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Evaluation of the impact of Bus Rapid Transit on air pollution in Mexico City

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ABSTRACT

Mexico City's bus rapid transit (BRT) network, Metrobus, was introduced in an attempt to reduce congestion, increase city transport efficiency and cut air polluting emissions. In June 2005, the first BRT line in the metropolitan area began service. We use the differences-in-differences technique to make the first quantitative assessment of the policy impact of a BRT system on air polluting emissions. The air pollutants considered are carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter of less than 10 µm (PM_{10}), and sulfur dioxide (SO_2). The ex-post analysis uses real field data from air quality monitoring stations for periods before and after BRT implementation. Results show that BRT constitutes an effective environmental policy, reducing emissions of CO, NO_X, and PM_{10}.

1. Introduction

In the literature of environmental and transport economics, road transport is widely considered one of the main sources of air pollution. More specifically, a large fraction of GHG emissions and air pollutants are recognized as being derived from road traffic: "In 2004, transport accounted for almost a quarter of carbon dioxide (CO_2) emissions from global energy use. Three-quarters of transport-related emissions are from road traffic" (Woodcock et al., 2009, p. 2).

The source of emissions coming from road transport is different depending on the area. While freight transport is an important source of polluting emissions in interurban areas, private vehicles are considered one of the main sources of emissions in urban areas. Moreover, pollution levels are particularly high in urban areas that suffer severe levels of traffic congestion such as the metropolitan area of Mexico City. Conventional road transport in metropolitan areas produces a series of pollutant emissions, which in high concentrations represent a hazard for the inhabitants. The most usual pollutants are particulate matter of different size fractions (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2).

Urban road transit can be broken down into different sectors, with one of the most relevant being that of public transport. Urban buses emit relatively high levels of CO, NO_X, PM_{10}, and CO_2. However, due to the use of cleaner, better quality fuels and to stricter regulations on road traffic emissions, the net air quality impact of buses can be positive if vehicles are replaced periodically. This is particularly true if cities adopt electric vehicles and this energy is generated from renewable sources.

Public transport systems, such as subways and light rail networks, are emission friendly transport options (compared to private combustion engine vehicles) that are able to transport huge numbers of people on daily basis. The downside of these modes of transportation, however, is the enormous initial investment they require, the rigidity of their services and the GHG emissions generated by their electricity source. Most governments operate under considerable budget constraints so that building or expanding local public transport infrastructure requires massive investment, while construction is not always feasible owing to the nature of the local geography.

In the last few decades, governments have sought alternatives that are similarly effective but at the same time more affordable. One such option is the Bus Rapid Transit (BRT) system, a high-quality bus service with a similar performance to that of a subway, but provided at a fraction of the construction cost (Cervero, 1998). Many countries around the world such as Brazil, China, South Africa and Turkey have adopted BRT systems. The main factors in their favor are the low initial investment costs (especially compared to a subway line), low maintenance costs, operating flexibility, and the fact that they provide a rapid, reliable service (Deng and Nelson, 2011). If a BRT line is unable to capture the projected transport demand, or if the usual route is under maintenance, the line can easily be rerouted.

The literature addressing the impact of BRT on air quality does not quantify the reduction in concentrations of the different pollutants. Most

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assessments are qualitative studies, computational simulations or take the form cost-benefit analyses that fail to provide details about individual pollutant levels. Our research seeks to address this gap in the literature. We study the impact of the BRT introduction in the Mexico City Metropolitan Area on the concentration of different air pollutants. The contributions of this paper are, as such, easily identifiable: a) to provide a rigorous quantification of the short-term impact on air quality of the introduction of a BRT network in the Metropolitan Area of Mexico City; b) to add to the few analyses to date that employ actual field data in their evaluations of public transport policy; and c) to employ the econometric-based method of differences-in-differences to analyze the environmental impact of a public transportation system like BRT.

2. Related literature

2.1. Studies on polluting emission reductions

Several studies have examined the impact of pollutants and report the potential effects for health. PM_{10} and $PM_{2.5}$ have been linked with a decrease in respiratory capacity, aggravating asthmatic conditions, and with severe heart and lung damage (WHO, 2001). Nitrogen oxides (NO_X) affect the respiratory system, Sulfur dioxide (SO_2) can worsen respiratory or cardiovascular diseases, and carbon monoxide (CO) is poisonous and in high concentrations can lead to unconsciousness and even death (Neidell, 2004; Schlenker and Walker, 2011). The effects of alleviating traffic congestion on infant health are analyzed in Currie and Walker (2011), who show that a reduction in congestion increases the health and development of infants (see also Kampa and Castanas, 2008; Wilhelm et al., 2008; and Lleras-Muney, 2010).

Many governments have introduced policies to reduce the emissions generated by their mobility services. Building up and expanding public transport infrastructure is a common strategy undertaken to reduce travel times, road congestion and polluting emissions. The study by Chen and Whalley (2012) looks at the introduction of Urban Rail Transit – the Metro – in Taipei and finds a reduction of between 5 and 15% in CO emissions. Topalovic et al. (2012) analyses the case of Hamilton in the US and points out that Light Rail Transit reduces emissions by displacing automobiles to alternative roads. An emission comparison between different transport modes, such as LRT and automobiles, is done by Shapiro et al. (2002), showing the benefits of public transport opposite to private car use. Similarly, Puchalsky (2005) also estimates lower emissions coming from electric forms of urban transport (LRT) compared to combustion engines such as the ones used by BRT units.

An alternative policy for abating emissions from road traffic is the introduction of maximum speed limits on highways or in certain metropolitan areas. Many studies have examined the impact of such policies by employing a vast range of analytical techniques. In this way, we find Gonçalves et al. (2008), who report modest reductions of polluting emissions in Barcelona; Keuken et al. (2010), who find a substantial reduction in polluting levels in the Netherlands; and, Keller et al. (2008), who estimate a 4% reduction in NO_X due to this policy in Switzerland. An alternative way of evaluating the impact of a policy on pollution levels is to measure the effect ex-post using field data. However, few studies of this type have been reported to date. Exceptions include Bel and Rosell (2013) and Bel et al. (2015) on the impact of an 80 km/h speed limit and a variable speed limit policy in the metro-area of Barcelona. They report that a variable speed limit was much more effective, reducing NO_X and PM_{10} emissions by 7.7–17.1% and 14.5–17.3% respectively. This suggests that reducing congestion (for which variable speed limit is a useful tool) is more effective than enforcing a fixed maximum speed limit. Another study that uses field data is that by Van Benthem (2015), who analyses speed limits on the U.S. West Coast highways, and concludes that the optimal speed, considering costs and benefits, is about 88 km/h (55 mph) and that increasing the speed would increase CO, NO_X, and O_2 levels.

2.2. Bus Rapid Transit and air pollution

Bus Rapid Transit –BRT– is a relatively new mode of public transportation that has found broad acceptance in developing countries since the early 1990s. By the end of 2016, 207 cities around the world had adopted some form of BRT. We find prominent examples in Bogotá, Curitiba, Guangzhou, Jakarta, and Istanbul. Latin America is seen as the epicenter of the global BRT movement (Cervero, 2013) with over 60 cities using BRT, moving about 20 million people each day; that is, 62% of the global demand for BRT services. Above all, cities in Brazil (34), Mexico (12) and Colombia (7) have led the rapid growth of BRT networks in the region. BRT has also developed in Europe and the U.S. Over 50 cities in Europe provide this service to an average of 2 million people daily. BRT systems exist in 18 cities in the US, transporting an average of almost half a million people daily (see http://brtdata.org/) for figures and statistics on BRT cities.

A key feature of BRT is that it acts not only as a transport policy, but also forms part of a country's environmental policy. In this latter regard, it needs to be borne in mind that old buses are being replaced by modern vehicles run on cleaner fuels, while the introduction of BRT lines should also reduce congestion. According to Cervero (2013, p. 19), BRT is 'likely' to have net benefits regarding emissions: "BRT generally emits less carbon dioxide than LRT [light rail train] vehicles due to the use of cleaner fuels". Cervero and Murakami (2010) consider that attracting former motorists to BRT can reduce vehicle kilometers traveled and thus polluting emissions. In addition, Bubeck et al. (2014) suggest that a better integrated public transport system would attract higher passenger volumes resulting in lower emissions.

