note that not all stations measure each of these pollutants, so the number of observations for each pollutant varies depending on the number of air quality stations measuring it. Also, due to measurement problems, we have found missing values for a few hours in each of the air quality stations.

'Strike' is the main variable of interest. It is a dummy variable taking 1 as a value when there is a strike during the hour 't', and zero in other cases. The strike variable refers to the different types of strike analyzed: a general strike, or all public transport strikes (All PTS) on bus, metro, or train (train RENFE, and train FGC). There is a separate variable for each kind of transport mode, except the tram. In fact, trams only experienced four strikes across all periods: specifically, two consecutive days on two different weeks in two different years. We do not believe that these low numbers of strikes, compressed in time, are sufficient to identify the effect of these strikes on air pollution. Besides, the results for the other transportation modes do not vary if we include these strikes.[4] Finally, we considered a particular general strike (27th January 2011) as a bus strike, because this strike was only successful in the bus transport sector, where the service was reduced by 25%.

[4] Results from the 'tram' model are available on request from the authors.

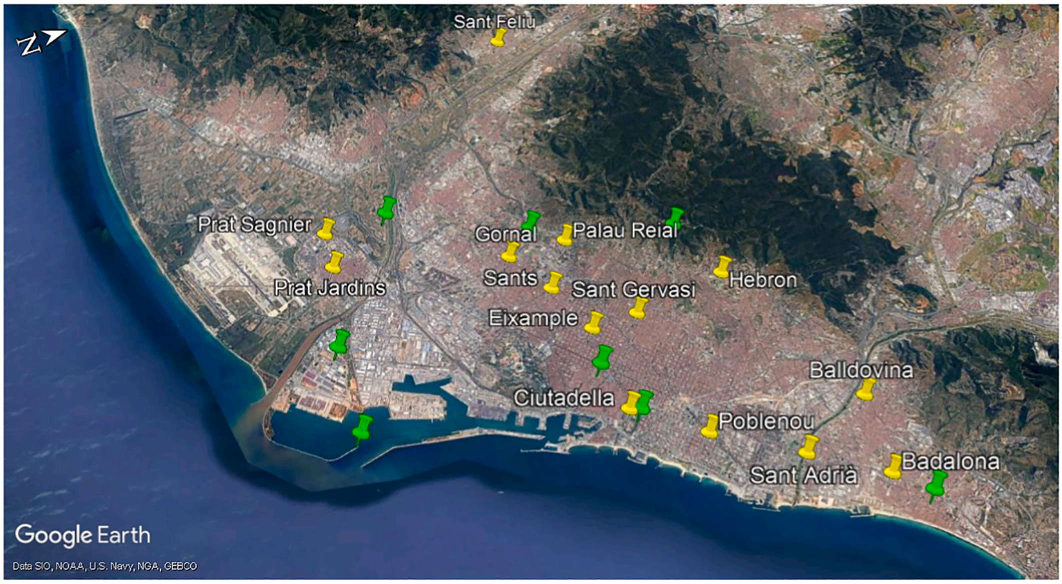

Fig. 2. Meteorological and air quality stations located in Barcelona, and adjacent municipalities. Source: Own elaboration.

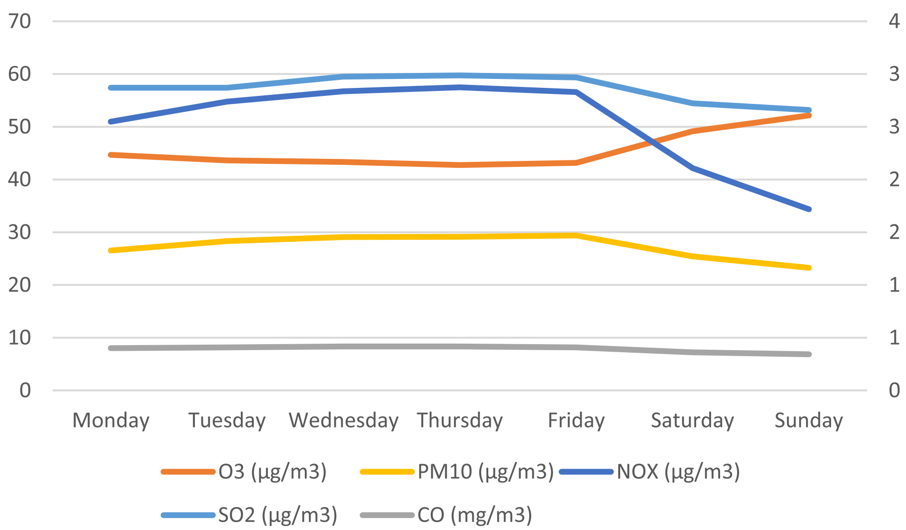

Fig. 3. Distribution of pollution by day of the week. Source: Own elaboration.

Table 3
Descriptive statistics for the pollutants in our sample.

Pollutant (unit of measure)	Mean	Std. Dev.	Minimum	Maximum
SO_2 (μg/m^3)	2.734	2.885	1	232
O_3(μg/m^3)	43.436	30.831	0	207
CO (mg/m^3)	0.429	0.297	0.1	7.1
PM_{10} (μg/m^3)	28.818	20.389	0	1484
NO (μg/m^3)	18.296	33.380	0	810
NO_2 (μg/m^3)	41.126	25.939	0	269

Source: Own elaboration.

As we expect that strikes increase the use of private cars, our hypothesis is that the coefficient of this variable would be positive, meaning that a strike on any mode of public transportation generates an increase of pollution during the hour t.

In addition to the dummy variables that collect public transport strikes, a set of control variables are included. These independent

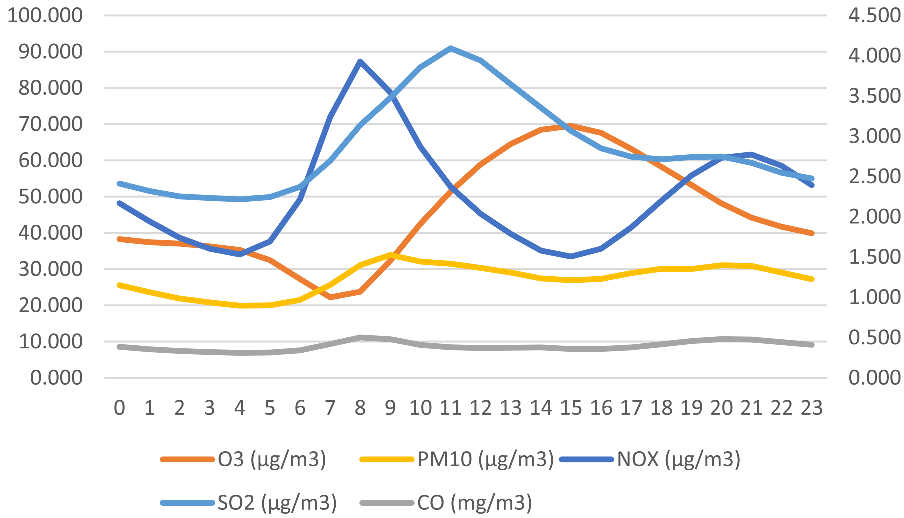

Fig. 4. Distribution of pollution by hours of the day. Source: Own elaboration.

variables are presented below, as well as the expected relationship with contamination levels:

- A dummy for each of the air quality stations. These variables collect any difference in the level of contamination from each of the air quality stations that does not change significantly throughout the entire period. In this way we can control the differences in the pollution levels of the different air quality stations because they are located in different parts of the city: proximity to high-capacity roads, production centers, …
- A dummy for each of the years of the sample. In this way, for each year we can capture any evolution in pollution levels that is common to all air quality stations, such as changes in economic activity or mobility.
- A dummy for each of the months of the year. These variables capture the evolution of pollution depending on the month of the year, associated with economic activity and atmospheric conditions that are repeated every year (less activity in the summer months, or more heat and less precipitation in certain seasons of the year, for example).
- A dummy for each day of the week. These variables capture any difference in the levels of pollution associated with the different days of the week, especially the variations in economic activity between weekdays (Monday to Friday) and weekends (Saturday and Sunday).
- A dummy for hour of the day. We collect the difference in economic activity and the level of traffic for each hour of the day. It is expected that levels of pollution are higher during the daytime hours of greatest economic activity and the times when people enter or leave the city (around 8 in the morning and 8 at night).
- A variable that grows over time and its square. These variables capture the trend in the level of contamination throughout the entire period. If the coefficient is negative, it indicates that contamination has been reduced throughout the period; while if it is positive, it has grown. If it is not significant, it has not changed. We include the squared variable to allow the relationship to be non-linear.
- The temperature associated with each of the air quality stations. We expect a positive coefficient since the higher the temperature is, the higher the levels of contamination, due to the chemical reactions that generate pollution are accelerated.
- The relative humidity associated with each of the air quality stations. Again, we expect a positive coefficient, since relative humidity causes the hygroscopic growth of aerosols and the consequent modification of their extinction coefficient.
- The rainfall associated with each of the air quality stations. We expect a negative value in this variable, since the rain helps to disperse pollution.
- The atmospheric pressure associated with each of the air quality stations. High pressures should generate higher levels of contamination, as they make it difficult for the contamination to spread.
- Wind speed, which should negatively affect pollution levels. The higher the wind speed, the lower the pollution levels.
- Dummy variables for the different wind directions. We include: NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW. In the case of the city of Barcelona, we expect that when the wind blows in a northeasterly direction, pollution levels decrease (as pollution is blown into the sea); while if it blows in a northwesterly direction, we expect higher levels of pollution, as it maintains pollution within the city.

Variable μ_i is the fixed effect by air quality station that captures any intrinsic characteristic of its location[5]. It was verified whether in our database there could be problems of heteroscedasticity (the variance of the errors is not constant in all the observations made)

[5] We perform a Hausmann test that confirms the preference of fixed effects over random effects.

Table 4
Levels of pollutants in transit and background air quality stations (strike Vs non-strike days).

	SO_2 (µg/m^3)			**O_3** (µg/m^3)			**CO** (mg/m^3)			**PM_{10}** (µg/m^3)			NO_X (µg/m^3)		
General	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ
Transit	3.333	2.955	0.378	32.953	38.286	−5.333	0.748	0.567	0.182	41.472	29.164	12.308	97.818	84.683	13.135
Background	2.803	2.850	−0.047	51.110	48.366	2.744	0.385	0.338	0.046	35.646	25.578	10.067	53.138	44.032	9.106
Δ	0.531	0.106		−18.157	−10.080		0.364	0.228		5.826	3.585		44.679	40.651	
Bus	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ
Transit	3.739	2.949	0.790	31.524	38.332	−6.808	0.702	0.566	0.136	35.930	29.131	6.800	110.587	84.514	26.072
Background	2.969	2.849	0.120	40.775	48.403	−7.628	0.423	0.338	0.085	32.970	25.533	7.437	66.385	43.948	22.437
Δ	0.770	0.100		−9.251	−10.071		0.279	0.228		2.961	3.598		44.201	40.566	
Metro	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ
Transit	3.248	2.955	0.294	39.509	38.278	1.231	0.680	0.567	0.113	33.766	29.153	4.613	97.752	84.658	13.095
Background	2.836	2.850	−0.014	51.446	48.362	3.084	0.372	0.338	0.034	28.791	25.570	3.221	53.548	44.019	9.528
Δ	0.413	0.105		−11.937	−10.084		0.308	0.228		4.975	3.584		44.205	40.638	
RENFE	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ
Transit	3.388	2.952	0.436	38.233	38.282	−0.048	0.701	0.566	0.135	31.167	29.153	2.014	99.826	84.568	15.258
Background	2.618	2.851	−0.233	48.323	48.368	−0.045	0.375	0.338	0.037	31.870	25.546	6.324	60.582	43.946	16.636
Δ	0.770	0.101		−10.090	−10.086		0.326	0.228		−0.702	3.607		39.244	40.622	
FGC	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ	Strike	No Strike	Δ
Transit	4.868	2.951	1.917	50.252	38.253	11.999	0.646	0.567	0.079	34.406	29.162	5.245	95.513	84.672	10.841
Background	3.033	2.849	0.184	56.123	48.352	7.771	0.373	0.338	0.035	33.052	25.575	7.477	52.823	44.024	8.799
Δ	1.835	0.102		−5.871	−10.099		0.272	0.229		1.354	3.587		42.690	40.648	

Source: Own elaboration.

Table 5
Descriptive statistics for the meteorological conditions in our sample.

Variable (unit of measure)	Mean	Std. Dev.	Minimum	Maximum
Temperature (°C)	16.872	6.334	−4.6	38.6
Atmospheric pressure (hPa)	1006.356	13.840	932.7	1036.7
Precipitation (mm)	0.038	0.436	0	30.2
Relative humidity (%)	65.795	15.607	4	100
Velocity of the wind (m/s)	2.333	1.578	0	16.4
Direction of the wind (°North)	203.007	96.615	0	359

Source: Own elaboration.

and autocorrelation (the correlation of a signal with a delayed copy of itself as a function of delay), which is why the one that used the Newey-West estimator that solves both problems. Once both problems are solved, our estimates are robust[6]. The following section provides the results.

4. Results

The main results of the regressions can be seen in Table 6. Each cell is the coefficient (β_i) obtained for each transport mode strike in the econometric regression and indicates the impact of the strike type on the concentration of each pollutant. In the table, we present only the relevant coefficient, but the complete econometric estimations are presented in Annex 1. As can be seen in Annex 1, the 10 estimates are jointly significant at 1%. Regarding R^2, the levels range from 0.12 to 0.42 depending on the type of pollutant[7]. Therefore, the degree of fit of the model can be considered adequate.

Regarding general strikes, we can see that they do not have a significant effect on pollution levels, with the exception of CO, which increases by 0.04 points (9.3%) and NOx, which decreases by 8.48 points (14.3%). The reduction in economic activity that occurs during the days of the general strike would explain this significant reduction in NOx levels[8].

Bus strikes have a similar impact to general strikes, although there is no significant reduction in NOx levels as they do not significantly reduce economic activity. In fact, bus strikes only seem to generate a small increase in CO of 0.05 points (11.9%); while it does not have significant effects on the other pollutants. Similarly, the FGC train strikes do not have a significant impact on pollution levels either, with the exception of PM_{10}, which decreases by 2.25 points (7.8%) and a slight increase in O3 levels, of 1.53 points (3.5%).

The result is very different for the other public transport modes, the metro and conventional train strikes, where there are very significant impacts on pollution. In the case of the metro, we can see how strikes generate a significant increase in all pollutants: SO2 by 0.41 points (15%), CO by 0.05 points (11%), PM_{10} by 3.58 points (12.4%) and NOx at 5.45 points (9.2%). Obviously when the levels of these pollutants are increased, the levels of O3 decrease, in this case by 3.31 points (7.6%).

Finally, the case of the train-RENFE strikes is very similar to that of the metro, but with a lower impact. As can be seen in Table 6, the train-RENFE strikes do not generate a significant impact on SO2, but on the other pollutants: the level of CO increases by 0.02 points relative to the average (4%), PM_{10} at 2.7 points (9.4%) and NOx levels at 3.92 points (6.6%).