The reduction in emission levels thanks to the introduction of BRT systems is noticeable. In Bogotá's TransMilenio, Hidalgo et al. (2013) estimate health-cost savings from reduced emissions following the completion of TransMilenio's first two phases at US$114 million over a 20-year period, based on a rough computation of data. They calculate that about 8% of total benefits can be attributed to air pollution and traffic accident savings (reductions in associated illnesses and deaths). However, the authors do not use real field data to quantify the pollution-reduction benefits. After the implementation of TransMilenio, the government of Bogotá reported a reduction of 43% in SO2 emissions, a reduction of 18% in NOx, and a 12% decline in particulate matter (Turner et al., 2012). Indeed, in Bogotá, the buses displaced by the BRT were reallocated to the urban edge and smaller surrounding townships, leading Echeverry et al. (2005) to argue that BRT may not have reduced the problem of polluting emissions but simply displaced it to other areas.

A study attempting to directly measure the air pollution impact of BRT is the one by Salehi et al. (2016), in which the authors study the development of different pollutants before and after the introduction of a BRT corridor in Tehran. Their measurements show a reduction of 5.8% for PM_{10}, 6.7% for CO, 6.7% for NO_x and 12.5% for SO_2. Their approach however does not consider the existence of a counterfactual, which would give their estimations broader validity. Using data from five air quality measuring stations during the time of the BRT introduction in Jakarta, Budi-Nugroho et al. (2011) find a reduction of PM_{10} and Ozone levels and argue that this decline is linked to the modal shift of commuters from private modes of transport to the BRT. By comparing polluting emissions from light rail trains and BRT in the UK, Hodgson et al. (2013) find that BRT produces lower PM_{10} emissions, but higher NO_x emissions.

The analysis of historical trends of energy demand, air pollutants and GHG emissions attributable to passenger vehicles commuting in Mexico City's metro-area done by Chávez-Baeza and Sheinbaum-Pardo (2014), reported that the primary sources of small particle matter are road passenger transport vehicles. According to in-vehicle measurements by Shiohara et al. (2005), carcinogenic risks caused by micro-buses were much higher than those caused by buses and the metro. In a related study, Gómez-Perales et al. (2004) measured (in-vehicle) commuters' exposure to $PM_{2.5}$, CO and benzene in micro-buses, buses and the metro in Mexico City during morning and evening rush hours. They reported that pollution levels inside the micro-bus units presented the highest concentrations for all the pollutants during rush hours. Wöhrnschimmel et al. (2008) compared micro-bus, regular bus and BRT unit emissions in Mexico City. Based on in-vehicle emission measurements, they concluded that Metrobus units were the least polluting of the three options given that the buses are newer, more efficient and run on diesel instead of regular fuel.

The studies analyzing the impact of BRT on polluting emissions are scarce. In order to have a good overview of the methods used and the results obtained in these we summarize these aspect in Table 1, below. This paper contributes to the existing literature by providing a robust quantification of the short-term impact on air quality of the BRT network in the metropolitan area of Mexico City. We employ actual field data in our evaluation, and use the quasi-experimental method of differences-in-differences to analyze the environmental impact of the Bus Rapid Transit System in Mexico.

3. Bus rapid transit in Mexico city

3.1. The metrobus policy

The Mexico City Metropolitan Area is one of the most heavily populated metropolitan areas in the world. The estimated population in 2005 was 19.2 million inhabitants, growing to over 20 million by 2010 (population density was estimated at 2560 inhabitants/km^2). The city has a subtropical highland climate and lies in an elevated basin at 2240 m above sea level. The valley is confined on three sides by mountain ridges (east, south, and west). Diurnal temperatures oscillate between 10 and 22 °C, and can easily climb above 30 °C on hot days and fall to freezing on cold winter days. Rainfall is intense from June to October, but it is scarce from November to May. Pollution levels are much higher during the dry season. Wind speed plays a critical role in the city's weather and pollution levels: weak winds and the shape of the valley do not allow air pollutants

Table 1
Overview of studies analyzing the impact of Bus Rapid Transit on Polluting Emissions.

Authors	Place and year	Method	Outcome
Wöhrnschimmel et al. (2008)	Mexico City (May–October 2005)	In-vehicle emission measurements	Reductions between 20% and 70% in commuters' exposure to CO, benzene and $PM_{2.5}$. No significant reductions in PM_{10}
Budi-Nugroho et al. (2011)	Jakarta (April, May, September, and October 2005)	Structural equation model combined with an artificial neural network	Significant reduction in the concentration of PM_{10}
Hidalgo et al. (2013)	Bogotá (1998–2006)	Data computation for Cost-Benefit Analysis	Positive impact on health due to reduced emissions of air pollutants
Hodgson et al. (2013)	Reading, UK (2011)	Reading Urban Network System (Transit evaluation model)	Compared to Light Rail Trains, BRT has lower PM_{10} emissions, but NO_x emissions are higher
Chávez-Baeza and Sheinbaum-Pardo (2014)	Mexico City (1990–2008)	Estimation of historical trends using a Vehicle Emissions Scenario	Reduction of 7% for PM_{10}, 2.4% for CO, 15.4% NO_x.
Salehi et al. (2016)	Tehran (2011)	Measurement of emissions at BRT stations	Reduction of 5.8% for PM_{10}, 6.7% for CO, 6.7% for NO_x and 12.5% for SO_2

to disperse.

It was only until the late 20th century that authorities recognized the Mexico City Metropolitan Area pollution problem and started to implement strategic measures to reduce polluting emissions. The measures implemented targeted industry emissions, vehicle emissions, commuter travel distances and travel times, and soil erosion. Although a downward trend was achieved, CO levels were above safety levels on 3% of the time, NO2 on 10%, and PM10 on 50% at least in some city areas between 1995 and 2000, while SO2 no longer surpassed official norm limits since 1993 (CAM, 2002).

The most known measure was the ‘Hoy no circula’ (today you do not circulate) program introduced in 1989. This program is coupled with an exhaust monitoring program (known as ‘*verificación*’), such that cars that do not fulfill emission criteria are not allowed on the road on one particular day during the week depending on the last number of their license plate. Analyzing the impact of this program with a regression discontinuity design, Davis (2008, p. 40) showed that this policy is not effective, but it also “led to an increase in the total number of vehicles in circulation as well as a change in the composition of vehicles toward high-emissions vehicles”.

On 5 November 2002, the governor of Mexico City announced an ambitious program to deal with the worst cases of congestion. The aim was to reduce commuting times and to tackle the city's air quality problems, and several policies were implemented. In 2004 a few buses from the public network were renewed. In 2006-07 some parts of the ‘second floor’ of the inner-city highway *Anillo Periférico* were inaugurated. This helped reducing congestion in some areas, but the overall amount of cars using both levels increased; so reduction of emissions was not significant. Other minor policies were introduced in 2007, such as a pilot project of a bicycle program. All in all, results obtained with these different programs and measures were modest.

At the heart of the 2002 program lay the introduction of a BRT (‘Metrobus’) system, designed to reduce traffic and air pollutant emissions. The intention was not to compete with existing public modes of transport; rather, BRT was seen as an alternative to existing options in order to reduce congestion. Note that, as found by Anderson (2014) for Los Angeles, congestion relief benefits alone may justify transit infrastructure investments. On March 2005, the *Secretaría de Mobilidad* (Mobility/Transport Secretariat, SEMOVI) oversaw the creation of the public entity Metrobus, with an initial operating budget of MXN 42.4 million pesos (USD 3.8 M in 2005). Metrobus was to be fully responsible for the BRT's operation planning and its control and administration.