Once analyzed the impact of strikes on air pollution throughout the city, we analyze the impact of strikes on the different air quality stations in Barcelona. It is important to note that air quality stations are classified as background or transit stations[9]. Transit stations are those which measure pollution levels related to the close influence of traffic emissions from one or more streets in the city. On the other hand, background stations measure pollution in the city produced by emissions from various sources once they have been mixed, and they are not affected by any main road (>10,000 vehicles/day) within a radius of 300 m or any other nearby source of emission[10]. The main results of the regressions can be seen in Table 7. Each cell is the coefficient (β_i) obtained for each transport mode strike depending on the type of air quality station. In the table, we present only the relevant coefficient, but the complete econometric estimations are presented in Annex 1.

Taking into account transit air quality stations, it is important to note that public transport strikes increase traffic emissions' pollution. Metro strikes impact all pollutants analyzed and, in general, these types of strikes increase air pollution due to traffic emissions. Results show that, during metro strikes, levels of NO_x increase by about 19.3%, the levels of CO increase by about 15.1%, the levels of PM_{10} increase by about 13.5%, and the levels of SO2 increase by about 13.9%.

[6] Newey-West robust standard errors with one lag. The introduction of two or three lags does not modify our main results.

[7] R-squared results for the different regressions (from A1 to A10) estimated are the following: A1: 0.21; A2: 0.12; A3: 0.42; A4: 0.13; A5: 0.22; A6: 0.21; A7: 0.12; A8: 0.42; A9: 0.13; A10: 0.22. It is important to note that the Newey2 estimators do not calculate the R-squared. To calculate the R-Squared we have estimated the regression using instrumental variables, correcting by heteroscedasticity. We don't include these estimations in the paper because these standard errors are biased, but the results are the same.

[8] The term 'positive effect' refers to the fact that the correlation between the independent dummy variable 'strike' and the dependent variable on the level of contamination is positive. At no time do we mean that the effect is positive for social welfare.

[9] The classification is made by the Surveillance Network and Atmospheric Pollution Forecast (XVPCA in Catalan), which is part of the Department of Territory and Sustainability.

[10] Surveillance Network and Atmospheric Pollution Forecast.

Table 6
Impacts of the strikes on pollution levels.

Pollutant	Strikes				
	General	Bus	Metro	Train RENFE	Train FGC
SO_2 (μg/m^3)	0.158	0.024	0.411***	−0.054	0.133
	(0.143)	(0.065)	(0.086)	(0.056)	(0.153)
O_3 (μg/m^3)	1.233	0.465	−3.314***	−1.751***	1.530**
	(1.445)	(0.349)	(0.647)	(0.370)	(0.777)
CO (mg/m^3)	0.040**	0.051***	0.047***	0.017***	−0.009
	(0.019)	(0.007)	(0.011)	(0.006)	(0.010)
PM_{10} (μg/m^3)	1.430	0.351	3.577***	2.696***	−2.246**
	(1.224)	(0.648)	(0.998)	(0.517)	(0.907)
NO_X (μg/m^3)	−8.477***	0.774	5.450***	3.942***	−1.856
	(2.114)	(0.911)	(1.080)	(0.704)	(1.271)

Standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
Source: Own elaboration, using Stata.

The second type of public stoppages affecting transit air quality stations is the RENFE strikes. In this regard, these strikes also impact all pollutants analyzed. Our results show that during RENFE strikes, levels of NO_x are 16.9% higher than average, levels of CO are 20.3% higher, the levels of PM_{10} are 3.6% higher and the levels of SO_2 are 14% higher.

The third type of public stoppages affecting transit air quality stations is bus strikes. In this regard, these strikes also impact all pollutants analyzed, except O_3. Our results show that during bus strikes, levels of NO_x are 13.2% higher than average, levels of CO are 18.4% higher, the levels of PM_{10} are 9.1% higher and the levels of SO_2 are 13% higher.

Finally, the results are not so conclusive for the cases of FGC strikes. Our results show that during FGC strikes, the levels of CO are higher, with an increase of about 14.2% over the average. The increase of NO_x is only significant at 5% and the increase of SO_2 is only significant at 10%. Surprisingly, FGC strikes decrease PM_{10} pollution (but only significant at 5%).

In sum, our results confirm that pollution increases in Barcelona's traffic zones when there are strikes on the metro, RENFE, and bus. Additionally the estimates for NO_x confirm that the increase in pollution is higher during metro or RENFE stoppages than during bus strikes. This result may be explained by the fact that there is greater use of private cars when metro or RENFE workers are on strike than when bus workers are on strike, as our NO_x show.

It may seem surprising that public transport strikes generate an increase in SO_2 levels, especially in the case of air quality stations that measure the effect of traffic, considering that the existing regulation limits the level of sulfur that fuels may contain. However, Park et al (2019) show in laboratory tests that diesel vehicles, and especially older ones that are not equipped with a catalyst, generate a significant amount of sulfur oxide. Specifically, data from Spain's "Dirección General de Tráfico" (General Directorate of Traffic, DGT[11]), show that in the province of Barcelona 95.8% of trucks, 78.5% of vans and 46% of cars were diesel in 2019. In addition, the data obtained from Barcelona City Council indicate that the fleet of vehicles is very old. In 2012, 49.7% of all vehicles were 10 or more years old (49.5% of passenger cars, 56.2% of vans and 61.2% of trucks[12]). Therefore, this high percentage of ageing diesel vehicles older than 10 years (with old technology) could explain the increase in pollution levels during public transport strikes, especially in the case of air quality stations that measure the effects of traffic.

It is true that there seem to be other activities that generate SO_2, such as industrial activity (especially petrochemicals) or the combustion of fuel oil by maritime transport. However, it is illogical to think that the increase in SO_2 levels detected in air quality stations is due to an increase in industrial activity or maritime transport, just in the hours when there are public transport strikes. Additionally, in the new approach where we differentiate between air quality stations related to traffic from those that analyze the level of background pollution, we can see how the impact of public transport strikes is significant for SO_2 in the former case, while it is only significant in the case of the metro in the latter.

In general terms, these results coincide with those obtained by Basagaña et al (2018), since they show a greater impact of metro and train strikes. However, our results - unlike those obtained by Basagaña et al (2018) - show an impact on a greater number of contaminants. The use of hourly data for all the air quality stations in the city, together with the control of meteorological variables, might explain this greater precision in our estimates.

This information is displayed in Figs. 5A–5E [13].

These estimated values correspond only to the hours in which there was a strike, without considering the impact it may generate during the hours in which no strike was called that same day. Therefore, the estimated effects are for hours where there was an effective strike, although calls for partial strikes may generate some kind of significant effect on the hours of that same day where there was no strike. This is because it is very probable that some public transport users, faced with the possibility of an unusual or inefficient

11 https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/subcategoria.faces
12 https://www.bcn.cat/estadistica/castella/dades/anuaris/anuari13/cap15/C1509030.htm
13 The graphs with the separate results for the traffic air quality stations and the non-traffic air quality stations are presented in Annex 2.

Table 7
Impacts of the strikes on pollution levels by type of air quality stations.

Pollutant	The impact of strikes on transit air quality stations					The impact of strikes on background air quality stations				
	General	**Bus**	**Metro**	**Train RENFE**	**Train FGC**	**General**	**Bus**	**Metro**	**Train RENFE**	**Train FGC**
SO_2 (μg/m^3)	0.265	0.356***	0.381**	0.383***	0.771*	0.108	−0.147**	0.403***	−0.236***	−0.115
	(0.336)	(0.131)	(0.191)	(0.112)	(0.449)	(0.138)	(0.071)	(0.093)	(0.064)	(0.126)
O_3 (μg/m^3)	−3.270	0.056	−4.842***	−2.823***	1.271	3.943**	0.782	−2.351***	−1.098**	1.699*
	(2.058)	(0.489)	(0.971)	(0.578)	(1.274)	(1.917)	(0.480)	(0.850)	(0.476)	(0.975)
CO (mg/m^3)	0.114***	0.079***	0.065***	0.087***	0.061***	−0.001	0.031***	0.027***	−0.023***	−0.023***
	(0.043)	(0.014)	(0.023)	(0.013)	(0.024)	(0.016)	(0.007)	(0.009)	(0.005)	(0.005)
PM_{10} (μg/m^3)	3.010**	2.628***	3.904**	1.041*	−2.511**	−0.915	−1.525*	3.253**	4.991*	−2.089
	(1.374)	(0.918)	(1.555)	(0.607)	(1.106)	(2.134)	(0.896)	(1.281)	(0.881)	(1.562)
NO_X (μg/m^3)	−0.951	7.840***	11.465***	10.016***	7.784**	−10.999***	−1.930**	3.615***	1.983***	−4.893***
	(5.398)	(2.089)	(3.028)	(1.805)	(3.877)	(2.139)	(0.968)	(1.063)	(0.722)	(1.126)

Standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

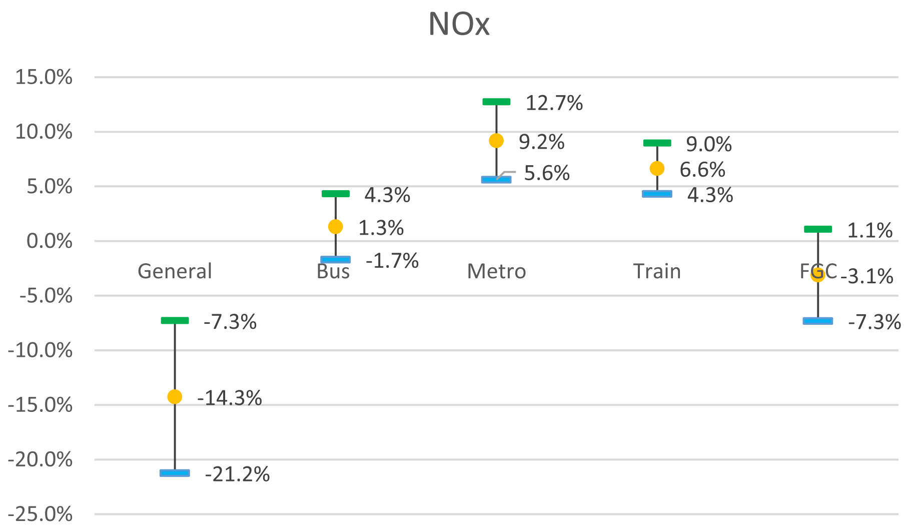

Fig. 5A. Percentage change in NO_x' concentrations (95% confidence intervals).

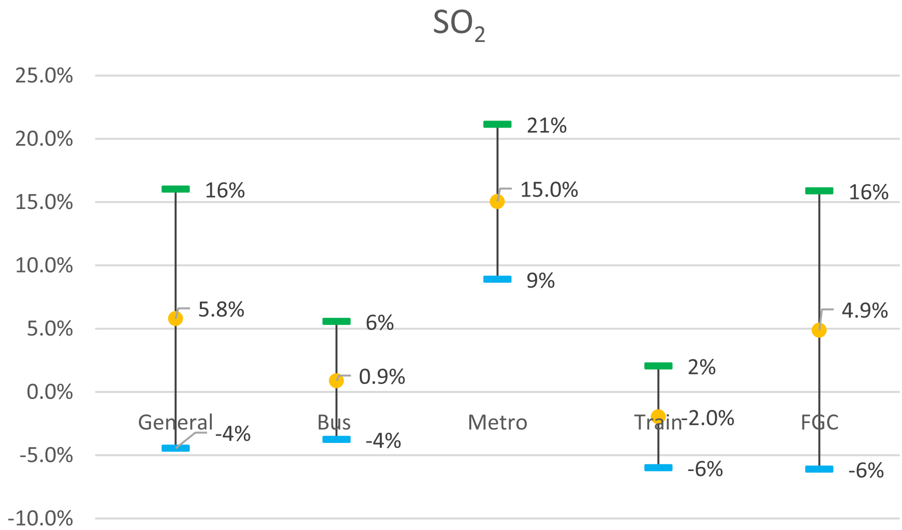

Fig. 5B. Percentage change in SO_2 concentrations (95% confidence intervals).

operation (lower frequency, a greater influx of passengers, etc.) of the service, will opt for private transport even though their journeys are outside strike hours. In this case, the effect of public transport strikes on pollution would be even greater.

5. Discussion

Before analyzing the policy implications of our results, note that in 2016, the transport sector was the main source of greenhouse gas emissions in Spain, as can be seen in Fig. 6.

Taking into account only emissions from the transport sector, it is important to note that cars are the main source of CO_2 emissions for the transport sector, as can be seen in Fig. 7.

Fig. 8 shows the CO_2 emissions in Spain in 2017 from different modes of transportation, depending on the trips made. As seen above, the main source is private cars, with higher emissions from interurban mobility, followed by private cars from urban mobility. On the other hand, collective public transportation (buses, metro, and trains) are among the lowest sources of CO_2 emissions.

Therefore, as the figures show, we can confirm that the use of private cars increases air pollution, in this regard, not only that but our analysis found that public strikes increased pollution in air quality stations that measure pollution emitted by traffic sources. As cars are the main source of air pollution among different transportation modes, and public transport the least, a reduction in public transport availability implying an increase in pollution should be due to an increase in the use of alternative and more pollutant modes of transportation.

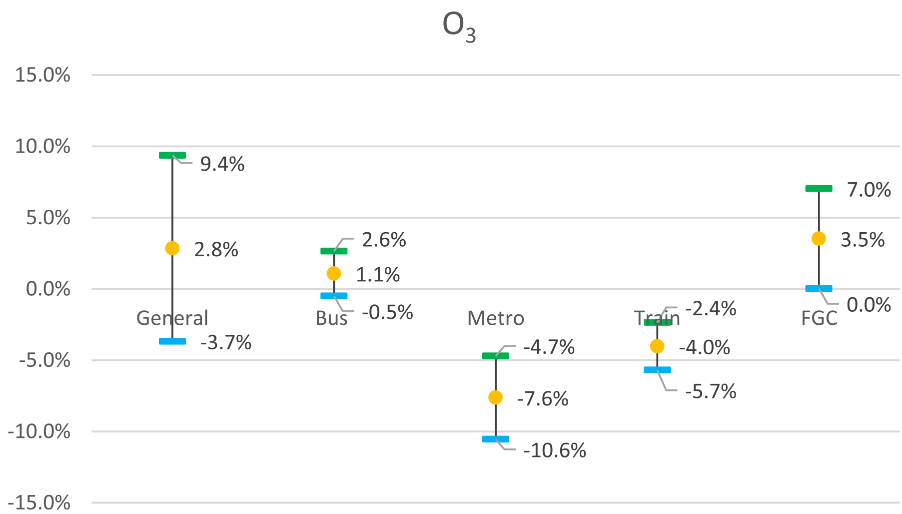

Fig. 5C. Percentage change in O_3 concentrations (95% confidence intervals).