The main idea underpinning the BRT system was to create an exclusive bus lane in which only authorized buses could operate subject to certain rules and criteria (schedule time, designated stops, physical dimensions of buses, and amount of emissions), to guarantee efficient operation. To promote the system, several stations had to be built to enable passengers to access the service. The project was implemented in 2005 with an initial investment of around USD $80 million to build up the infrastructure (Schipper et al., 2009). The investment included the construction of 37 BRT stations and exclusive bus lanes and the introduction of new articulated buses run on conventional diesel fuel. BRT was first opened on *Av. de los Insurgentes;* the initial fleet had a size of 80 units and the first line in this corridor was 19.6 km long (it was extended to 28.1 km in 2008 while the fleet grew to 98 units) (see Fig. 1). BRT lanes reduced traffic congestion, as the measure eliminated overlapping of services with other bus lines. At the same time, flow in the car lanes was improved as traffic no longer had to stop whenever a bus or a micro-bus made a stop.

Following the introduction of the Metrobus, 90 buses where reallocated to other areas on the mountain side of the city,[1] while 192 buses

[1] We have run the analysis excluding the air quality measuring stations close to this area, to avoid possible changes of our results. Coefficients remain unchanged in sign and significance. Results are available upon request.

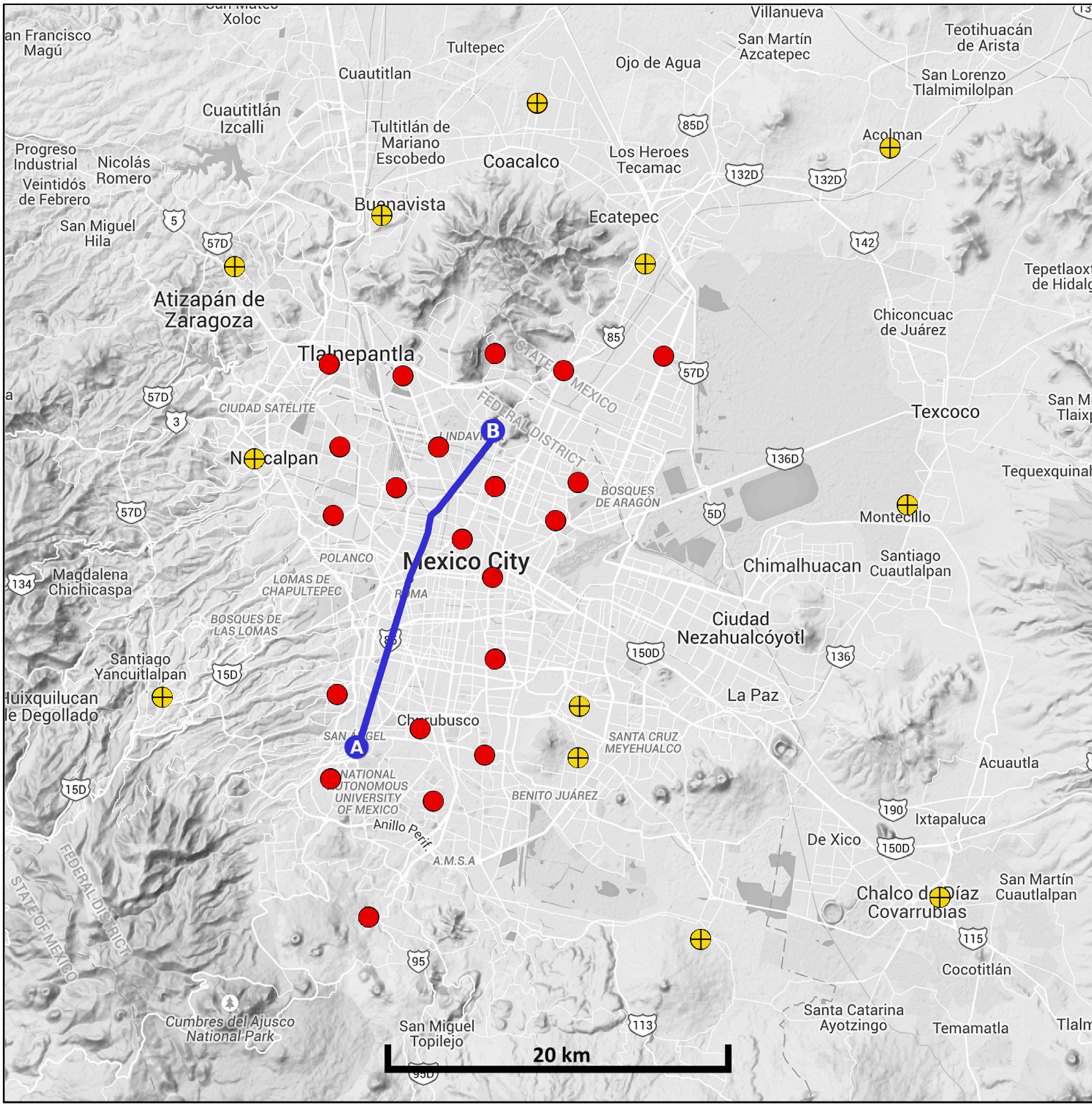

Fig. 1. Map of the Metrobus line 1 (19.6 km) and location of the air quality monitoring stations.
Source: Original Map from Google Maps. Own inclusion of the Metrobus line and air quality monitoring stations for all areas considered [0–2.5 km (6); 2.6–5.0 km (4); 5.1–10.0 km (11); 10.1–30.0 km (12)]. Treated stations are marked red and control stations are marked yellow.

and micro-buses were completely destroyed. In general, Micro-buses are poorly maintained and produce serious amounts of health-threatening gases for people. In 2004, 61% of all minibuses in Mexico City ran on gasoline, 35% used Liquefied Petroleum Gas (LPG); the remaining ones ran on natural gas or diesel (GDF-SMA, 2006). The new BRT units used modern and certified diesel technology. Therefore, the substitution of the old units represented an important change in terms of the air quality conditions in the areas adjacent to the new Metrobus route. One of the aims of the policy was to lower the air polluting emissions of public transportation, and the units operating the BRT network satisfy specific standards (Euro V emission standard).

While it seems intuitive that there is less pollution because of vehicle substitution, it is not clear whether pollution levels in the metropolitan area have also been reduced. Less congestion on a particular route may induce more people to use it. Hence, an increase in demand may even increase pollution levels in a given area if a sufficient number of commuters are attracted to use it. According to the Metrobus office, standard commuting times have fallen from 1 h 30 min to 1 h on the route, while passenger exposure to benzene, CO, and $PM_{2.5}$ has fallen by up to 50 percent, compared to the figures for the previous bus service operating in this corridor. The office also claims that CO_2 emissions have been cut by 35,000 tons per annum. However, the accuracy of this information is questionable as these outcomes are likely to be based on computations from in-vehicle emission changes, rather than real field data.

The Mexico City government monitors the air quality within its metropolitan area, by measuring levels of various pollutants within its network of automatic air quality monitoring stations distributed across the city. These stations have been operational during a number of years and the information is made publicly available. We use this information to measure the impact of the introduction of the Metrobus system on the concentrations of five pollutants.

3.2. Mexico City's metrobus network

The number of passengers using BRT has increased over the years (see Table 2) as has the size of the BRT-bus fleet. Since 2005 and the opening of the first line, the network has been expanded: line one was extended to the south in March 2008, and lines two (20 km) and three (17 km) came into operation in December 2008 and February 2011, respectively. At the same time, the overall size of the BRT fleet has grown to serve this expanding network, growing from 80 to 98 units (following the extension of line one), and subsequently to 167 (opening of line two) and 281 (opening of line three). In April 2012, line four (14 km) was inaugurated and, in November 2013, line five (10 km) was added. By which date the fleet had expanded to 396 units. In 2014, the Metrobus network transported a total of 254 million passengers, and with the expanding reach of the Metrobus network and the increasing number of buses required to operate each new line (which acts as a multiplier), passenger numbers continue to increase.