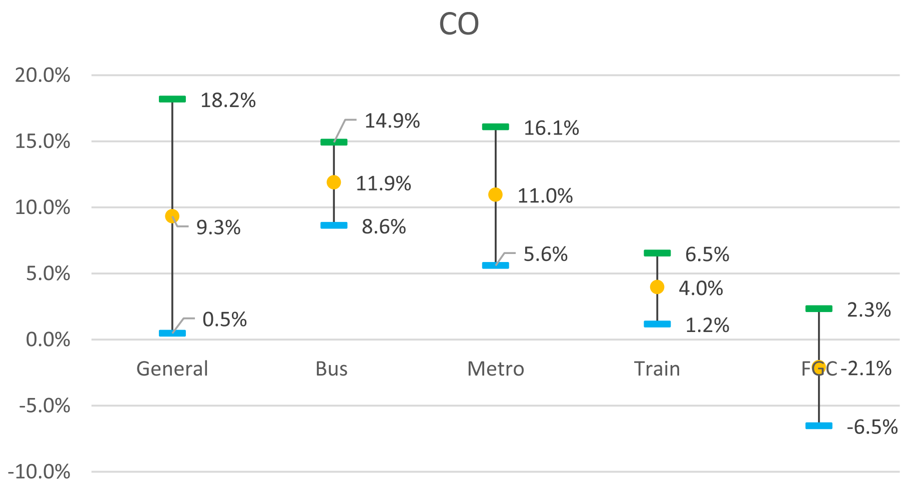

Fig. 5D. Percentage change in CO' concentrations (95% confidence intervals).

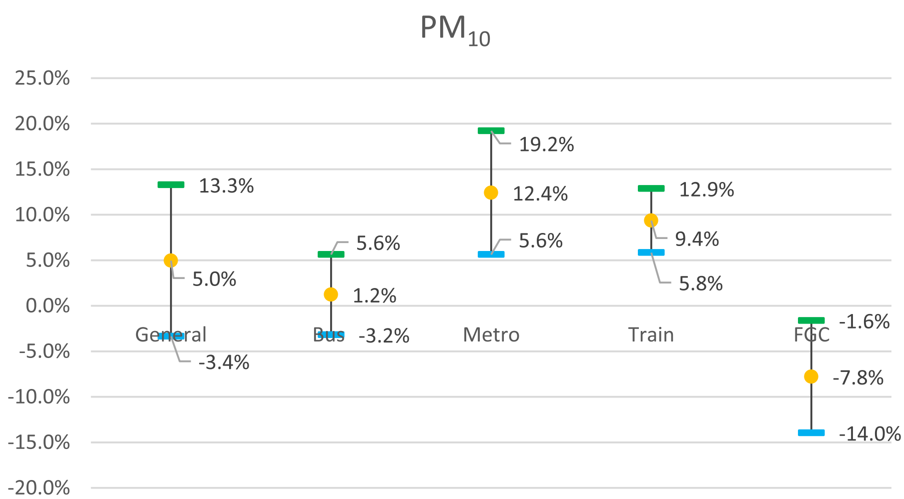

Fig. 5E. Percentage change in PM_{10} concentrations (95% confidence intervals). Source: Own elaboration.

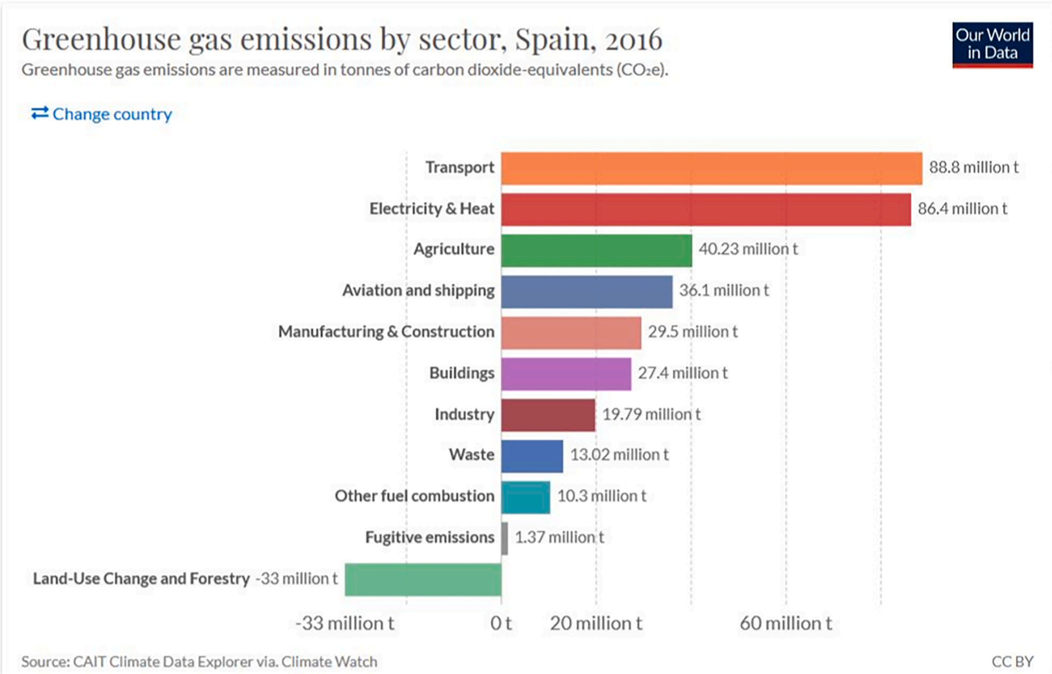

Fig. 6. Greenhouse gas emissions by sector in Spain, 2016. Source: CAIT Climate Data explorer via Climate Watch. Retrieved from our world in data.

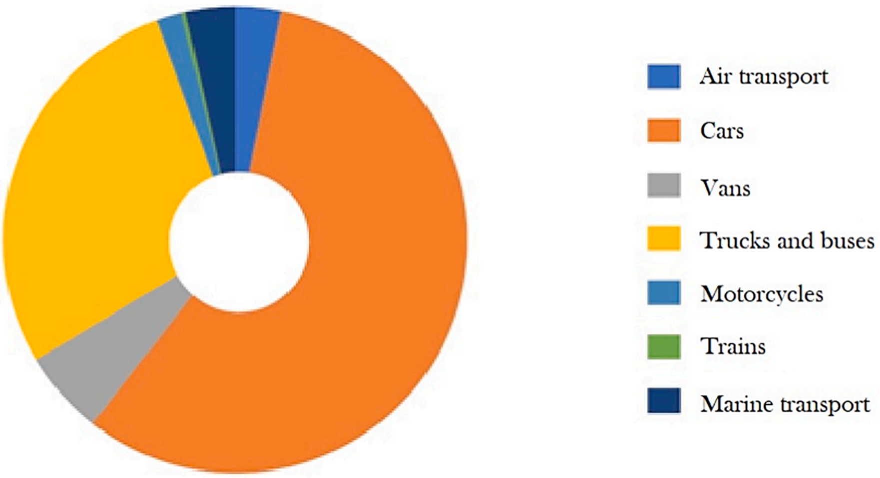

Fig. 7. CO_2 emissions by mode of transportation in Spain (2017). Source: MITECO (2020).

In this regard, Bauernschuster, et al. (2017) show that there is a direct relationship between the concentration level of pollutants and car traffic, mainly due to engine exhaust gases. Further, Negrenti (1999), Int Panis et al. (2006) and Smith et al. (2008) show that the level of air pollution can increase on congested routes where speed is not constant. During strikes some people[14] have to substitute their preferred mode of transportation with another, meaning that there is a chance that the use of private cars increases, which leads to congestion. Note that, in 2008, in Barcelona, the number of cars per household was 0.94, and the number of private vehicles[15] per household was 1.38[16].