4. Empirical strategy

The first part of the analysis employs the differences-in-differences method to facilitate the measurement of the impact of the new BRT system on polluting emissions. By so doing, the intention is to estimate the atmospheric concentration of pollutants in Mexico City between 2003 and 2007 and to assess the impact of the introduction of the Metrobus.

The data panel used for this analysis is unbalanced. This characteristic of our panel comes from the fact that some stations were in operation from the beginning of the period of analysis, while other new ones were introduced at a later point in time, sometimes substituting older ones. On the other hand, most stations required maintenance at some point. The introduction or switching-off of the stations is exogenous and not correlated with the variables in the model.

In the absence of a randomized trial, the method we adopt is an extension of the differences-in-differences estimation procedure specified as a two-way fixed effects model. As stated in Wooldridge (2010: 828), "the usual fixed effects estimator on the unbalanced panel is consistent".

$$Y_{it} = \alpha + \beta X_{it} + \gamma Z_{it} + \theta_i + \delta_t + \varepsilon_{it} \tag{1}$$

where Y_{it} is air pollutant concentration at station i for period t, α is a constant term, X_{it} is a vector of time-varying control covariates that include atmospheric characteristics, and Z_{it} is the BRT impact dummy variable to be evaluated. As usual in this kind of models, θ_i are station-specific fixed effects, δ_t are time-specific fixed effects and ε_{it} is the random error. Station fixed effects control for time-invariant station-specific omitted variables; time fixed effects control for trends around each monitoring station.

The key parameter in this differences-in-differences approach is γ, which measures the difference between the average change in air pollutant concentrations for the treatment group (stations within a radius of 10 km around the Metrobus line) and average change in concentrations for the control group (stations located between 10 and 30 km away from the area through which the Metrobus passes). Specifically,

$$\gamma = [E(Y_B|\, BRT = 1) - E(Y_A|\, BRT = 1)] - [E(Y_B|\, BRT = 0) - E(Y_A|\, BRT = 0)] \tag{2}$$

where Y_B and Y_A denote the air pollutant concentrations before and after Metrobus came into operation. BRT = 1 and BRT = 0 denote treatment and control group observations respectively.

The equation for the dependent variables (CO, NO_X, PM_{10}, and SO_2) is:

$$Y_{it} = \alpha + \gamma_1 Metrobus_{it} + \beta_1 Pollutant\ Lag_{it} + \beta_2 Humidity_{it} + \beta_3 Temperature_{it} + \beta_4 Wind\ Direction_{it} + \beta_5 Wind\ Speed_{it} + \beta_6 Rainfall_{it} + \theta_i + \delta_t + \varepsilon_{it} \tag{3}$$

A basic assumption when using differences-in-differences is that the temporal trend in the two areas is the same in the absence of the intervention. If this were not the case, the impact being measured would be biased.

In conducting the analysis, the parallel trend assumption is first tested to determine whether the pollutant concentration trend was parallel in the period prior to treatment (i.e. before policy implementation). To conduct this test, the data were grouped by trimester. After testing and satisfying this assumption for all pollutants (with the exception of PM_{10}), we can verify that in the absence of intervention, the trend presented by the treated group is equal to that presented by the control. The evolution in pollutant levels over time is shown in graph form in Figure A1 in the Appendix. These graphs show how the treated and the non-treated pollutant levels behaved similarly during the pre-treatment period.

The failure to satisfy the parallel trend assumption in the case of PM_{10} leads to a biased impact evaluation for this particular pollutant. However, despite this slight upward bias, the PM_{10} analysis is included because of the importance of this pollutant. The impact evaluation of the remaining pollutants, however, is not biased since the parallel trends assumption is satisfied. Furthermore, and as pointed out above, no major policy interventions took place during the period of study, giving the differences-in-differences analysis the required validity.

Endogeneity is a problem that can sometimes bias an impact evaluation. However, the great appeal of the differences-in-differences estimation "comes from its simplicity as well as its potential to circumvent many of the endogeneity problems that typically arise when making comparisons between heterogeneous individuals […]." (Bertrand et al.,

Table 2
Number of passengers using Mexico-City's Metrobus Network.

Year	Line 1	Line 2	Line 3	Line 4	Line 5	Total
2005	34,720,301	0	0	0	0	34,720,301
2006	74,218,369	0	0	0	0	74,218,369
2007	77,652,339	0	0	0	0	77,652,053
2008	88,840,439	963,900	0	0	0	89,804,339
2009	93,381,006	33,753,903	0	0	0	127,134,909
2010	98,906,091	38,009,587	0	0	0	136,915,678
2011	112,322,116	43,192,375	31,668,509	0	0	187,183,000
2012	122,082,471	47,364,386	39,890,301	10,982,706	0	220,319,864
2013	124,717,045	48,005,198	40,476,438	13,586,594	3,157,914	229,943,189
2014	127,044,608	48,946,595	43,000,735	18,572,161	21,712,834	259,276,932

Source: Data from the Metrobus Public Information Office.

2004, p. 250). Moreover, the implementation of this policy did not respond to a sudden deterioration in air quality, but rather to a long-standing and persistent congestion problem. As such, potential endogeneity issues are not likely to affect the present policy evaluation.

When using differences-in-differences in a panel data setting, regressions have to be undertaken with fixed effects: the correlation between the error components of station *i* and the explanatory variables should be different from zero. Closely related to this, an important assumption here is that unobservable variables and unobservable characteristics remain constant over time. By running the Hausman test and rejecting the null-hypothesis, we confirm the correct use of fixed effects in this panel. We test the model's basic assumptions (homoscedasticity, time dependence, spatial dependence and exogeneity of explanatory variables). To account for first order autocorrelation, we include a one-period lag of the respective pollutant in each regression. By using Driscoll-Kraay standard errors, the estimator is modified in such a way that it is robust to cross-section and time dependence. In this way, standard errors are also heteroscedasticity-consistent (Driscoll and Kraay, 1998).

For the analysis, we considered five different models, allowing the treatment group to change each time. This enables us to identify a distance band from the BRT corridor in which pollutant levels are affected by the introduction of the BRT. The control group remains the same for all five models: air quality monitoring stations in a radius of 10–30 km around the Metrobus corridor (here we consider the shortest straight-line distance between stations and the closest point on the Metrobus route).

By focusing on different treatment groups, we are able to identify different patterns in the pollutant concentrations and in the dispersion of emissions. The distance bands around the BRT line are defined as follows: 0.0–2.5 km (6 stations), 2.6–5.0 km (4 stations), 5.1–10.0 km (11 stations) and 10.1–30.0 km (12 stations). These distance bands were defined based on the number of available air monitoring stations measuring each pollutant and their distance from the BRT corridor.

Models 1–3 consider a treatment group of different sizes in the direct proximity of the Metrobus corridor: Model 1 uses the area in a 2.5-km radius around the Metrobus route, while Models 2 and 3 expand that radius to 5 and 10 km, respectively. It should be noted that Model 3 includes all available air quality monitoring stations. In contrast, models 4 and 5 do not consider direct proximity to the corridor, but focus instead on specific areas around the Metrobus route (2.6–5.0 km and 5.1–10.0 km, respectively). We expect to see the most marked changes in model 1, while models 2 and 3 should show weaker effects. The inclusion of Models 4 and 5 should help us identify more precisely the areas driving the results of Models 2 and 3. Intuitively, the effects in model 1 should be greater than those in models 4 and 5 (that is, if there are any noticeable effects).

5. Data and variables

Pollution levels vary depending on a range of meteorological factors that have to be taken into consideration to capture this variation. Air contaminants are not static and so the average daily wind speed and average daily wind direction are included in the model. Wind direction is an important factor as a significant amount of pollution might be created in heavily industrial areas and then transported to other parts of the metropolitan area. Not only are pollutants transported, they also undergo a number of reaction processes. The rates of these reactions are influenced by temperature, so the average daily temperature needs to be considered. Water can result in a reactive change in the equilibrium or it may increase sedimentation; thus, relative humidity and daily rainfall are both included. Rainfall also reduces significantly the amount of pollutants in the air and so this meteorological variable has to be included. Note, however, that owing to data limitations, rainfall is calculated as the sum of daily rainfall amounts.

Data on air-related control variables (relative humidity, temperature, wind direction and wind speed) were obtained from Mexico City's Environment Secretary, which serves as the official monitoring entity. Data on air quality and amount of polluting emissions come from the Atmosphere Monitoring System (SIMAT), which comprises a network of around 40 monitoring points distributed across the Mexico City metro-area (see Table A1 in the appendix for the exact location of the stations). The SIMAT network is divided into four monitoring subsystems, each measuring different atmospheric components and factors. The emission measurements takes place automatically every 10 min.

For the analysis of air pollutants, the RAMA (Automatic Network for Atmospheric Monitoring) subsystem serves as the source for all pollutant measurements. The RAMA network comprises 29 monitoring stations (their location is displayed in Figure A1 in the Appendix). The pollutants monitored are carbon monoxide (CO), nitrogen oxides (NO_X), sulfur dioxide (SO_2), particles of the order of 10 μm or less in aerodynamic diameter (PM_{10}). A few stations –only seven-also collect data for particles of the order of 2.5 μm or less ($PM_{2.5}$). Air quality monitoring stations are commonly installed on top of buildings, but not at street level directly. They are usually at a tree's height.[2]

Data on the meteorological parameters are obtained from the Meteorology and Solar Radiation Network subsystem (REDMET), which comprises 19 continuous monitoring stations that measure wind direction, wind speed, temperature, humidity, atmospheric pressure and solar radiation. Unfortunately, data on atmospheric pressure and solar radiation are not available after 2003, which is a limitation of the model presented below.

Further data on rainfall were provided by Mexico City's Water Systems office (SACM). This network of rainfall measuring stations comprises 78 monitoring stations distributed across the metropolitan area. Information on the exact location of the stations was denied for reasons of “national security”, given that details regarding the city's waterworks infrastructure are restricted access only. However, the names of the stations were provided and as these typically include a reference to their location, it was possible with Google Maps to approximate the location of most of them. Of the stations, 70.5% were easy to locate, 16.7% were roughly approximated and 12.8% of the stations were impossible to locate based on their name. Rainfall data was obtained only by day, which led us to build the model based on daily averages as shown in Table 3.

Some of these variables are transformed into logarithms, such that relative changes can be interpreted more easily. The variables that are not transformed are relative humidity (which is already in percentage), temperature and wind direction (both of which follow an ordinal scale).

As the air quality monitoring stations and rainfall measuring stations did not coincide, a matching was undertaken. Using the location of the air quality monitoring stations the closest rainfall station within a range of less than 10 km was selected. We assume that the weather conditions present at the air quality stations and at their closest respective rainfall stations do not differ. The rainfall stations that could not be located are not considered here given the impossibility of matching them to the air quality monitoring stations (the result of the station matching is available upon request).

Our analysis of Metrobus focuses solely on line 1 (opened on 19 June 2005). We measure its impact for the two-year period prior to its opening and the two-year post-operational period, i.e. from 19 June 2003 until 18 June 2007. Table 4 presents descriptive statistics of the variables.

6. Results

Tables 5–9 present the results for the fixed effects regressions. The models for CO, NO_X, PM_{10}, and SO_2 are all jointly statistically significant at the 1% level. All estimations include year dummies, which capture

[2] Should the local government update its infrastructure, it would be useful to install new air quality monitoring stations at street level, such that future research can make a more detailed analysis.

Table 3
Description and Source of the model variables.

Variable	Description	Source
CO	Carbon Monoxide daily average concentration (ppm)	RAMA
NO_X	Nitrogen oxides daily average concentration (ppm)	RAMA
PM_{10}	Particulate Matter with less than 10 µm daily average concentration (µg/m^3)	RAMA
SO_2	Sulfur Dioxide daily average concentration (ppm)	RAMA
CO(-1), NO_X(-1), PM_{10}(-1), SO_2(-1)	One period lag (1 day) of the polluting variables	RAMA
Metrobus	Binary variable: 1 if the Metrobus is implemented; 0 otherwise.	Metrobus Public Information Office
Relative humidity	Daily average relative humidity (%)	REDMET
Temperature	Daily average temperature (°C)	REDMET
Wind Direction	Daily average wind direction (Azimuth Degrees)	REDMET
Wind speed	Daily average wind speed (m/s)	REDMET
Rainfall	Sum of the daily rainfall (mm)	SACM
Day Dummies	Binary variables for each day of the week (e.g. 1 if the day is Monday; 0 otherwise).	
Month Dummies	Binary variables for each month of the year (e.g. 1 if the month is January; 0 otherwise)	
Year Dummies	Binary variables for each year between 2003 and 2007	

Note: ppm = parts per million; µg/m^3 = micrograms per cubic meter; m/s = meters per second; mm = millimeters.

Table 4
Descriptive statistics of the model variables.

Variable	Mean	Std. Deviation	Min.	Max.	Obs.	Stations
CO	1.294	0.601	0.39	6.84	23,589	17
NO_X	59.444	30.011	3.75	241.65	24,139	17
PM_{10}	51.397	25.074	1.67	318.29	17,925	14
SO_2	9.928	9.928	0.86	115	29,935	23
Metrobus	0.5	0.5	0	1	1461	–
Relative humidity	56.461	12.44	24.74	87.23	16,491	18
Temperature	16.194	2.406	7.45	23.57	15,469	18
Wind Direction	186.96	23.53	116.4	295.93	16,612	17
Wind speed	1.74	0.449	0.92	3.84	16,612	17
Rainfall	1.633	2.877	0	18.88	113,958	78

time fixed effects (coefficients for year and holiday month dummies are not included in the outputs, and are available upon request). The within-R^2 values range between 0.62 and 0.64 for CO, 0.58–0.60 for NO_X, 0.56–0.57 for PM_{10}, and 0.34–0.36 for SO_2.

Table 5 presents the output for the fixed effects estimation of carbon monoxide. Results shows a downward trend in the relationship between the impact of the introduction of Metrobus on pollution and distance from the Metrobus route. In areas near the BRT line, the reduction in concentration was 7.17%, while in areas lying between 2.5 and 5 km and between 5 and 10 km from the route, the reduction was not significant. Comparing models 1–3 with models 4 and 5, we see that the area driving the significance of model 2 is the one lying between 0 and 2.5 km from the route.

The results also identify the positive influence of the time lag on current levels of carbon monoxide, i.e., yesterday's CO-pollution levels largely determine today's pollution levels. A further factor playing a key role in the levels of CO in the air is the day of the week. Thus, pollutant levels are much higher during the week, when workers have to commute, than on the weekends. Environmental factors such as wind and humidity also play a marked role in air pollutant concentrations over the city, with both variables being significant.

The estimations of NO_X (Table 6) present a similar pattern to that presented by CO. Although the outcome is significant in all areas considered in the treatment group, the reduction in NO_X concentrations is greater in areas closest to the Metrobus route. The coefficient sign is negative, which is consistent with that of the other pollutants, and it presents values between 4.68 and 6.46%. The temporal lag plays an important role in the case of NO_X, as well as in all the areas defined around the Metrobus route. Higher wind speeds have a significant effect on the concentration levels, blowing the pollutant into other areas when the wind speed is high. Weekdays have a similar effect on pollutant concentrations as that described above for CO. For this pollutant, the year dummies are significant, capturing unobserved characteristics related to the time trend.

As noted, the results for PM_{10} present a slight upward bias and should be treated with caution. However, the reduction in concentrations was significant in all areas. In the area lying within a 2.5-km radius of the Metrobus route, the PM_{10} level fell by 7.65% following the opening of the line. The areas lying between 2.5 and 5 and between 5 and 10 km from the route experienced a reduction of 7.70 and 7.27% in their levels of PM_{10}, respectively (all reductions are statistically significant). Table 7 shows how the impact on this pollutant fell across all distances, unlike the patterns presented by NO_X and CO.

Humidity levels, wind speed, and temperature have a high statistically significant influence on PM_{10} concentration levels across all treatment groups. Higher humidity levels and higher wind speeds both reduce PM_{10} concentrations in the air, whereas rising temperatures increase concentration levels. The temporal lag of the endogenous variable indicates that past emission levels significantly affect today's concentration levels. Commuting to work or school at peak times during the week creates congestion within the city, which increases pollution levels in areas closest to these congested roads.

When analyzing PM_{10} concentration levels, special attention should be paid to particle matter of 2.5 µm or less in diameter ($PM_{2.5}$). However, only seven of the air quality monitoring stations in the network collect data about this pollutant, which provided us with a considerably smaller number of observations. Despite this, we were able to calculate differences-in-differences estimates for the area lying in a 10-km radius of the Metrobus corridor (with almost 2000 observations). Our results point to a significant reduction (17.9% at the 1% level) in pollutant concentration. The results of this estimation are available upon request.

Finally, our estimations of the SO_2 concentrations (Table 8) do not show any significant effect of the introduction of the Metrobus in any of the three areas defined around *Av. de los Insurgentes*. As expected, the signs of the coefficients are negative. The variation of the error term is too high to capture any significant impact from the Metrobus operation. Moreover, this higher variation of the error term is significantly larger than that of the estimations for CO, NOX and PM10, leading to a wider confidence interval. The SO2 concentration reduction caused by the BRT introduction falls therefore inside this larger confidence interval, and thus the non-significance. Interestingly, the model for this pollutant performs worse in terms of explanatory power, as the within-R^2 coefficient of determination is below that of the other pollutants.[3]

BRT units running on diesel came to replace Microbuses using Gasoline and Liquefied Petroleum Gas. The non-significance of the policy coefficient is likely to be this way because vehicles using gasoline produce less SO2 emissions than vehicles running on diesel. The main sources of SO2 emissions are a) factories using fossil fuels, coal, diesel

[3] Our period of analysis overlaps with the PEMEX Magna gasoline with ultra-low Sulphur introduction in October 2006. Because of this overlapping, we restricted the period of analysis to September 30, 2006. The results, which are available upon request, remain unchanged in sign and significance. Ultra-low Sulphur versions of the PEMEX Premium gasoline and PEMEX Diesel were introduced after our period of analysis (2008–2009). For more information see NOM-086-SEMARNAT-SENER-SCFI-2005 (*Diario Oficial de la Federación*: 30/01/2006).

Table 5
Estimation of the logarithm of Carbon Monoxide (CO) daily average concentration.

Dependent Variable:	(1)	(2)	(3)	(4)	(5)
Log(CO)	0.0–2.5 km	0.0–5.0 km	0.0–10.0 km	2.5–5.0 km	5.0–10.0 km
Metrobus	−0.0717**	−0.0546**	−0.0294	−0.00490	0.0330
	(0.0245)	(0.0225)	(0.0202)	(0.0294)	(0.0223)
Temporal lag: Log(CO)	0.560***	0.570***	0.554***	0.543***	0.522***
	(0.0220)	(0.0206)	(0.0177)	(0.0205)	(0.0173)
Humidity	0.00787***	0.00695***	0.00600***	0.00811***	0.00790***
	(0.00135)	(0.00127)	(0.00119)	(0.00147)	(0.00142)
Temperature	0.0159*	0.0152**	0.00514	0.0230**	0.00660
	(0.00698)	(0.00633)	(0.00631)	(0.00706)	(0.00739)
Wind Direction	−0.000494**	−0.000288*	−0.000203	−0.000241	−0.000357
	(0.000180)	(0.000151)	(0.000138)	(0.000180)	(0.000203)
Log(Wind Speed)	−0.414***	−0.411***	−0.432***	−0.417***	−0.448***
	(0.0296)	(0.0279)	(0.0280)	(0.0310)	(0.0324)
Log(Rainfall)	3.46e-06	0.000729	−0.00104	−0.00255	−0.00468
	(0.00412)	(0.00392)	(0.00361)	(0.00507)	(0.00441)
Constant	−0.369	−0.332	−0.152	−0.317	−0.153
	(0.264)	(0.272)	(0.252)	(0.216)	(0.201)
Number of Obs.	2957	3566	5249	2164	3238
Within-R^2	0.638	0.632	0.629	0.616	0.624

The regressions include fixed effects for the air quality monitoring stations, the days of the week, the months of the year and for the years in the sample of analysis. Driscoll-Kraay standard errors in parentheses. *p < .10, **p < .05, ***p < .01.

Table 6
Estimation of the logarithm of Nitrogen Oxides (NO_X) daily average concentration.

Dependent Variable:	(1)	(2)	(3)	(4)	(5)
Log(NOx)	0.0–2.5 km	0.0–5.0 km	0.0–10.0 km	2.5–5.0 km	5.0–10.0 km
Metrobus	−0.0646*	−0.0612**	−0.0546**	−0.0634*	−0.0468**
	(0.0285)	(0.0270)	(0.0226)	(0.0319)	(0.0206)
Temporal lag: Log(NOx)	0.460***	0.457***	0.433***	0.445***	0.421***
	(0.0210)	(0.0201)	(0.0191)	(0.0234)	(0.0221)
Humidity	0.00571***	0.00458***	0.00354***	0.00532***	0.00483***
	(0.00124)	(0.00114)	(0.000991)	(0.00131)	(0.00120)
Temperature	0.00917	0.00577	−0.00143	0.0164**	0.00583
	(0.00651)	(0.00594)	(0.00545)	(0.00673)	(0.00613)
Wind Direction	−0.000529**	−0.000347**	−0.000322**	−0.000428**	−0.000543***
	(0.000163)	(0.000125)	(0.000112)	(0.000155)	(0.000164)
Log(Wind Speed)	−0.415***	−0.404***	−0.429***	−0.412***	−0.451***
	(0.0281)	(0.0251)	(0.0233)	(0.0284)	(0.0279)
Log(Rainfall)	−0.00680	−0.00450	−0.00499	−0.00365	−0.00693
	(0.00404)	(0.00375)	(0.00332)	(0.00471)	(0.00409)
Constant	2.022***	2.169***	2.447***	2.172***	2.398***
	(0.230)	(0.224)	(0.166)	(0.202)	(0.167)
Number of Obs.	2986	3585	5299	2482	3597
Within-R^2	0.598	0.590	0.603	0.575	0.603

The regressions include fixed effects for the air quality monitoring stations, the days of the week, the months of the year and for the years in the sample of analysis. Driscoll-Kraay standard errors in parentheses. *p < .10, **p < .05, ***p < .01.

and natural gas; b) processes such as oil refinement, the production of sulfuric acid and the smelting of zinc, copper and plumb; c) geothermic activity taking place in close by volcanos (e.g. the Popocatepetl volcano 72 km far away from Mexico City); d) vehicles using diesel, which in the case of the Mexico City Metro Area are mostly larger trucks. All of these sources of SO2 are normally not located in the area cover by the treatment stations, but further away from the BRT route.

As above, however, the lagged value of the endogenous variable, and the wind and weekday variables have a significant influence on the concentration level of SO_2. Higher wind speeds reduce levels of concentration while the levels rise on days when commuters take to the roads.

The estimation outputs of the different pollutant molecules show that the introduction of the Metrobus had a marked impact on the concentration levels of most of the different pollutants in the areas defined. To appreciate better the impact of the Metrobus operation on air quality in the Mexico City metropolitan area, Table 9 summarizes this impact for all pollutants.

In the case of CO and NO_X, pollutant concentrations fall with distance from the Metrobus corridor; however, in the case of PM_{10}, the pattern is not clear. The fact that particulate matter can have both an anthropogenic and non-anthropogenic origin (WHO, 2013) may explain why a decreasing reduction with distance from the Metrobus route was not found for PM_{10}.

It should be stressed that the results reported herein are valid only for the short term. In the long term, the frequent improvement of existing public transport modes will be necessary in combination with "space–transport development strategies with the aim of increasing accessibility and reducing air pollution" (Ambarwati et al., 2016). To achieve abiding reductions, behavioral changes are needed and these are unlikely to occur unless middle/high income earners stop perceiving the metro and other modes of public transport as inferior goods (Crôtte et al., 2009).

Table 7
Estimation of the logarithm of Particulate Matter with less than 10 μm (PM_{10}) daily average concentration.

Dependent Variable:	(1)	(2)	(3)	(4)	(5)
Log(PM10)	0.0–2.5 km	0.0–5.0 km	0.0–10.0 km	2.5–5.0 km	5.0–10.0 km
Metrobus	−0.0765**	−0.0884**	−0.0922***	−0.0770*	−0.0727**
	(0.0308)	(0.0292)	(0.0299)	(0.0314)	(0.0269)
Temporal lag: Log(PM10)	0.442***	0.444***	0.434***	0.446***	0.434***
	(0.0280)	(0.0268)	(0.0256)	(0.0279)	(0.0260)
Humidity	−0.0112***	−0.0111***	−0.0114***	−0.0125***	−0.0130***
	(0.00173)	(0.00167)	(0.00160)	(0.00188)	(0.00175)
Temperature	0.0358***	0.0332***	0.0327***	0.0371***	0.0383***
	(0.00832)	(0.00812)	(0.00769)	(0.00885)	(0.00803)
Wind Direction	−0.000526*	−0.000395*	−0.000267	−0.000311	−0.000175
	(0.000231)	(0.000197)	(0.000165)	(0.000193)	(0.000170)
Log(Wind Speed)	−0.258***	−0.258***	−0.260***	−0.226***	−0.239***
	(0.0356)	(0.0328)	(0.0285)	(0.0328)	(0.0273)
Log(Rainfall)	0.0116*	0.0118**	0.0106**	0.0102	0.00839
	(0.00494)	(0.00445)	(0.00407)	(0.00525)	(0.00463)
Constant	2.720***	2.761***	2.768***	2.825***	2.765***
	(0.235)	(0.232)	(0.214)	(0.245)	(0.203)
Number of Obs.	2054	2658	3697	1611	2046
Within-R^2	0.573	0.564	0.561	0.573	0.574

The regressions include fixed effects for the air quality monitoring stations, the days of the week, the months of the year and for the years in the sample of analysis. Driscoll-Kraay standard errors in parentheses. *p < .10, **p < .05, ***p < .01.

Table 8
Estimation of the logarithm of Sulfur Dioxide (SO_2) daily average concentration.

Dependent Variable:	(1)	(2)	(3)	(4)	(5)
Log(SO2)	0.0–2.5 km	0.0–5.0 km	0.0–10.0 km	2.5–5.0 km	5.0–10.0 km
Metrobus	−0.0490	−0.0693	−0.0446	−0.102	−0.0168
	(0.0584)	(0.0550)	(0.0570)	(0.0669)	(0.0520)
Temporal lag: Log(SO2)	0.456***	0.459***	0.447***	0.416***	0.411***
	(0.0270)	(0.0250)	(0.0240)	(0.0273)	(0.0269)
Humidity	−0.00127	−0.000469	−0.000548	−0.00369	−0.00277
	(0.00383)	(0.00349)	(0.00336)	(0.00350)	(0.00362)
Temperature	0.0472**	0.0501**	0.0466**	0.0514**	0.0473**
	(0.0193)	(0.0177)	(0.0168)	(0.0180)	(0.0182)
Wind Direction	0.00151**	0.00161***	0.00181***	0.00212***	0.00227***
	(0.000513)	(0.000437)	(0.000408)	(0.000454)	(0.000469)
Log(Wind Speed)	−0.384***	−0.413***	−0.414***	−0.432***	−0.420***
	(0.0837)	(0.0758)	(0.0657)	(0.0826)	(0.0700)
Log(Rainfall)	0.0158	0.0143	0.00501	0.0143	0.00243
	(0.0131)	(0.0116)	(0.0112)	(0.0145)	(0.0138)
Constant	0.309	0.318	0.244	0.593	0.294
	(0.474)	(0.433)	(0.413)	(0.412)	(0.422)
Number of Obs.	3211	3962	6198	2618	4103
Within-R^2	0.338	0.355	0.343	0.342	0.315

The regressions include fixed effects for the air quality monitoring stations, the days of the week, the months of the year and for the years in the sample of analysis. Driscoll-Kraay standard errors in parentheses. *p < .10, **p < .05, ***p < .01.

Table 9
Summary of the impact of the Metrobus implementation on the different pollutants.

	(1)	(2)	(3)	(4)	(5)
	0.0–2.5 km	0.0–5.0 km	0.0–10.0 km	2.5–5.0 km	5.0–10.0 km
CO	−0.0717**	−0.0546**	−0.0294	−0.00490	0.0330
	(0.0245)	(0.0225)	(0.0202)	(0.0294)	(0.0223)
NOx	−0.0646*	−0.0612**	−0.0546**	−0.0634*	−0.0468**
	(0.0285)	(0.0270)	(0.0226)	(0.0319)	(0.0206)
PM10	−0.0765**	−0.0884**	−0.0922***	−0.0770*	−0.0727**
	(0.0308)	(0.0292)	(0.0299)	(0.0314)	(0.0269)
SO2	−0.0490	−0.0693	−0.0446	−0.102	−0.0168
	(0.0584)	(0.0550)	(0.0570)	(0.0669)	(0.0520)

Driscoll-Kraay standard errors in parentheses. *p < .10, **p < .05, ***p < .01.

6.1. Robustness checks

In order to make sure that the empirical strategy is consistent, alternative approaches were employed to analyze the data.[4] First, the regressions were run again but dropping the year 2005 in order to account for the adoption time of the new transport mode. The signs and the significances remained unchanged, and the magnitudes did not present major differences. The reductions for the area lying within a 2.5-km radius of the BRT corridor were 11.5% for CO, 13.7% for NOx, and 8.7% for PM10.

Furthermore, we open the spectrum of analysis and use an alternative empirical method. Instead of employing a differences-in-differences approach, we resorted to a Regression Discontinuity Design (RDD) in order to identify the effects of the BRT introduction. For this approach, the Metrobus operation's start (19 of June 2005) is seen as the cutoff point around which the mean of observations before and after are expected to be significantly different. For this robustness check, different time bands on each side of the cutoff point – the Metrobus introduction –

[4] The results of all approaches used for the robustness checks are available upon request.

were considered: 2 years, 1 year and 6 months. This robustness analysis focuses solely on the area between 0 and 2.5 km around the Metrobus. The technical details of this procedure can be found in Hahn et al. (2001) or in Khandker et al. (2009). The results of the covariate-adjusted sharp regression discontinuity estimates can be found in Table A2 in the appendix. We obtain similar results in terms of sign and significance, which supports the results obtained in the differences-in-differences estimation. However, we consider the differences-in-differences method to be more robust and therefore better suited for the Metrobus impact evaluation on air pollution.

7. Conclusions

This paper evaluates the short-term impact of the introduction of Bus Rapid Transit on pollution levels in Mexico City. The analysis is based on real field data obtained from automatic air quality monitoring stations and has focused specifically on four pollutants: CO, NO_X, PM_{10} and SO_2.

Results from the differences-in-differences analysis show a significant reduction in the concentrations of all the pollutants, except SO_2. Specifically, CO concentrations were reduced by between 5.5 and 7.2%, NO_X by between 4.7 and 6.5%, and PM_{10} by between 7.3 and 9.2%, depending on the city area.

In the case of SO_2, our results are negative though not statistically significant. The estimation using Driscoll-Kraay standard errors failed to reveal any significant impact of the introduction of BRT.

It would be inappropriate to generalize the impact of BRT on air quality reported here to a longer time framework and to all cities, given that we have focused on evaluating short-term effects for the Mexico-City Metropolitan Area. Clearly, geographical and atmospheric traits will differ from one location to another. Moreover, further studies are needed in order to determine whether commuters show an enduring behavioral change (switching from private cars to BRT) and whether road congestion in the treated area was actually reduced. To date, the statistics indicate that the number of people using BRT continues to increase as the network expands. Future research would also benefit from comparing the reduction in emissions reported here with those detected in other metropolitan areas based on real field data, and from determining whether the latter are consistent with the findings herein.

For cities with similar characteristics to those of Mexico City, our results might encourage the expansion of their BRT networks, the regular introduction of cleaner BRT-units, and an increase in the size of their BRT fleets to provide a better standard of service, measures that should motivate more people to switch from private cars to public transport. It is important to recall, however, that the emission impact of each BRT line will be different for every corridor, and that other factors are likely to play a role.

Acknowledgements

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APPENDIX

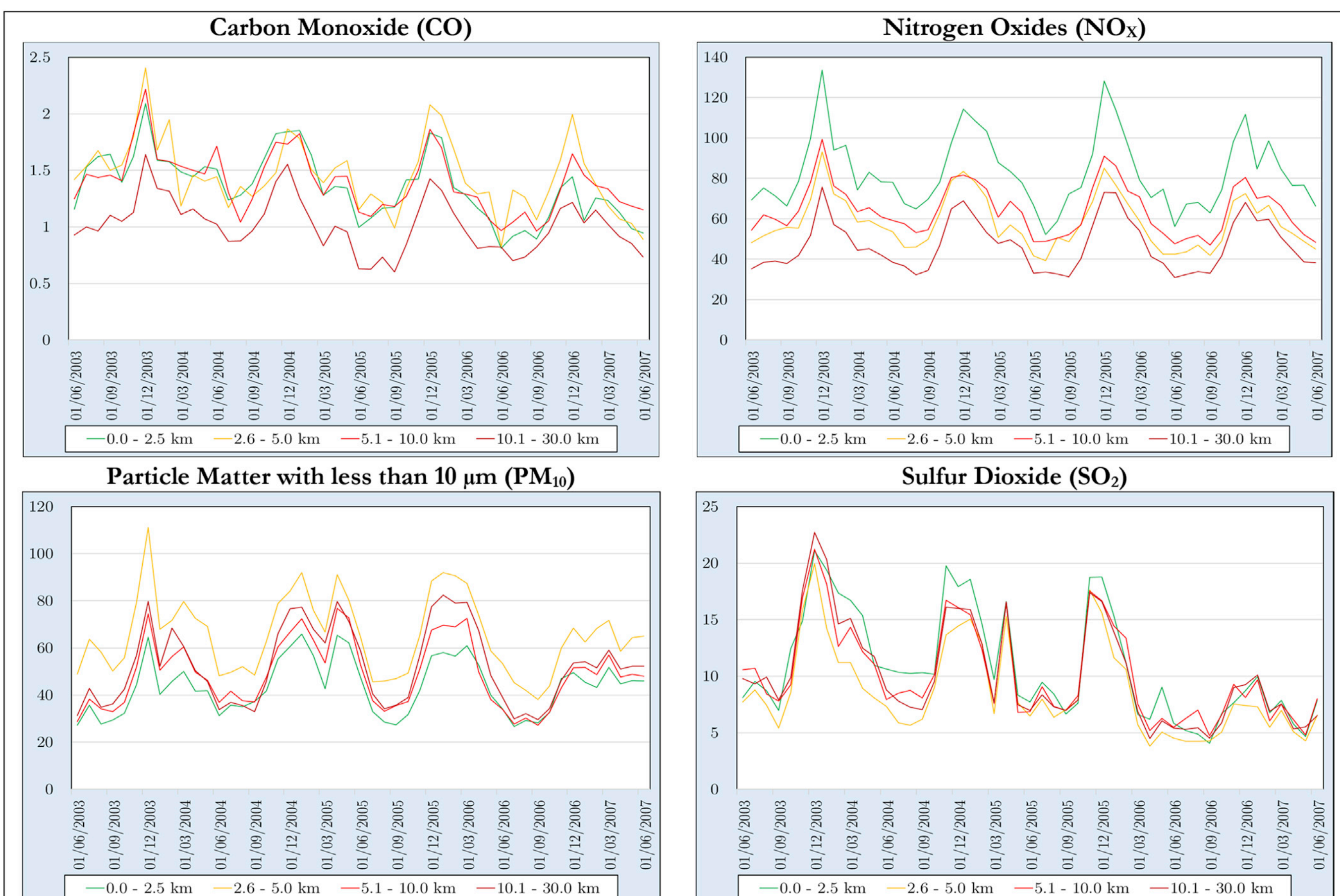

Fig. A1. Evolution of the different pollutant concentrations in the period June/2003–June/2007.

Table A1
Coordinates of the automatic air quality measuring stations and distance to the Metrobus corridor

Code	Air Quality Measurement Station	Latitude	Longitude	Distance to BRT Corridor (in KM)
ACO	Acolman	19.635501	−98.912003	26.30
ARA	Aragón	19.471380	−99.074546	5.30
ATI	Atizapán	19.576963	−99.254133	16.70
AZC	Azcapotzalco	19.488893	−99.198653	6.22
CAM	Camarones	19.468404	−99.169794	2.41
CES	Cerro de la Estrella	19.335884	−99.074675	11.70
CHO	Chalco	19.266948	−98.886088	29.87
COY	Coyoacán	19.350258	−99.157101	2.95
CUA	Cuajimalpa	19.365313	−99.291705	10.90
FAC	FES Acatlán	19.482473	−99.243524	10.10
IMP	Instituto Mexicano del Petróleo	19.488720	−99.147294	2.06
IZT	Iztacalco	19.384413	−99.117641	5.82
LAG	Lagunilla	19.443581	−99.135184	1.91
LLA	Los Laureles	19.578792	−99.039644	11.90
LPR	La Presa	19.534727	−99.117720	3.71
LVI	La Villa	19.469051	−99.117754	1.71
MER	Merced	19.424610	−99.119594	4.15
MON	Montecillo	19.460415	−98.902853	23.00
PED	Pedregal	19.325146	−99.204136	1.98
PLA	Plateros	19.367028	−99.200105	1.90
SAG	San Agustín	19.532968	−99.030324	9.83
SJA	San Juan de Aragón	19.452592	−99.086095	5.44
SUR	Santa Úrsula	19.314480	−99.149994	5.04
TAC	Tacuba	19.455068	−99.202453	5.19
TAH	Tláhuac	19.246459	−99.010564	21.60
TAX	Taxqueña	19.336841	−99.123203	6.77
TLA	Tlalnepantla	19.529077	−99.204597	9.59
TLI	Tultitlán	19.602542	−99.177173	12.80
TPN	Tlalpan	19.257041	−99.184177	9.10
UIZ	UAM Iztapalapa	19.360794	−99.073880	11.00
VAL	Vallejo	19.523598	−99.165702	5.55
VIF	Villa de las Flores	19.657671	−99.096307	17.60
XAL	Xalostoc	19.525995	−99.082400	4.62

Table A2
Results of the Regression Discontinuity Design

	(1)	(2)	(3)
	CO	NOx	PM10
2 years			
Coefficient	−0.295***	−0.247***	−0.149***
Standard Errors	(0.0293)	(0.0901)	(0.0299)
Observations	1402	1103	1047
1 years			
Coefficient	−0.236***	−0.256***	−0.0144
Standard Errors	(0.0436)	(0.0854)	(0.0421)
Observations	692	551	556
6months			
Coefficient	−0.216***	−0.0623	0.0656*
Standard Errors	(0.0346)	(0.0465)	(0.0350)
Observations	256	216	224

Standard errors adjusted by station clustering in parentheses. *$p < .10$, **$p < .05$, ***$p < .01$.

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