The transport interruptions recorded during our study caused an increase in the concentration of pollutants related to traffic

[14] In 2019 only 8.6% of workers worked from home, with around half of them, 4.6%, being usual teleworkers.
[15] Cars, motorcycles and mopeds
[16] https://www.bcn.cat/estadistica/castella/dades/anuaris/anuari09/cap15/C1509070.htm

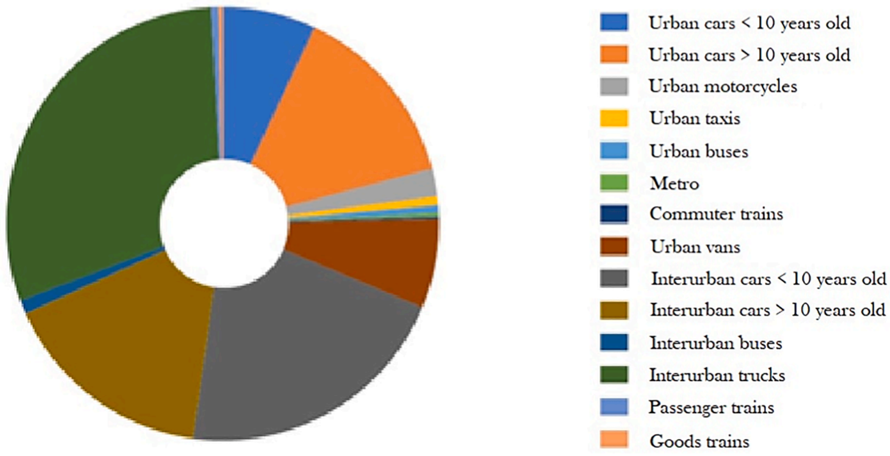

Fig. 8. CO_2 emissions by mode of transportation and trips done in Spain (2017). Source: MITECO (2020).

emissions, such as NOx, CO2, and PM_{10}. When there are public transport strikes the whole city is affected in terms of increasing pollution. Our results show that during strikes, there is an increase in NOx pollution between 3.92 and 5.45 points (between 6.6% and 9.2%), an increase in CO pollution between 0.02 and 0.05 points (that is, between 4% and 11%) and an increase in PM_{10} between 2.7 and 3.58 points (between 9.4% and 12.4%).

If we focus on neighborhoods near traffic areas, however, the situation is worse. Although metro and train strikes predominantly affected air quality throughout the city, in high traffic areas, not only those strikes but also bus and train-FGC stoppages affected air quality. Results confirm that during strikes, NO_x pollution in those areas increase between 7.79 and 11.46 points (that is, an increase between 13.2% and 19.3%). Also, public transportation increases CO pollution near traffic areas between 0.061 and 0.087 points (an increase of between 14.2% and 20.3%). Finally, the impact of public strikes on the increase in PM_{10} concentration in traffic areas is between 1.04 and 3.9 points (an increase of about 3.6% and 13.5%)

Surprisingly, our results also confirm an increase on SO_2 pollution during public transport strikes. Although the impact throughout the city is only significant for metro strikes, it is important to note that for vicinities near traffic areas any public transport strike increases SO_2 pollution. In this regard, the increase in SO_2 concentrations ranges between 0.36 and 0.38 points; an average increase of about 13% and 14%.

These results confirm that the availability of public transportation in the city creates a positive effect in terms of reducing pollution, mainly due to a supposed reduction in the use of private cars. In this regard, our main recommendation to policy makers around the world should be to promote the use of public transportation in cities as a method to reduce pollution. Specifically, in the case of Barcelona, due to congestion[17][18] on some modes of transport, an increase in supply should increase the number of users, and reduce pollution due to a reduction in private car use.

Although we don't have data about traffic and public travel passengers for the period analyzed, our results are similar to Tsapakis, et al. (2012), Anderson (2014) and Bauernschuster, et al. (2017). These authors found that the increase in pollution levels during a public transport strike was associated with the rise in traffic of private vehicles. As people in general have to go to work during public strikes and each household has, at least, one private vehicle we assume that, as our results are in line with previous studies, there should be a relationship between a public strike and an increase in the use of private cars for, at least, the strikes where pollution increased. Note that the use of temporal variables captures the usual effect of traffic and pollutants emissions during periods with no strikes, so increases in pollution during strike hours should be attributed to a specific change that is common during these strikes, and, as previous authors have shown, the most likely reason should be an increase in traffic. The opposite occurs with the ozone level because it generates a negative effect during the metro and RENFE strikes. The concentration of O_3 decreases during these strikes due to chemical reactions transforming emissions of NO and NO_2 in the atmosphere to lower levels of O_3 (Eckhardt, et al., 2013).

In general, we show that transport strikes generate an increase in the levels of pollution in Barcelona in the case of the metro and RENFE. In this regard, metro strikes increase pollution for all pollutants analyzed, and RENFE strikes increase pollution for all pollutants analyzed, except SO_2. Taking into account traffic air quality stations, pollution in these areas increases when metro, RENFE, or buses are on strike for all pollutants analyzed.

On the other hand, for the general case, our results are not conclusive for the case of bus and FGC strikes where air pollution is slightly or statistically non-significant by these types of strikes. In the case of bus strikes, only CO levels are higher. When focusing on high traffic areas, only FGC has non-conclusive results. Taking into account these results, we infer that there is an increase in the use of

[17] In 2017 the metro acknowledged that in peak hours the network was saturated and overcrowded (Metro, 2021).

[18] In 2019, Rodalies and FGC have approximately 88% of places occupied on average during rush hour, with journeys where occupation is higher than 100% (RACC, 2019).

private cars when the metro, RENFE, or buses are on strike.

The consistent results build confidence in the hypothesis. Additionally, we found larger effects for those modes of transportation with no direct substitutes, such as RENFE and the metro. These results give us confidence that our ability to attribute a causal role for the substitution modes should be correct. One exception is the results for FGC, but, results are only significant at 5%, and additionallyalso, it is a mode of transportation with fewer commuters.

As we use hourly panel data, our estimates allow us to infer how commuters substitute between transportation modes. That is, the variation of pollution levels when there is a public strike allow us to try to identify how commuters have substituted their principal mode of public transport when it is unavailable for more polluting private cars or public (or alternative) transport, which is less polluting. In this regard, our findings suggest that, as expected, metro, RENFE, and bus commuters switch to the use of private cars when there is a strike, thereby increasing pollution. On the other hand, our results suggest that users of FGC switch to another form of public transport (or alternative mode of transportation). These results are useful for policymakers to understand commuter patterns regarding the real available options between different modes of transportation when trying to reduce air pollution or increase public transportation usage.

Specifically, one implication is that as pollution increases, throughout the city and also in high traffic areas, when there is a metro strike, we can infer that a substantial number of commuters who use the metro as a first option to travel inside the city, substitute this mode of transportation for private cars. It is important to note that during these strikes, the frequency of other modes of transportation is marginally increased (or not increased), so the increase in pollution is mainly due to an increase in the use of private vehicles and also due to the roads being more congested. These results may show that users of the metro usually travel long distances; making it difficult to substitute these journeys for trips by foot or bicycle. Another possible reason for these results is that commuters who use the metro between destinations are not well covered by other modes of public transport or, if they exist, are not as fast as the metro, which discourages its use during metro strikes.

Second, results for RENFE are similar to those for metro strikes, so, we assume that commuters who use RENFE trains should tend to substitute this mode of transport with private vehicles when there are strikes. In this regard, this result may be explained by the fact that commuters who travel by RENFE usually use this mode of transport to travel from outside Barcelona to Barcelona center, or vice versa. In this sense, there are very few options to substitute RENFE trains with other public transport modes, as there are very few coaches to travel into Barcelona, or, when this option exists, the frequency is very low or the duration of the journey is too long, due to a large number of stops. Besides, as results show, the increase in pollution from RENFE strikes is lower than that from metro strikes, possibly because the number of RENFE users is lower than that of the metro, so the increase in public vehicles used during a RENFE strike should be lower in comparison when the metro is on strike. Also, this lower increase in pollution inside the city could be due to the fact that part of the congestion generated by cars is on city entries, so pollution is generated outside the city, and only part of it is transported to the city center.

On the other hand, results in the general analysis for bus strikes are mixed, although the sign for all pollutants is positive; it is only significant for O_3 and CO. Further, when taking into account the different types of air quality stations, results are slightly similar to those of the metro and RENFE. In this regard, although the bus has the second-highest number of public transport users, when there is a strike some effects go in the opposite direction. First, on a bus strike, there is less (or no) frequency of buses operating, so pollution should decrease; but on the other hand, as users cannot go by bus they may switch to private cars and pollution should be expected to increase. Depending on the magnitude of these two effects, pollution may decrease or increase. As results show, in comparison with metro and RENFE strikes, NO_X pollution is not so affected by bus strikes, so, we can infer that only a fraction of bus commuters switch to private cars, while the rest switch to non-pollutant modes (metro, bicycle, or by foot). This result can be justified by the fact that bus trips may be shorter than metro or RENFE journeys, and they can be more easily substituted by foot or bicycle. For the longer trips, users can substitute bus journeys with the metro or private cars, without too much increase in time.

Although it is important to note that our transport mode substitution has not been empirically tested, our results are not only in line with those found by Anderson (2014) and Bauernschuster, et al. (2017), but also, as public strikes increase pollution in traffic air quality stations, we can infer that one of the reasons for an increase in pollution in those air quality stations should be related to traffic activites, such as the use of private cars. If our hypothesis about transport mode substitutions are valid, our findings suggest that policymakers should make a comprehensive analysis of the various public transport alternatives when considering new policies; by taking into account the different substitution modes. This analysis, on the one hand, could be focused on how to complement different methods of transportation and, on the other, should focus on how to increase the use of public transportation when there is no possibility of complementation. First, policymakers should increase the complementarity of different public transport modes; as we can see, bus users substitute buses with metro but, on the contrary, metro users do not substitute the metro with the bus. One way to reduce pressure on the subway system could be to increase this complementarity to allow metro commuters to use bus transport as an alternative, as stated by Harbering and Schlüter (2020) in their study on the Valley of Mexico. This policy not only will move commuters from metro to bus but should also increase the number of users of public transport, due to new commuters using new bus routes and new commuters using metro lines that are not so overcrowded. One easy way forward is to implement efficient bus routes that complement metro lines. Also, policymakers should focus on the availability of new resources in those modes of transportation with fewer substitutes, which in the case of Barcelona should be RENFE trains; as we can see, our results confirm that when RENFE is unavailable, pollution increases, confirming that RENFE is the main public transport mode used to enter and exit the city. As it has no direct substitute, one way to increase public transport users and reduce pollution would be by increasing the frequency of RENFE trains.

In sum policymakers, when implementing policies to increase public transportation and reduce air pollution, should take into account two main factors: facilitating complementarity between transportation modes and increasing the frequency or the capacity of transport with no direct public transport substitutes.

Encouraging and improving public transport would therefore be an efficient measure to improve air quality in cities, but not the only one. Another measure would be to discourage the purchase and use of private vehicles as much as possible. There are different tools to discourage the use of private vehicles, such as: 1) the establishment of a payment for parking on the street. Albalate and Gragera (2020) show how allowing free parking for the citizens of Barcelona increases the number of private vehicles as well as their use; 2) the establishment of Low Emission Zones (LEZ) (Malina and Scheffer, 2015), where only vehicles that comply with a certain technology are allowed to circulate. In this way, older vehicles (those with more polluting technology) are withdrawn from circulation, reducing pollution levels. However, empirical evidence shows that the effectiveness of this measure would be significantly reduced in the long term, as individuals substitute old vehicles for new vehicles that can circulate, increasing traffic again. 3) The introduction of access tolls, where a price is imposed for accessing the interior of cities, thereby reducing the number of private vehicles. This measure, already introduced in many European cities such as London (Mackie, 2005), Stockholm (Eliasson, 2009), Milan (Percoco, 2013) and Gothenburg (Andersson and Nässén, 2016), has shown not only to be efficient in reducing the levels of pollution, but also generating resources for the public sector that can be used to finance improvements in public transport.

In addition to reducing the private vehicle fleet and its use, measures can be introduced to modify characteristics of the existing fleet, mainly by promoting the introduction of the electric vehicle. The implementation of "Cash for clunkers" programs, or subsidies for the purchase of electric vehicles, can help reduce the price differential that still exists between internal combustion engines and electric vehicles. This electrification could also occur in public transport, especially in the bus fleet. Currently, the Barcelona bus network already has a high percentage of buses that work with alternative energies: electric or hybrid (31%), Natural Gas (32%) and conventional diesel (37%)[19].

Finally, for shorter trips within the city, promoting the use of alternative modes of transport, such as bicycles or electric scooters, can significantly modify mobility within cities; helping to reduce pollution levels. The creation of bike lanes, as well as allocating part of the space currently allocated for private vehicles to promote the circulation of bicycles and electric scooters, can be useful to promote this type of mobility.

6. Conclusion

Barcelona has one of the highest levels of air pollution in Europe, caused principally by private vehicles. In this regard, Spain has been referred to the European Court of Justice (CJEU) for exceeding air pollutant limits – mainly for NO_X in Madrid and Barcelona.

The main objective of this paper has been to analyze the impact of public transport strikes on air quality in the city, through an econometric model, using a set of hourly data from 2008 to 2016. Our results show that public transportation strikes have a significant effect on the concentration levels of CO, SO_2, PM_{10}, and NO_X; increasing pollution all over the city. The analysis has found that the increase in pollution specifically occurs when there is a metro or RENFE (train) strike. On the other hand, we have not found pollution effects for bus or FGC (train) strikes. Separately, while evaluating 'general strikes', it was observed that the negative effects on air quality were found in terms of NO_X. In this sense, the results prove that Barcelona's public transport system presents an opportunity to reduce pollutant emissions. Therefore, we can infer that with more and better public transport, pollution levels would be lower.

Additionally, our results help us to try identify how commuters from different transport modes substitute their preferred transportation mode when there is a strike. That is, we infer how each mode of transport is substituted. In this regard, we suppose that the majority of commuters using the metro or RENFE prefer to use private cars when there is a strike on these modes. On the other hand, when there are bus strikes, commuters should substitute this transport mode with more polluting modes, such as private cars; but also with non-polluting means, such as bicycles, the metro, or by foot.

These results may help policymakers to improve urban public transport to cope with pollution generated by traffic. Firstly, to avoid increased use of private cars during metro or RENFE strikes, policymakers should redesign other transportation routes to complement these two transportation modes and absorb commuters from them. Increasing the number of alternatives to metro and RENFE trains would increase the use of public transport and reduce pollution. Another recommendation for policymakers is to increase the frequency, when possible, of transportation methods with no direct substitutes, as in the case of RENFE. Greater frequency would lead to an increase in users and a reduction in pollution.

In the case of bus transportation, our results confirm that bus strikes do not affect air quality in the city, although they have an impact in traffic areas. In this case, separate policy recommendations are advised. First, as some studies show, an efficient bus fleet network can reduce air pollution (Sanz and Perdiguero (2021), Jimenez and Roman (2016)), for example due to an increase in the average speed of buses, lowering the time buses wait at stops or traffic lights, or modernizing the fleet with more energy efficient buses …; in this context, the City Council and TMB started to implement this policy some years ago. We recommend not only a redesign of the bus fleet network for Barcelona but also for the neighboring cities, and also for intercity bus routes. This policy could provide an efficient network and reduce pollution as well as increase users of intercity buses, which would reduce the number of private cars entering the city. Furthermore, policymakers should modernize the bus fleet to increase the use of non-pollutant fuels, such as making them electric to reduce pollution. In this regard, the substitution of buses using pollutant fuels by buses using non-pollutant fuels would improve air quality.

[19] https://www.tmb.cat/documents/20182/94438/Dades+viatgers+bus+metro+2020_CA_EN/41aa4b84-420e-4fb0-adc9-3f3e3f87eb65

CRediT authorship contribution statement

Lyna González: Investigation, Formal analysis, Data curation, Writing - original draft. **Jordi Perdiguero:** Methodology, Formal analysis, Investigation, Writing - review & editing. **Àlex Sanz:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing.

Acknowledgments

This work has been supported by the Barcelona Council (20S01909-001). Jordi Perdiguero thanks the finantial support of Secretaria d'Universitats i Recerca del departament d'Empresa i Coneixement de la Generalitat de Catalunya (2020 PANDE 00058).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2021.102952.

References

Adler, M.W., van Ommeren, J.N., 2016. Does public transit reduce car travel externalities? Quasi-natural experiments' evidence from transit strikes. J. Urban Econ. 92, 106–119.
Albalate, D., Gragera, A., 2020. The impact of curbsideparking regulations on car ownership. Regional Sci. Urban Econ. 81, 103518.
Álvarez, C., Galera, S., Campos-Celador, Á., Díaz, J., Linares, C., Barqueros, I., Casadevante, J. L., 2019. INFORME SOBRE SOSTENIBILIDAD EN ESPAÑA 2019 - Por qué las ciudades son clave en la transición ecológica. Madrid: Fundación Alternativas.
Anderson, M.L., 2014. Subways, Strikes, and Slowdowns: The Impacts of Public Transit on Traffic Congestion. Am. Econ. Rev. 104 (9), 2763–2796.
Andersson, D., Nässén, J., 2016. The Gothenburg congestion charge scheme: A pre-post analysis of commuting behavior and travel satisfaction. J. Transport Geography 52, 82–89.
Àrea d'Ecologia, Urbanisme i Mobilitat, 2018. Dades bàsiques de mobilitat Barcelona. 2017. Barcelona: Ajuntament de Barcelona. Retrieved from http://hdl.handle.net/11703/111727.
Basagaña, X., Triguero-Mas, M., Agis, D., Pérez, N., Reche, C., Alastuey, A., Querol, X., 2018. Effect of public transport strikes on air pollution levels in Barcelona (Spain). Sci. Total Environ. 610–611, 1076–1082.
Bauernschuster, S., Hener, T., Rainer, H., 2017. When Labor Disputes Bring Cities to a Standstill: The Impact of Public Transit Strikes on Traffic, Accidents, Air Pollution, and Health. Am. Econ. J.: Econ. Policy 9 (1), 1–37.
Bel, G., Rosell, J., 2013. Effects of the 80 km/h and variable speed limits on air pollution in the metropolitan area of Barcelona. Transport. Res. Part D: Transport Environ. 23, 90–97.
Ceballos, M.Á., Segura, P., Gutiérrez, E., Gracia, J.C., Ramos, P., Reaño, M., Veiras, X., 2018. La calidad del aire en el Estado español durante 2018. Ecologistas en Acción Madrid.
Chaloulakou, A., Kassomenos, P., Grivas, G., Spyrellis, N., 2005. Particulate matter and black smoke concentration levels in central Athens, Greece. Environ. Int. 31 (5), 651–659.
da Silva, C., Saldiva, P., Amato-Lourenco, L., Rodrigues-Silva, F., Miraglia, S., 2012. Evaluation of the air quality benefits of the subway system in Sao Paulo, Brazil. J. Environ. Manage. 101, 191–196.
Eliasson, J., 2009. A cost-benefit analysis of the Stockholm congestion charging system. Transport. Res. Part A 43, 468–480.
European Commission, 2019, July 25. Air quality: Commission refers Bulgaria and Spain to the Court for failing to protect citizens from poor air quality. European Commission - Press release. Retrieved from https://ec.europa.eu/commission/presscorner/detail/EN/INF_19_4251.
Gong, Z., 2017. Traffic air pollution: Regulation and impact in Barcelona. Master thesis. CEMFI.
Harbering, M., Schlüter, J., 2020. Determinants of transport mode choice in metropolitan areas the case of the metropolitan area of the Valley of Mexico. J. Transport Geography 87, 102766.
Int Panis, L., Broekx, S., Ronghui, L., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Sci. Total Environ. 371, 270–285.
Jiménez, F., Román, A., 2016. Urban bus fleet-to-route assignment for pollutant emissions minimization. Transport. Res. Part E: Logistics Transport. Rev. 85, 120–131.
L' Agència de Salut Pública, 2017. Avaluació de la qualitat de l'aire a la ciutat de Barcelona Informe 2017. Barcelona: L' Agència de Salut Pública (ASPB). Retrieved from https://www.aspb.cat/documents/qualitat-de-laire-informe-2017/.
Mackie, P., 2005. The London congestion charge: A tentative economic appraisal. A comment on the paper by Prud'homme and Bocajero. Transp. Policy 12, 288–290.
Malina, C., Scheffler, F., 2015. The impact of Low Emission Zones on particulate matter concentration and public health. Transp. Res. Part A 77, 372–385.
Meinardi, S., Nissenson, P., Barletta, B., Dabdub, D., Sherwood Rowland, F., Blake, D., 2008. Influence of the public transportation system on the air quality of a major urban center. A case study: Milan, Italy. Atmos. Environ. 42 (34), 7915–7923.
Metro, 2021. Reptes de futur. Retrieved from https://transparencia.tmb.cat/ca/home.
Negrenti, E., 1999. 'Corrected Average Speed' approach in ENEA's TEE model: an innovative solution for the evaluation of the energetic and environmental impacts of urban transport policies. Sci. Total Environ. 235, 411–413.
Park, G., Mun, S., Hong, H., Chung, T., Jung, S., Kim, S., Seo, S., Kim, J., Lee, J., Kim, K., Park, T., Kang, S., Ban, J., Yu, D.-G., Woo, J.-H., Lee, T., 2019. Characterization of emission factors concerning gasoline, LPG and diesel vehicles via transient chassis-dynamometer test. Appl. Sci. 9, 1573.
Percoco, M., 2013. Is road pricing effective in abating pollution? Evidence from Milan. Transp. Res. Part D 25, 112–118.
Perdiguero, J., Sanz, A., 2020. Cruise activity and pollution: The case of Barcelona. Transp. Res. Part D 78, 102181.
RACC, 2019. Análisis de la capacidad del transporte público en los accesos de Barcelona.
Rahman, A., Luo, C., Rahaman Khan, M., Ke, J., Thilakanayaka, V., Kumar, S., 2019. Influence of atmospheric PM2.5, PM10, O_3, CO, NO_2, SO_2, and meteorological factors on the concentration of airborne pollen in Guangzhou, China. Atmospheric Environ. 212, 290–304.
Rivers, N., Saberian, S., Schaufele, B., 2020. Public transit and air pollution: Evidence from Canadian transit strikes. Can. J. Econ. 53 (2), 496–525.
Rojas-Rueda, D., de Nazelle, A., Teixidó, O., Nieuwenhuijsen, M., 2012. Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: A health impact assessment study. Environ. Int. 49, 100–109.
Sanz, A., Perdiguero, J., 2021. Does urban bus fleet-to-route assignment improve air quality? Work in progress.
Smit, R., Brown, A.L., Chan, Y.C., 2008. Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow? Environ. Modell. Software 23, 1262–1270.
Tsapakis, I., Heydecker, B.G., Cheng, T., Anbaroglu, B., 2012. Effects of Tube Strikes on Journey Times in Transport Network of London. Transp. Res. Rec. 2274, 89–92.

WHO, 2005. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Geneva: World Health Organization . Retrieved from https://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/.
WHO, 2016. Ambient air pollution: A global assessment of exposure and burden of disease. Geneva: World Health Organization. Retrieved from https://apps.who.int/iris/handle/10665/250141.
WHO, 2018. World health statistics 2018: monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization.