

Free rides to cleaner air? Examining the impact of massive public transport fare discounts on air quality

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Abstract

We quantify the effect of public transportation fare subsidies on air quality by exploiting the sharp discontinuity in the cost of ridership introduced by policy intervention. We identify this effect by taking advantage of four months of massive discounts for transit services introduced in Spain on September 1, 2022, as part of the national plan to tackle the global energy crisis. Across pollutants and specifications, we find no evidence that low-cost or free-of-charge public transportation financing schemes have improved air quality. Our results reveal that measures aimed at reducing transit prices may fail to achieve the claimed environmental benefits through a modal shift from private to collective modes of transport, which suggests that massive fare discounts may not represent an efficient allocation of public funds.

Keywords: Public transportation, Air quality, Externalities, Pollutants, Modal shift

JEL Classification Numbers: L92, Q53, R41, R48

1. Introduction

Air pollution is a major environmental issue that poses significant negative effects on human health, including cardiovascular and respiratory diseases. It has a profound impact on society, as 99% of the global population is exposed to harmful air pollution levels, leading to approximately 4.2 million premature deaths per year worldwide. In Europe alone, this figure accounts for approximately 400,000 premature deaths per year (WHO, 2019; EEA, 2020). To tackle this issue, the World Health Organization (WHO) has proposed air pollutant concentration thresholds to eliminate such burdens, and many countries have established their own (less strict) thresholds

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by passing air quality legislation and establishing monitoring networks². Policy-makers are im-
plementing management plans to improve air quality and reduce long-term exposure levels, with
a particular focus on urban areas where automobiles are a significant source of pollution. This
process involves implementing regulations on urban vehicle access and promoting more sustain-
able transport modes, which have become priorities on the agenda of many cities in developed
countries (especially on the European continent) following the increased social awareness about
the negative impacts of private vehicle mobility such as—among others—air pollution³.

By focusing on air quality improvement, the effect of transport policies such as driving
restrictions (Davis, 2008, 2017), road pricing schemes (Percoco, 2013), and gasoline regulations
(Auffhammer and Kellogg, 2011) have been widely discussed. Likewise, the effect of new public
transportation infrastructure supply on air quality has been extensively investigated. This is the
case for new urban public transportation openings (Chen and Whalley, 2012; Gendron-Carrier
et al., 2022; Lu et al., 2018; Sun et al., 2019; Zheng et al., 2019) and expansions (Goel and
Gupta, 2017; Li et al., 2019), as well as related improvements in terms of quality (Beaudoin
et al., 2015), service (Lalive et al., 2018), speed (Bel and Holst, 2018), and routing (Gallego
et al., 2013). However, little is known about the effects of low-cost or free-of-charge public
transportation financing schemes on air quality. Hence, the aim of this paper and its main
contribution is to further investigate whether increased transit accessibility through massive
public transport discounts improves air quality.

Currently, both political and academic interest in the effects of these public transportation
financing schemes is growing worldwide, especially after their introduction in large EU countries
such as Germany and Spain. This interest represents a qualitative leap in the scale of the
adoption of such measures, as they were previously mainly implemented in isolated cities of
different sizes. Free public transport has been periodically discussed within the sustainable
mobility policy agenda, and it is often suggested as a tool with which to foster cleaner air,
together with low emission zone policies and other pollution-reducing transport measures (such
as road pricing schemes) that policy-makers are reluctant to implement due to political economy
considerations⁴ (De Borger and Proost, 2015).

As widely recognised, public transportation systems play a key role in mitigating negative
externalities (e.g., Adler and van Ommeren, 2016; Anderson, 2014; Bauernschuster et al., 2017).

²Examples of this are the European Union (EU) 2008/50/EC Directive on Ambient Air Quality and Cleaner
Air for Europe (EEA, 2021), the United States (US) Clean Air Act and their National Ambient Air Quality
Standards (NAAQS) (EPA, 2022), and China’s Atmospheric Pollution Prevention and Control Law (Huang
et al., 2017).

³There is a broad and interdisciplinary literature that proves the importance of limiting private vehicle
mobility to reduce various negative externalities such as public health impacts (Chay and Greenstone, 2003;
Knittel et al., 2016; Zhang and Batterman, 2013), traffic accidents (Albalade and Fageda, 2021; Parry et al.,
2007), greenhouse gas emissions (Chapman, 2007; Proost and Van Dender, 2012; Zhang et al., 2019), and noise
(Kaddoura and Nagel, 2018).

⁴This research question is very relevant in the EU context due to the proposed revision of the *Ambient Air
Quality Directives*, which will enforce the creation of air quality plans for municipalities to ensure that they
comply with the pollution level standards. For further details, see the publications online at the following:
https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en.

First, mobility is an important source of social well-being. Hence, maintaining a dynamic,
40 effective, and efficient transportation system is essential to the social and economic prosperity
of metropolitan areas even when constraining private vehicle mobility is desirable (Basso et al.,
2021). Second, a broad literature shows that to reduce private vehicle use, an efficient alternative
should be offered to provide incentives for car users to shift their mode of use. Several policy
mechanisms or incidence pathways exist to encourage a modal shift. Governments can influence
45 the relative attractiveness of private and public transportation by affecting the components of
the generalised transportation cost function. On the one hand, they can reduce the monetary
cost of public transport or increase the cost of private transport through—for instance—road
pricing schemes (Parry and Bento, 2001; Parry and Small, 2005). On the other hand, they can
provide public transportation improvements in terms of time savings through higher frequencies,
50 new routes, or increased speeds.

By focusing on measures aimed at subsidising public transportation, there is enough con-
sensus in the economic literature to support the role of subsidies due to both the economies of
scale of transit and the negative externalities generated by private modes (Basso et al., 2011;
Hörcher and Tirachini, 2021; Parry and Small, 2009). Indeed, some scholars and policy-makers
55 advocate extending budgetary or third-party funding down to free-of-charge financing schemes
to promote not only a modal shift but also fairer, more sustainable outcomes. For instance,
several cities in the US are considering fare-free public transportation schemes for at least low-
income users⁵. A bill—known as the *Freedom to Move Act*—has even been introduced in the
US Senate to grant federal funds to allow both state and local governments, as well as transit
60 agencies, to implement fare-free travel.

In a similar direction, some authors have estimated the social welfare gains produced by free-
of-charge measures. Among others, Davis (2021) calculated that free public transportation in
Mexico City would imply an increase of 400 million riders per year (equal to approximately 25%
growth), which would translate into additional operating costs equal to 183 US\$ million and a
65 revenue loss equal to 350 US\$ million. In return, and beyond the enormous growth of consumer
surplus due to tariff cancellations, the welfare gains due to the reduction of negative externalities
would amount to 303 US\$ million annually. Similarly, other assessments question the efficiency of
these schemes in achieving sustainable goals from both financial and environmental perspectives.
On the one hand, if other anti-congestion policies are applied, there is evidence showing that
70 the marginal contribution of increased transit subsidies diminishes rapidly due to substitution
effects between policies (Basso and Silva, 2014). On the other hand, some empirical papers and
reviews of case studies have questioned the effectiveness of this policy in its ability to attract
sizable proportions of private vehicle users (Bull et al., 2021; Cats et al., 2017; UITP, 2020).

⁵For further details, see the articles by Abigail Johnson Hess on *CNBC.com* (available online at the following: <https://www.cnbc.com/2020/03/02/free-public-transportation-is-a-reality-in-100-citiesheres-why.html>) and Bruce Gellerman on *Boston's mayoral race* (available online at the following: <https://www.wbur.org/news/2021/07/21/massachusetts-fare-free-public-transit-debates>).

To further investigate the consequences of the aforementioned measures, this paper takes
75 advantage of a four-month period of massive discounts (starting on September 1, 2022) that
were applied to public transportation fares in Spain to empirically evaluate how public trans-
portation low-cost or free-of-charge financing schemes affect air quality⁶. This massive reduction
in monetary costs was expected to affect the relative generalised cost of public transport vs. pri-
vate modes, making transit relatively more attractive. Thus, such a measure was expected to
80 incentivise a modal shift from the most polluting modes (e.g., private vehicles) to collective or
massive ones (e.g., trains, trams, buses, and subways).

The key empirical challenge in estimating the effect of this policy is one of identification.
Indeed, variations in mobility patterns that are not confounded by other factors that affect air
pollution are rare. In this paper, we address this identification issue by exploiting the sharp
85 threshold in time produced by the implementation of the policy. By collecting air pollution
data for a range of pollutants for 23 Spanish cities from January 1, 2019, to December 31, 2022,
we rely on a regression discontinuity in time (RDiT) approach to identify the effect of massive
public transport fare discounts on air quality.⁷ Overall, our findings reveal that the investigated
policy had no statistically significant effect on air quality, therefore suggesting that such massive
90 fare discounts may not represent an efficient allocation of public funds.

The remainder of the paper is organised as follows. Section 2 reviews the relevant literature
on the topic. Section 3 summarises the public transport fare policy discounts implemented in
Spain. Section 4 describes the data used for the analysis. Section 5 presents the empirical
strategy, the main results, and some robustness checks. Section 6 discusses the mechanisms
95 driving our results. Section 7 concludes the paper.

2. Low-cost or free-of-charge experiences

The policy examined in this paper has some historical precedents, and it cyclically pops up
in the policy debates that occur among urban planners and policy-makers. However, the evidence
collected from the literature is not clearly encouraging about its ability to induce a modal shift
100 from private to collective modes of transport; at the very least, it seems less favourable than
what might be assumed.

Indeed, Cats et al. (2017) evaluated the effects of free public transportation in Tallinn,
which was the first European capital to provide free public transportation starting in January
2013. The authors found an increase in its use of 14%—especially in the case of low-income
105 families—but not a significant reduction in the use of private vehicles. Indeed, the congestion
relief provided by the relative attractiveness of public transport decreased the generalised cost

⁶The measure was later extended for the entire 2023 year.

⁷As highlighted by Hausman and Rapson (2018), such a methodological framework particularly suits appli-
cations where policy implementation affects all observed subjects (i.e., all 23 Spanish cities considered in our
sample) on the same day so that the lack of cross-sectional variation in treatment exposure makes the difference-
in-differences approach not suitable.

of transportation for private car users, particularly for those with higher income who usually value time savings the most. Nevertheless, the results seemed to highlight an increase in public transport demand, pushing the Estonian government to improve transit capacity and quality. 110 Other cities have opted for pilot experiments, such as the one documented by Bull et al. (2021) in Santiago de Chile, which also reported poor results. Although travellers with free-of-charge vouchers increased their use of public transport, they did so only during off-peak hours, indicating that the increase in use was mainly explained by leisure activities, while private car use was not reduced. In Monterrey, the subway was offered free of charge for two months in 2009 115 (shortly before the general elections) to alleviate the economic crisis among the population. Similarly, Slovakia and the Czech Republic have introduced massive fare discounts (equal to 100 and 75%, respectively) for children, students, and pensioners on their long-distance railway and bus services since November 2014 and September 2018, respectively. As reported by Davis (2021) and Tomeš et al. (2022), ridership increased by 61% in the Mexican city and significantly 120 for the targeted groups in both central European countries; however, those articles do not reveal what the impact has been on private transport.

Such evidence is coherent with the findings of a review elaborated by the International Association of Public Transport (UITP), which is mainly formed by operators of public transportation services and public transport authorities. Indeed, the UITP (2020) report concluded 125 that there is no clear evidence that a free-of-charge financing scheme alone is enough to bring about a modal shift, social inclusion, and economic development in a city. According to the analysis discussed in the report, “*public transport is already cheaper than car use and a small further improvement in the price is unlikely to lead to a significant shift. It should not be a surprise that studies suggest a shift instead from other low-cost modes such as walking and cycling*”. Therefore, the report does not consider free public transport to be the main priority over 130 improving its capacity, frequency, and overall quality. Consistent with this argument, the French city of Lyon rejected the implementation of such a measure after concluding that even if transit demand increases by between 15 and 30% (according to their estimates), few private transport users would be transferred to the collective transportation system (approximately 2%).

Other low-cost or free-of-charge public transportation experiences can be found worldwide, but research articles providing quasiexperimental or high-quality quantitative analysis are not available. In Luxembourg, the gratuity of all modes of public transport has been implemented since 2020, which means that this small, high-income country was the first to consolidate universal free transit. Malta followed suit in October 2022. In the USA, Kansas City became the first 140 major city to adopt free transit fares in 2019. In Europe, free public transportation supply is offered in the municipalities of Cascais (Portugal), Torrevieja (Spain), and Livigno (Italy), as well as in the 34 municipalities of the Attica region in Greece. In France, the municipalities of Calais, Dunkirk, Nantes, and Strasbourg—as well as some suburbs of Marseille and Toulouse—apply some sort of free public transport mobility for specific subsets of users, services, routes, and 145 days of the week. In Paris, transit has also been free for those under 18 years of age since 2020. Since 2022, a similar policy has also been operating in Scotland for youth under 22 years old

who are travelling by bus across the country⁸.

Contrary to the previously mentioned cases, the massive discounts applied to public transportation fares in Spain seem to be inspired by the flat fare applied to transit services in Germany between June and August 2022, which was aimed at alleviating the cost of living and combating the 2021-2022 global energy crisis exacerbated by the recent escalation of the *Russo-Ukrainian War*⁹. More specifically, the *9-Euro-Ticket* was a German scheme through which passengers could travel for 9 euros per month on local and regional transport nationwide.

Such policy interventions have gained the attention of researchers, and the first recently available empirical evidence suggests a positive relation between transit fares and air quality (Aydin and Kürschner Rauck, 2023; Gohl and Schrauth, 2022; Yang and Tang, 2018). In particular, fare discounts have been found to reduce pollutant concentration levels, which appears to be at odds with the findings reported earlier in this section; therefore, these works may face some methodological concerns. For example, the yet unpublished paper of Gohl and Schrauth (2022) solely exploits time variation for a daily aggregate air pollution index for the month before (May) and after (June) the implementation of the policy, using the months of May 2018 and May 2019 as pretreatment periods. Hence, it does not fully control for seasonal patterns and other potential confounding factors. In contrast, the working paper of Aydin and Kürschner Rauck (2023) proposes an alternative identification based on a difference-in-differences strategy where the treated monitoring stations are those located in core traffic areas and the control monitoring stations are those located in background areas; therefore, the study measures the differential treatment across stations instead of the average treatment effect and opening up the door to potential biases. Finally, the work of Yang and Tang (2018) combines synthetic control and difference-in-differences strategies to assess the impact of a transit fare hike on an aggregate air quality index. However, the selection of the synthetic treatment units is based on weather characteristics and geographic proximity, leaving out other pollution determinants that might change over time and disregarding that some pollutant species can travel quite far distances, which could lead to biased estimates.

Overall, the large amount of public funds devoted to these types of financing schemes and the seemingly contradictory evidence clearly motivate the need to provide robust causal estimates of the effect of public transportation fare subsidies on air quality.

⁸To provide a comprehensive review, more cities offering illustrative examples of free public transport services should be mentioned. In North America, other free transit systems are the *Metromover* in Miami (Florida), the *Silver Line* in Boston (Massachusetts), the *Downtown Circulator* in Columbus (Ohio), rail services in Tacoma (Washington), and the *CTrain* in Calgary (Canada). In Europe, the *Metroshuttle* in Manchester (England) should be mentioned. In Asia, the free buses in Chengdu and Changning (China), the free *BMTA* buses in Bangkok (Thailand) and the *GoKL* city bus in Kuala Lumpur (Malaysia) represent other examples. In Australia, other cases are the free city loop of Brisbane and the free transit zones of Adelaide and Perth.

⁹This is an ongoing international conflict between Russia (alongside Russian-backed political groups) and Ukraine, which began in February 2014. In February 2022, the conflict saw a major escalation as Russia launched a full-scale invasion of Ukraine.

3. The policy: massive fare discounts in Spain’s public transportation systems

In the following section, we provide a detailed description of the policy implemented in Spain and evaluated in this paper.

180 In July 2022, the President of Spain, Pedro Sánchez announced a four-month period of massive discounts on fares for public transportation services managed by the central government to mitigate inflationary pressures (particularly related to energy and fuel prices) resulting from the economic consequences of the *Russo-Ukrainian War*. The stated motivation of the policy was to promote public transport and reduce the use of private vehicles, which would contribute
185 to reducing Spain’s energy dependence and carbon footprint. On August 1st, 2022, a royal decree¹⁰ was approved by the government to execute the PTD policy¹¹ based on the gratuity of multitrip tickets for short- and medium-distance railway services¹² operated by the national railway company, *Renfe*.

The policy was implemented as a specific transit subscription through a voucher (available
190 starting on August 24, 2022) that was valid for unlimited trips in each metropolitan or regional area of the country between September 1 and December 31, 2022. To target commuters and frequent travellers, the voucher would be free for all users who made a minimum of 16 trips between the same origin-destination city pair during the four months in which the voucher was valid. To acquire a voucher for short-distance railway services, customers had to pay a deposit
195 of 10 euros. To acquire a voucher for medium-distance conventional railway services, customers had to pay a deposit of 20 euros. In both cases, the deposits was returned at the end of the period, subject to compliance with the minimum requirement of 16 trips. Furthermore, other 50% fare discounts were also granted to medium-distance high-speed railway services and bus lines concessioned by the state, most of which covered public service obligations.

200 Additionally, the royal decree also allowed public transport authorities to cut fares for multimodal tickets in metropolitan areas by 30% thanks to funding provided by the Ministry of Transport. Hence, regional and local governments could simultaneously contribute their funds to decreasing prices further on services operated by their owned transportation companies, typically bringing discounts up to 50% or even more. This specific discount setup is heterogeneous
205 across metropolitan areas and depends on how discounts are applied to transit subscriptions and multipass tickets within the variety of fare schemes available. For example, cities such as Madrid and Barcelona have applied a 50% discount to subscriptions and a 30% discount to multipass tickets, while cities such as Bilbao and Vitoria have applied a 50% discount to both. Other

¹⁰For further details, see the royal-decree law (RDL 14/2022) available online at the following: <https://www.boe.es/buscar/act.php?id=BOE-A-2022-12925>.

¹¹For the sake of simplicity, we refer to the policy implemented in Spain as the “PTD” (i.e., public transportation discounts) policy throughout the rest of the paper.

¹²Short-distance railway services operate within a metropolitan area and its suburbs within a radius of approximately 60 kilometres. According to the Spanish rail transport system, these short-distance railway services are called *Cercanías* and *Rodalies*. Medium-distance railway services provide intra- and interregional connections of between 60 and 300 kilometres. They are called *Media Distancia* (for conventional railway services) and *Avant* (for high-speed railway services). For a detailed map of the aforementioned railway services, see Figure B.1.

cities, such as Valencia, Sevilla, Zaragoza and Granada, have generally used a 30% discount, while some others have gone as high as 75% (Oviedo) or even 100% (Palma de Mallorca).

These combined measures were welcomed by hundreds of thousands of transportation users. By the start of the four months, approximately half a million users had applied for *Renfe*'s discounts alone. According to the declarations made by the Minister of Transport (Raquel Sánchez) and *Renfe*, the number of users had reached 900 000 by mid-September and more than two million by the end of 2022¹³. However, monthly ridership figures for the railway services affected by the PTD policy gathered by the *Ministry of Transport* (and shown in Figure 1) suggest that the increase in short-distance ridership in September 2022 (reaching 35 million trips) was approximately 33.5% when compared to September 2021 but only approximately 1.4% when compared to the same month of 2019, therefore revealing that the prepandemic level has only been matched. Regarding medium-distance railway services, the increase in September 2022 (reaching 3.5 million trips) was approximately 21.5% when compared to that in September 2019.

Figure 1: Evolution of ridership for railway services affected by the PTD policy, 2019-2022



Notes: The unit of observation is the month. Source: Authors' own elaboration.

Such evidence has been confirmed by a recent press release (MITMA, 2023) that stated how short-distance ridership had not significantly increased from 2019 levels and that the major change had simply been a shift away from multipass tickets towards this transit subscription. However, the press release argued that the increase in medium-distance transit ridership, paired with a general decrease in mobility for trips above 50 kilometres and a slight decrease in fuel

¹³For further details, see the publications available online at the following: <https://www.renfe.com/es/es/grupo-renfe/comunicacion/renfe-al-dia/ultimas-publicaciones>.

consumption, is indicative of a shift away from car travel and of a positive environmental impact of the policy¹⁴. In short, such evidence suggests that the PTD policy may have concentrated its impact on medium-distance railway services only, which represent just approximately 10% of the trips affected by this financing scheme.

4. Measuring air quality in Spanish cities

To investigate the impact of the PTD policy on air quality, we rely on data provided by the *Air Quality Open Data Platform*, which reports the daily median pollution levels based on multiple measurements recorded by several monitoring stations per city. Our sample includes data from across 23 Spanish cities (for the detailed list, see Table A.1). In particular, we focus on those harmful pollutants that are direct products of incomplete fuel combustion, such as particulate matter (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ground-level ozone (O_3). We collect data from January 1, 2019, to December 31, 2022; this four-year time window allows us to credibly control for seasonal variations.

Figures 2a–2d plot the daily median pollution levels in Spain during our period of analysis. Such national daily averages are constructed by weighting by the number of measurements recorded by the monitoring stations, which vary across cities, days, and pollutants. Given that the vertical lines indicate the implementation day of the PTD policy, as well as the same day of all previous years, we can visually notice how the levels of all pollutants vary widely across days and do not exhibit long-term decreasing trends significantly different from their seasonal patterns.

Table 1 reports the standard descriptive statistics of the pollution levels, as well as the temperature, atmospheric pressure, humidity, and wind speed recorded by the same stations used to monitor air quality. Accordingly, the table reports the descriptive statistics of the average number of measurements used to monitor all variables in Panels A–B. In addition, we take into account other natural events affecting the concentration levels of PM_{10} , such as *Calima* and biomass combustion events. More specifically, *Calima* events refer to Saharan air masses—usually carried by a sirocco wind—that bring high temperatures, dust, and sand and produce natural haze. Biomass combustion events refer to wildfires that occurred in different areas of the country during our period of analysis. Consistently, the table also reports the descriptive statistics of these natural events.

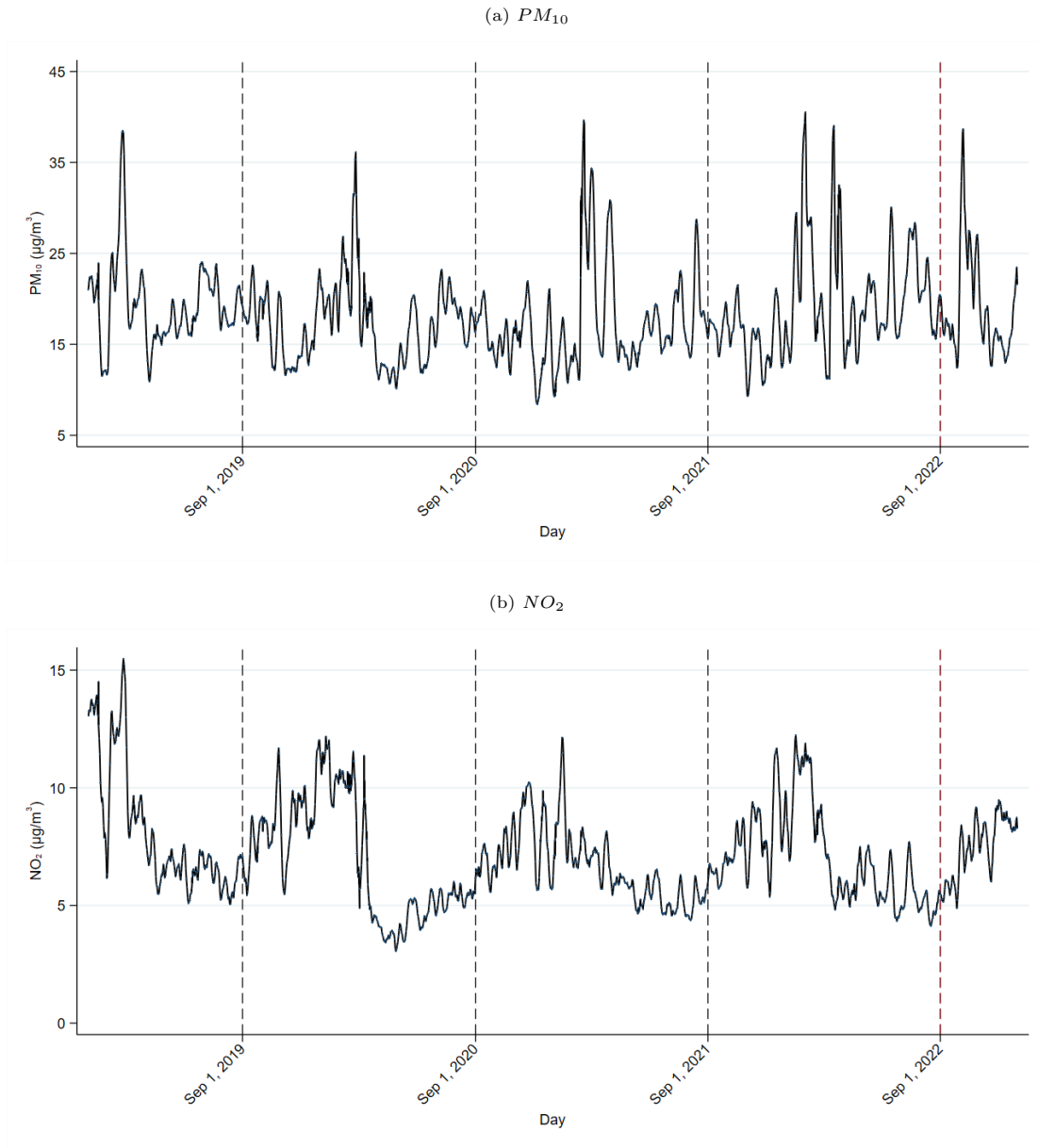
5. The effect of the PTD policy on air quality

5.1. Empirical strategy

In this section, we describe our empirical approach in terms of econometric specifications. to identify the causal impact of a shock in public transportation fares on the change in pollutant

¹⁴For the sake of clarity, note that MITMA (2023) offers no further evidence supporting their claim about the positive PTD policy impact.

Figure 2: Air quality in Spanish cities, 2019–2022



Notes: The time series represents a 7-day moving average weighted by the number of measurements recorded by the monitoring stations. *Source:* Authors' own elaboration.

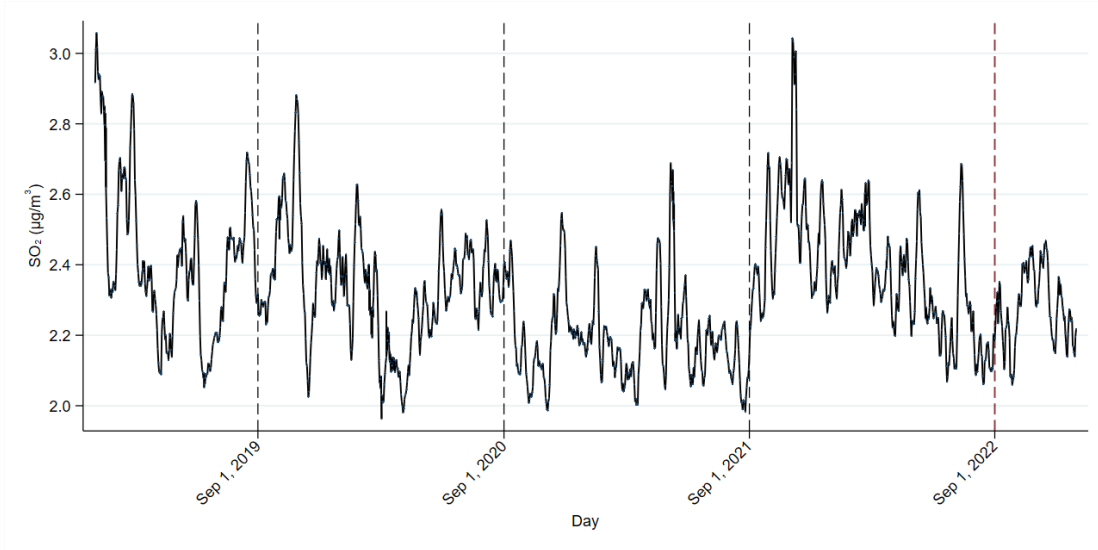
concentration levels. First, we estimate the following simple ordinary least squares (OLS) model:

$$y_{it} = \delta_0 + \delta_1 T_t + \delta_2 W_{it} + \delta_3 C_{it} + \delta_4 B_{it} + \delta_5 X_t + \alpha_i + \epsilon_{it} \quad (1)$$

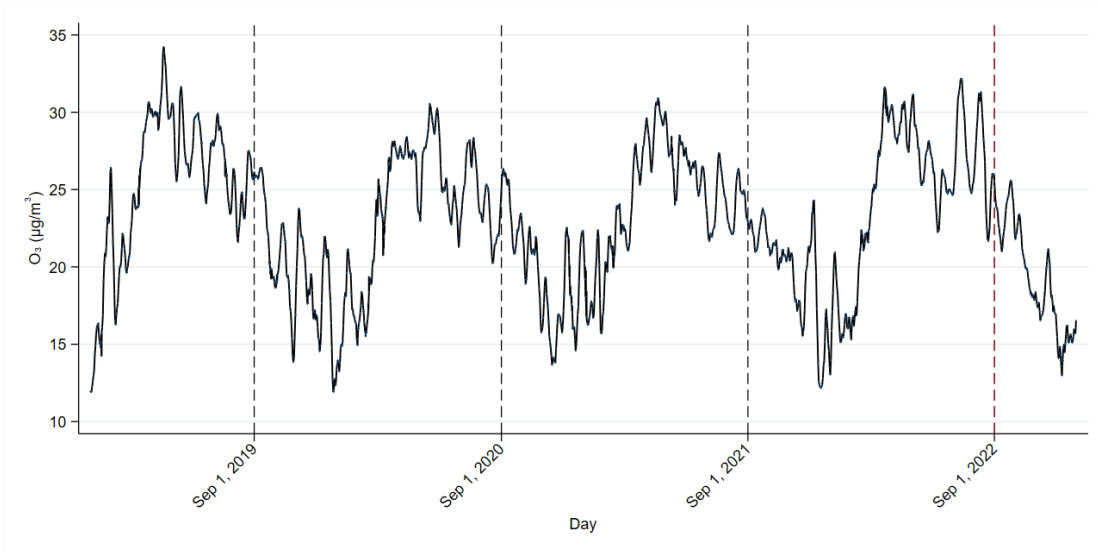
where y_{it} is the log of the city-median concentration for a given pollutant—among those de-

Figure 2: Air quality in Spanish cities, 2019–2022

(c) SO_2



(d) O_3



Notes: The time series represents a 7-day moving average weighted by the number of measurements recorded by the monitoring stations. Source: Authors' own elaboration.

scribed in Section 4—in city i on day t , while T_t is the running variable indicating the treatment
265 period, taking a value of one for all days after the introduction of the PTD policy and a value of
zero before its implementation. Given that atmospheric conditions have significant explanatory
power for air pollution, we control for general weather conditions affecting pollutants' chemistry

Table 1: Descriptive statistics

	Mean	SD	Minimum	Maximum	Observations
<i>Panel A: Pollutants</i>					
Particulate matter (PM_{10})	17.84	12.93	1.00	828.00	32 758
Nitrogen dioxide (NO_2)	6.92	4.53	0.20	56.80	32 788
Sulfur dioxide (SO_2)	2.18	1.61	0.10	148.80	31 965
Ground-level ozone (O_3)	23.19	8.47	0.50	53.90	32 026
<i>Panel B: Atmospheric conditions</i>					
Temperature	16.43	6.68	-8.50	39.00	32 015
Atmospheric pressure	1016.66	12.06	599.90	1039.70	32 011
Humidity	66.20	17.76	1.00	100.00	32 017
Wind speed	3.57	3.39	0.10	33.00	31 703
<i>Panel C: Measurements</i>					
Measurements	143.76	101.06	14.63	448.13	30 263
<i>Panel D: Natural events</i>					
Calima	0.27	0.44	0.00	1.00	33 077
Biomass combustion	0.08	0.27	0.00	1.00	33 077

Notes: The unit of observation is the daily median for all variables in Panels A–C. The unit of observation is the day for all variables in Panel D. All variables in Panel A are expressed in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), temperature is expressed in degrees Celsius, atmospheric pressure is expressed in millibars, humidity is expressed in percentage terms, and wind speed is expressed in meters per second.

Source: Data for all variables in Panels A–C are retrieved from *Air Quality Open Data Platform*. Data for all variables in Panel D are retrieved from the *Ministry of Environment*.

and dispersion with a vector of covariates, W_{it} , including current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, as well as the average number of
270 measurements recorded by the monitoring stations to control for the size of the samples used for calculating the daily median values.

In addition, we control for *Calima* and biomass combustion events affecting PM_{10} concentration levels by including two dummy variables, namely C_{it} and B_{it} , which take a value of one if these phenomena occurred in city i on day t and zero otherwise. We also control for seasonality
275 with a vector of indicator variables, X_t , including day of the week, day of the month, week of the year, month of the year, quarter of the year, and year fixed effects, as well as the full set of interactions between i) week of the year and year fixed effects (to control for COVID-19-related restrictions on mobility and fuel tax reductions applied by the Spanish government in 2022) and ii) day of the week and month fixed effects (to control for potential changes in commuting
280 patterns). Finally, α_i denotes a full set of city fixed effects, while ϵ_{it} denotes heteroskedasticity- and autocorrelation-consistent standard errors clustered at the city level.

Such simple prepost settings serve as a useful baseline to estimate the conditional correlation between the implementation of the PTD policy and air quality. However, potential unobserved factors changing over time and affecting air quality may cause ϵ to be correlated with time and
285 thus with the PTD policy, producing biased estimates of our main coefficient of interest δ_1 .

To address such endogeneity concerns, we take advantage of an exogenous source of variation in the accessibility to Spain’s public transportation systems by exploiting the sharp discontinuity

in time in the cost of ridership that occurred on the implementation day of the massive public transport fare discounts. By doing so, the unobserved factors affecting air quality around the implementation of the PTD policy are likely to be similar so that pollutant concentration levels just before the implementation of the policy form a valid counterfactual group for pollutant concentration levels just after the implementation of the policy. Specifically, we use OLS to also estimate the following regression discontinuity in time (RDiT) model:

$$y_{it} = \delta_0 + \delta_1 T_t + f(\tilde{x}_t) + \delta_2 W_{it} + \delta_3 C_{it} + \delta_4 B_{it} + \delta_5 X_t + \alpha_i + \epsilon_{it} \quad (2)$$

where all terms are the same as those described for Equation 1 except for the addition of a highly flexible p^{th} -order polynomial time trend, $f(\tilde{x}_t)$, to control for the aforementioned potential smooth changes in the relationship between air pollution levels and time functional form, where \tilde{x}_t is centred at x_0 (i.e., the day of the PTD policy implementation) so that $\tilde{x}_t = x_t - x_0$.

Our identification strategy relies on the key assumption of local randomisation around the implementation date. That is, the date of the introduction of the PTD policy is exogenous, as it was not driven by specific atmospheric conditions. In other words, there is no manipulation of the running variable depending on high pollution episodes, which would otherwise bias our main coefficient of interest. Thus, the identifying assumption is that in the absence of the PTD policy, air quality would not discontinuously change in Spanish cities on September 1, 2022.

By flexibly controlling for nonlinearities in pollutant concentration levels from other confounding factors through the polynomial time trend, we can disentangle changes in air quality solely due to the PTD policy. Our coefficient of interest, δ_1 , estimates the reduced form effect of the introduction of the massive public transport fare discounts on air quality, measuring the local estimation of the treatment effect around the date of implementation. Our empirical approach, which is in line with that used by Davis (2008) and Chen and Whalley (2012), offers clear advantages when the evaluated policy affects all observed subjects simultaneously (i.e., all the monitoring stations of the 23 Spanish cities considered in our sample), leaving no appropriate counterfactual available¹⁵.

5.2. Estimation results

Table 2 reports OLS estimates from fitting Equation 1. Each column presents the results of a regression that estimates the correlation between the PTD policy and each of the pollutant concentration levels without including any polynomial time trend. Ranging from -0.09 to 0.09, none of the coefficients are statistically significant. Hence, the OLS estimates provide no evidence that the PTD policy has improved the air quality.

Table 3 reports RDiT-OLS estimates from fitting Equation 2. Each column presents the results of a regression that estimates the effect of the PTD policy on each of the pollutant

¹⁵As discussed in Section 2, our empirical strategy is a convenient complement to check the validity of the counterfactuals used by those papers adopting a difference-in-differences approach to measure the impact of transit discounts on air quality, as pollution spillovers carry over long distances and can affect the control groups.

Table 2: Effect of the PTD policy on pollutants' concentration levels: OLS

	PM_{10}	NO_2	SO_2	O_3
Model:	OLS (1)	OLS (2)	OLS (3)	OLS (4)
PTD policy	0.019 (0.069)	-0.085 (0.080)	0.093 (0.077)	-0.074 (0.051)
Calima	Yes	No	No	No
Biomass combustion	Yes	No	No	No
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	30 121	30 121	30 121	30 121
R^2	0,48	0,57	0,07	0,56

Notes: The table reports estimates from 4 separate OLS regressions fitting Equation 1. The unit of observation is the daily median, and the sample for all regressions extends from January 1, 2019, to December 31, 2022. The dependent variables are the pollutants' concentration levels in logs, where PM_{10} is particulate matter, NO_2 is nitrogen dioxide, SO_2 is sulfur dioxide, and O_3 is ground-level ozone. Specifications also include current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, plus the average number of measurements recorded by the monitoring stations. Time fixed effects include indicator variables for day of the week, day of the month, week of the year, month of the year, quarter of the year, and year, as well as interactions between week of the year and years and day of the week and months. Standard errors clustered at the city level appear in parentheses. Significance values: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

concentration levels, including a third-order polynomial time trend to flexibly control for potential omitted variables. The choice of the third-order polynomial for our baseline specification is because i) higher-order polynomials do not increase the precision of our estimates and ii) odd-order polynomials tend to be preferred from the econometric properties point of view, as suggested by the work of Porter (2003). Ranging from -0.06 to 0.10, the coefficients are in line with the previous OLS estimates; once again, none of them are statistically significant. Hence, the RDiT-OLS estimates provide no evidence that the PTD policy has improved the air quality.

Given that regression discontinuity in time estimates can be sensitive to changes in the polynomial time trend, it is important to evaluate alternative specifications. Hence, Table A.2 reports estimates using alternative polynomials ranging from first- to fifth-order¹⁶, while Table A.3 reports estimates using interactions between the same alternative polynomials and the treatment variable to allow the time trend in pollution to differ on either side of the day of the implementation of the PTD policy. Overall, the estimated coefficients and both Akaike's information criteria (AIC) and the Bayesian information criteria (BIC) are very similar to our baseline, suggesting that our results are not driven either by the choice of the polynomial order or by the interacted functional form.

¹⁶The work of Gelman and Imbens (2019) suggests that polynomials that are too high should not be used in regression discontinuity designs.

Table 3: Effect of the PTD policy on pollutants' concentration levels: RDiT-OLS

Model:	PM_{10}	NO_2	SO_2	O_3
	RDiT-OLS (1)	RDiT-OLS (2)	RDiT-OLS (3)	RDiT-OLS (4)
PTD policy	0.014 (0.069)	-0.062 (0.080)	0.102 (0.080)	-0.063 (0.051)
Calima	Yes	No	No	No
Biomass combustion	Yes	No	No	No
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	30 121	30 121	30 121	30 121
R^2	0.48	0.57	0.07	0.56

Notes: The table reports estimates from 4 separate RDiT-OLS regressions from fitting Equation 2. The unit of observation is the daily median, and the sample for all regressions extends from January 1, 2019, to December 31, 2022. The dependent variables are the pollutants' concentration levels in logs, where PM_{10} is particulate matter, NO_2 is nitrogen dioxide, SO_2 is sulfur dioxide, and O_3 is ground-level ozone. Specifications also include a third-order polynomial time trend, as well as current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, plus the average number of measurements recorded by the monitoring stations. Time fixed effects include indicator variables for day of the week, day of the month, week of the year, month of the year, quarter of the year, and year, as well as interactions between week of the year and years and day of the week and months. Standard errors clustered at the city level appear in parentheses. Significance values: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

5.3. Robustness checks

In this section, we provide some robustness checks to corroborate our baseline results. For this purpose, Table 4 reports other RDiT-OLS results by repeating our main estimation model for different specifications. The first specification (Panel A) includes standard errors clustered at the 5-week level within cities to take into account serial correlation. The second specification (Panel B) consists of a restricted sample that excludes all observations for the year 2020 where the severity of the COVID-19 pandemic significantly changed the mobility patterns of commuters. The third specification (Panel C) adopts a nonparametric estimation.

The rationale for the latter is that our main identification strategy consists of a global parametric approach that implicitly departs from local randomisation by including observations that are far away from the cut-off determined by the implementation date of the PTD policy. Indeed, they are needed to credibly control for seasonal patterns. We further check the robustness of the results obtained in Table 3 by estimating the local estimation of the treatment effect within a closer bandwidth around the implementation date using a local linear regression on the residualised daily median pollutant concentration levels, in line with the methodology discussed in Lee and Lemieux (2010). More specifically, we construct the residualised outcome variables by estimating a model for each pollutant that includes all covariates described in Equation 2 except the treatment variable and the polynomial time trend.

Then, we subtract the prediction of such models from the original outcome variables to keep the variability unexplained by the included confounder factors. By doing so, we explicitly incorporate the bias in the distributional approximation introduced by the nonparametric approach

Table 4: Effect of the PTD policy on pollutants' concentration levels: RDiT-OLS with alternative specifications

Model:	PM_{10}	NO_2	SO_2	O_3
	RDiT-OLS (1)	RDiT-OLS (2)	RDiT-OLS (3)	RDiT-OLS (4)
<i>Panel A: alternative standard errors</i>				
PTD Policy	0.014 (0.071)	-0.062 (0.077)	0.102 (0.081)	-0.063 (0.048)
Observations	30 121	30 121	30 121	30 121
R^2	0.48	0.57	0.07	0.56
<i>Panel B: restricted time window</i>				
PTD Policy	0.044 (0.066)	0.009 (0.085)	0.119 (0.084)	-0.032 (0.062)
Observations	22 515	22 515	22 515	22 515
R^2	0.49	0.55	0.07	0.57
<i>Panel C: local linear regression on the residualized outcomes</i>				
PTD policy	-0.014 (0.045)	-0.050 (0.055)	0.001 (0.060)	-0.022 (0.036)
Observations	30 121	30 121	30 121	30 121
No-treated Treated	820 834	711 731	908 917	711 731
Optimal bandwidth (days)	39.56	34.26	43.89	34.42
Robust p-value	0.75	0.36	0.99	0.53
Calima	Yes	No	No	No
Biomass combustion	Yes	No	No	No
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes

Notes: The table reports estimates from 12 separate RDiT-OLS regressions fitting Equation 2. The unit of observation is the daily median. The dependent variables are the pollutants' concentration levels in logs, where PM_{10} is particulate matter, NO_2 is nitrogen dioxide, SO_2 is sulfur dioxide, and O_3 is ground-level ozone. Specifications also include a third-order polynomial time trend, as well as current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, plus the average number of measurements recorded by the monitoring stations. Time fixed effects include indicator variables for day of the week, day of the month, week of the year, month of the year, quarter of the year, and year, as well as interactions between week of the year and years and day of the week and months. In Panel A, the sample for all regressions extends from January 1, 2019, to December 31, 2022, and standard errors clustered at the 5-week level within cities appear in parentheses. In Panel B, observations for the year 2020 are excluded for all regressions, and standard errors clustered at the city level appear in parentheses. In Panel C, coefficients report the local estimations of the treatment effect using a local linear regression on the residualised daily median pollutants' concentration levels with a uniform kernel; estimates are computed using the data-driven MSE optimal bandwidth choice and robust bias-corrected statistics proposed in Calonico et al. (2018, 2022). Significance values: ***p<0.01, **p<0.05, *p<0.10.

near the cut-off under a data-driven mean squared error (MSE) optimal bandwidth choice, and we report the estimates using a uniform kernel with robust bias-corrected statistics, as proposed in Calonico et al. (2018, 2022).

Overall, the results across the three panels are consistent with our baseline estimates and provide no evidence that the PTD policy has improved daily median pollution concentration levels. Moreover, note that the results in Panel C are robust to alternative specifications using zero and quadratic polynomial time trends, as well as to specifications using different bandwidths set arbitrarily.

Additionally, we are aware that a possible threat to our identification strategy is the potential

dynamic effect of the measure we are analysing. If travellers changed their behaviour anticipating the PTD policy or if its impact built up or faded out after the implementation date, our estimates would be biased. However, any anticipation effect is unlikely as transit discounts were not effective until the implementation date, making hard for travellers to adapt in the absence of the cost reduction. Dynamic effects could potentially occur if commuters had changed their travel behavior at any point during the four-month period of validity of the voucher, but the uncertainty associated with the long-term duration of the policy made such postpone decisions less likely to occur. In any case, to assess the magnitude of this potential issue, we visually inspect the relationship between the residualised daily median pollutant concentration levels (as described in the previous paragraph) and the running variable (i.e., time) in a symmetric time window (i.e., within four months before and after the implementation date). Figures 3a–3d suggest that during this eight months time span, there are no clear dynamic patterns in the variability of pollutant concentration levels not explained by the confounding factors included in our empirical model, which limits the concerns about this possible source of bias.¹⁷

Finally, we also acknowledge that the policy timing might bias our estimates if the sharp change in the cost of ridership that occurred on September 1, 2022 interacts with other factors determining ridership (and air pollution) levels over time, making the expected discontinuity either grow or shrink over time by other factors rather than the evaluated policy. Given that Figure 1 shows how the PTD policy was introduced around the end of the summer holiday period, we gathered descriptive evidence on potential year-to-year changes in holiday patterns to check whether the distribution of vacations changed in Spain after the COVID-19 pandemic. Based on a survey on the tourist behavior of Spanish residents, we see no year-to-year differences in the way residents allocate their summer holidays despite the behavioral and work changes induced by the aforementioned pandemic¹⁸.

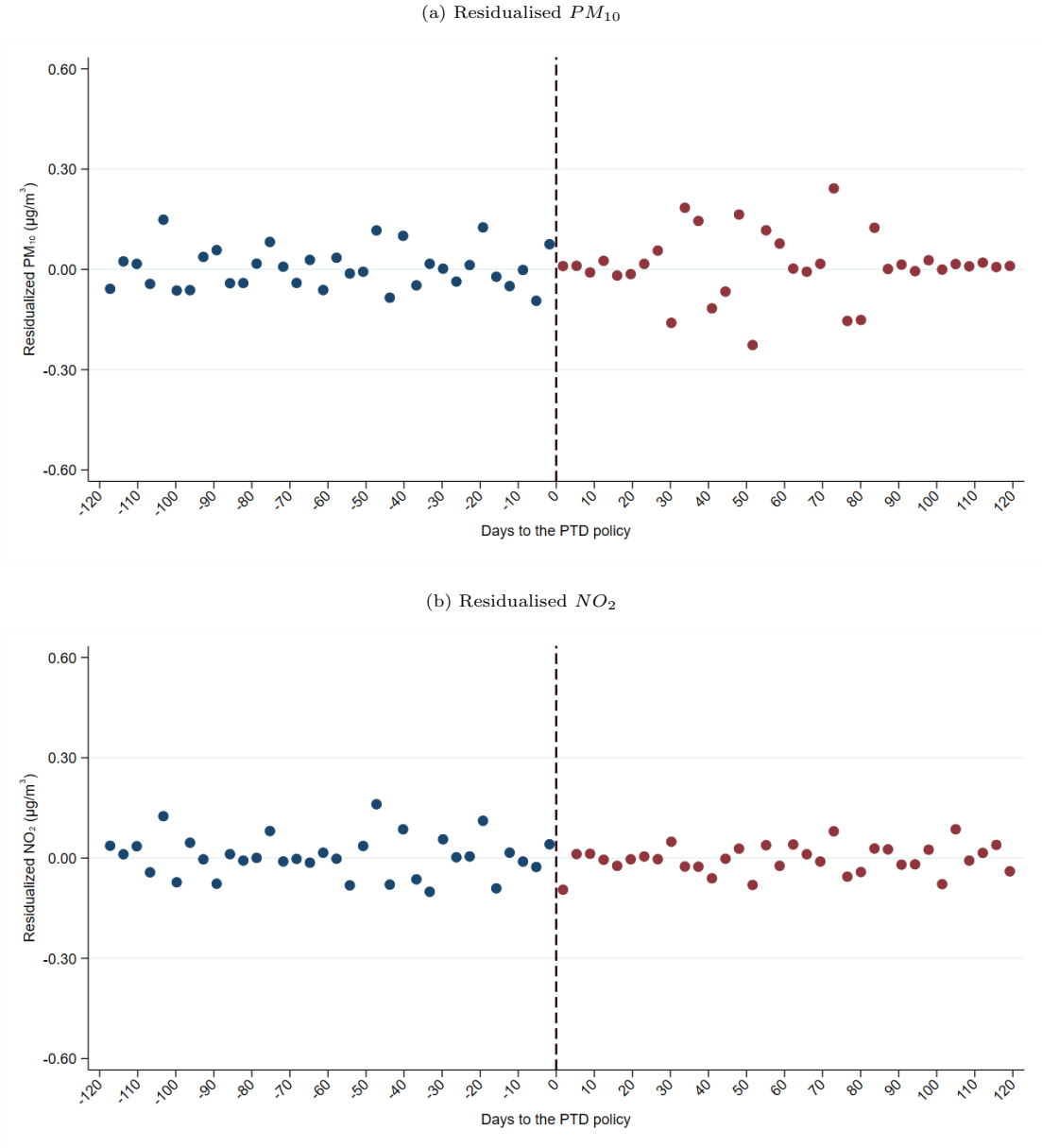
6. Mechanisms and discussion

As discussed throughout the paper, the mechanism underlying our research question is that the increased accessibility in transit ridership thanks to massive public transport fare discounts should induce a modal shift from private modes of transport and, consequently, improve the air quality. Given that our estimates provide no evidence that the PTD policy has reduced pollutant concentration levels, it appears that this measure has been unable to induce the aforementioned modal shift. Although the absence of granular data does not allow us to test the impact of this policy directly on road traffic, we run a simple regression of monthly ridership figures at the national level (i.e., the ones used to plot Figure 1) for the different railway services affected by

¹⁷Moreover, note that the transit industry applies a rule of thumb for the ramp-up in demand after transport service improvements equal to three months, which is within the period of our analysis.

¹⁸For further details, see the publications available online at the following: <https://www.ine.es/daco/daco42/etr/etr0322.pdf>. As an additional robustness check, we estimated Equation 2 by adding an interaction between a September 1, 2022 dummy variable and a year trend. We find no substantial deviations from our baseline estimates.

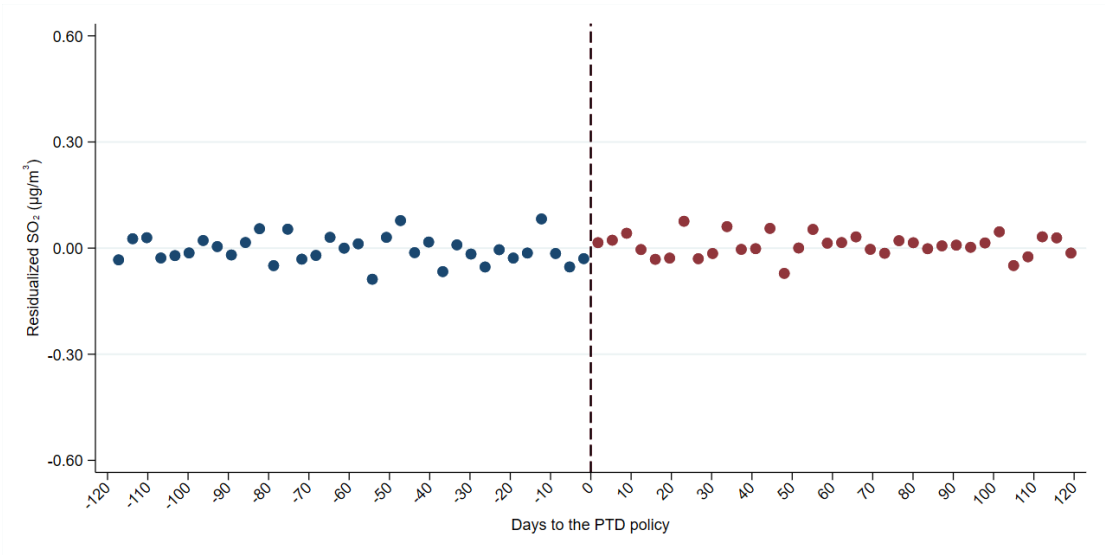
Figure 3: Plot of the residualised daily median pollutants' concentration levels, May–December 2022



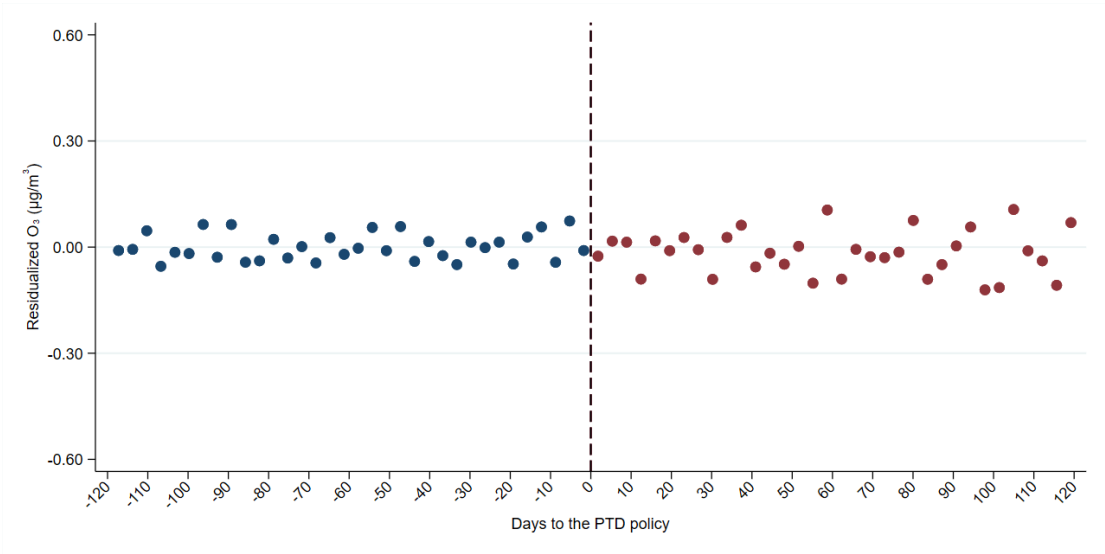
Notes: The residualised daily median pollutants' concentration levels are in log. Source: Authors' own elaboration.

Figure 3: Plot of the residualised daily median pollutants' concentration levels, May–December 2022

(c) Residualised SO_2



(d) Residualised O_3



Notes: The residualised daily median pollutants' concentration levels are in log. Source: Authors' own elaboration.

400 the PTD policy against the treatment variable and both month and year fixed effects to assess the average difference in ridership values before and after the implementation of the policy.

Consistent with the evidence provided by MITMA (2023), Table 5 shows a statistically nonsignificant increase in public transportation use for short-distance railway services (either for the cities of Madrid and Barcelona when considered individually), while it shows a 29.1% increase for medium-distance railway services operated by conventional trains¹⁹. This confirms
405 that the PTD policy may have concentrated its impact on medium-distance railway services only, which represent a very limited share of trips compared to the bulk of mobility that occurs within metropolitan areas. Hence, the policy may have made a slim contribution to improving the air quality.

Table 5: Correlation between the PTD policy and ridership: OLS

	Passengers		
	Short-distance	Medium-distance (conventional)	Medium-distance (high-speed)
Model:	OLS (1)	OLS (2)	OLS (3)
PTD Policy	0.052 (0.133)	0.291* (0.161)	0.090 (0.251)
Month FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	48	48	48
R^2	0.58	0.64	0.60

Notes: The table reports estimates from 3 separate regressions by OLS. The unit of observation is the month and the sample for all regressions is from January 2019 to December 2022. The dependent variables are the number of passengers (in logs) carried by i) short-distance, ii) medium-distance (conventional) and iii) medium-distance (high-speed) railway services. Robust standard errors appear in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

410 It is important to clearly state what might be driving such outcomes. Public transport fare demand elasticity roughly moves in the range between -0.2 and -0.75 in the short run, which implies an inelastic demand, as fare reductions would increase ridership less than proportionally to the fare change made (Matas, 2004; Holmgren, 2007). In addition, car usage across elasticity to public transport fares is close to zero, which implies that changes in transit fares would only
415 marginally attract car users (Asensio, 2002). This is in line with evidence showing that ridership growth under massive public transport fare discount schemes develops mainly from i) travellers shifting away from other slower or low-cost transportation modes (such as walking and cycling) and ii) induced demand, rather than from travellers shifting away from their cars (Fearnley, 2013).

420 Supporting this argument, the results of a travel survey that was recently made available and focused on the metropolitan area of Barcelona shows that only 1.2% of respondents switched to

¹⁹Unfortunately, *Renfe* has not been able to fulfil our request for passenger data at the daily and city levels that are needed for a proper causal analysis of the PTD policy on ridership.

public transport after the implementation of the PTD policy, and only 8.4% of them increased transit usage (EMEF, 2023). By monitoring car access in the Catalan capital, the level of traffic reduction has been almost imperceptible from September 2022 onwards²⁰

425 Thus, it seems unlikely that the PTD policy has led to a sizable modal shift in favour of short-distance transit trips, while it might have led to such a shift in favour of medium-distance transit trips for which the monetary cost is more relevant than the travel time. In short, even though an upward trend in ridership figures exists, it is hardly coming from a significant volume of users shifting away from their cars.

430 In contrast with the results obtained by Aydin and Kürschner Rauck (2023); Gohl and Schrauth (2022); Yang and Tang (2018), our empirical analysis does not support the positive relation between transit fares and air quality. Compared to these works, we believe that our regression discontinuity in time approach is much more effective than other methods in detecting the causal effect of public transportation fare subsidies on air quality because all the monitoring stations are affected by the policy²¹. We believe that including this identification strategy in these previous works would corroborate the validity of their differences-in-differences methods and could shed light on the potential biases introduced by the previous issue. In any case, differences in the methodologies, policy designs, and characteristics of the transport system make it difficult to discuss the divergences across studies, which opens up interesting lines of further research.

7. Conclusions

Within urban areas, automobile pollution poses significant negative effects on human health. With the aim of reducing vehicle traffic and improving air quality, policy-makers are promoting more sustainable transport modes by—for instance—reducing the monetary cost of public transport. However, little is known about the air pollution effects of such measures. This paper seeks to fill this gap by quantifying the impact of public transportation low-cost or free-of-charge financing schemes on air quality by taking advantage of a four-month period during which massive discounts (starting on September 1, 2022) were applied to transit fares in Spain.

450 By exploiting the sharp discontinuity in the cost of ridership that occurred on the implementation day of the policy through a regression discontinuity in time approach, our analysis provides no evidence that the PTD policy has reduced the concentration levels of any pollutant examined. Hence, our results suggest that measures aimed at reducing transit prices may fail to either induce a significant modal shift from private to collective modes of transport or yield environmental benefits that are worth the use of public funds.

²⁰For further details, see the articles by Dani Cordero on *La Vanguardia* (available online at the following: <https://elpais.com/espana/catalunya/2022-10-10/la-gratuidad-de-rodalies-deja-indiferente-a-los-conductores.html>) and David Guerrero on *La Vanguardia* (available online at the following: <https://www.lavanguardia.com/local/catalunya/20230210/8746626/usuarios-transporte-publico-iba-coche-gratuidad.html>).

²¹Particularly when potential dynamic effects are ruled out, as discussed in Section 5.3

455 If we compare the PTD policy outcomes with those obtained by public transport supply-
oriented interventions in the available literature, it becomes clear that the latter are much
more effective in tackling the air pollution issue. Our results have a high policy relevance, as
we show that the often-claimed positive relationship between transit fares and air pollution
460 does not necessarily broadly apply. In light of our results, it seems fair to conclude that heavily
subsidised public transportation fares might not represent an efficient use of resources to address
air quality in urban environments.

From an overall policy analysis perspective, it is important to mention the other objectives
of the PTD policy. As a pure transfer between agents in the society with no effect on welfare,
the other main goal of the evaluated policy was to mitigate inflationary pressures related to the
465 economic consequences of the *Russo-Ukrainian War* and, consequently, increase households'
disposable income. Therefore, while any equity evaluation is beyond the scope of this paper, the
PTD policy may have effectively addressed the rising cost of living through an economic relief
to low-income travellers, who are more used to rely on public transportation.

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Declaration of interest

475 We have no conflicts of interest to disclose.

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Appendices

Appendix A Additional Tables

Table A.1: List of cities

City
<i>Barcelona</i>
<i>Bilbao</i>
<i>Burgos</i>
<i>Castellón de la Plana</i>
<i>Córdoba</i>
<i>Granada</i>
<i>Huelva</i>
<i>Palmas de Gran Canaria</i>
<i>Madrid</i>
<i>Murcia</i>
<i>Málaga</i>
<i>Oviedo</i>
<i>Palma</i>
<i>Pamplona</i>
<i>Salamanca</i>
<i>San Sebastián</i>
<i>Santa Cruz de Tenerife</i>
<i>Santander</i>
<i>Sevilla</i>
<i>Valencia</i>
<i>Valladolid</i>
<i>Vitoria</i>
<i>Zaragoza</i>

Table A.2: Effect of the PTD policy on pollutants' concentration levels: RDiT-OLS with alternative polynomials

Model:	PM_{10}	NO_2	SO_2	O_3
	RDiT-OLS (1)	RDiT-OLS (2)	RDiT-OLS (3)	RDiT-OLS (4)
<i>Panel A: 1st-order polynomial</i>				
PTD policy	0.020 (0.069)	-0.085 (0.080)	0.093 (0.077)	-0.074 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21721	20329	28462	16943
BIC	21945	20570	28703	17184
<i>Panel B: 2nd-order polynomial</i>				
PTD policy	0.024 (0.069)	-0.050 (0.081)	0.101 (0.080)	-0.066 (0.050)
R^2	0.48	0.57	0.07	0.56
AIC	21726	20296	28455	16944
BIC	21976	20529	28671	17193
<i>Panel C: 3rd-order polynomial (baseline estimates)</i>				
PTD policy	0.014 (0.069)	-0.062 (0.080)	0.102 (0.080)	-0.063 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21719	20290	28457	16935
BIC	21960	20540	28681	17151
<i>Panel D: 4th-order polynomial</i>				
PTD policy	0.014 (0.069)	-0.061 (0.080)	0.103 (0.080)	-0.063 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21723	20289	28453	16940
BIC	21980	20547	28677	17181
<i>Panel E: 5th-order polynomial</i>				
PTD policy	0.013 (0.069)	-0.062 (0.080)	0.102 (0.079)	-0.063 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21712	20276	28454	16944
BIC	21937	20492	28687	17201
Calima	Yes	No	No	No
Biomass combustion	Yes	No	No	No
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	30 121	30 121	30 121	30 121

Notes: The table reports estimates from 20 separate RDiT-OLS regressions fitting Equation 2. The unit of observation is the daily median, and the sample for all regressions extends from January 1, 2019, to December 31, 2022. The dependent variables are the pollutants' concentration levels in logs, where PM_{10} is particulate matter, NO_2 is nitrogen dioxide, SO_2 is sulfur dioxide, and O_3 is ground-level ozone. According to the different panels, specifications also include a 1st-, 2nd-, 3rd-, 4th-, or 5th-order polynomial time trend, as well as current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, plus the average number of measurements recorded by the monitoring stations. Time fixed effects include indicator variables for day of the week, day of the month, week of the year, month of the year, quarter of the year, and year, as well as interactions between week of the year and years and day of the week and months. Standard errors clustered at the city level appear in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

Table A.3: Effect of the PTD policy on pollutants' concentration levels: RDiT-OLS with alternative polynomials interacted with the PTD policy

Model:	PM_{10}	NO_2	SO_2	O_3
	RDiT-OLS (1)	RDiT-OLS (2)	RDiT-OLS (3)	RDiT-OLS (4)
<i>Panel A: 1st-order polynomial $\times T$</i>				
PTD Policy	0.021 (0.069)	-0.085 (0.081)	0.092 (0.077)	-0.074 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21719	20325	28458	16942
BIC	21943	20549	28691	17183
<i>Panel B: 2nd-order polynomial $\times T$</i>				
PTD Policy	0.033 (0.067)	-0.039 (0.082)	0.096 (0.081)	-0.068 (0.049)
R^2	0.48	0.57	0.07	0.56
AIC	21730	20286	28458	16934
BIC	22012	20511	28691	17151
<i>Panel C: 3rd-order polynomial $\times T$</i>				
PTD Policy	0.024 (0.065)	-0.051 (0.080)	0.093 (0.081)	-0.068 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21722	20281	28458	16929
BIC	21988	20506	28690	17195
<i>Panel D: 4th-order polynomial $\times T$</i>				
PTD Policy	0.034 (0.063)	-0.033 (0.082)	0.103 (0.080)	-0.046 (0.051)
R^2	0.48	0.57	0.07	0.56
AIC	21713	20272	28453	16914
BIC	21945	20529	28677	17155
<i>Panel E: 5th-order polynomial $\times T$</i>				
PTD Policy	0.023 (0.063)	-0.018 (0.081)	0.097 (0.076)	-0.031 (0.057)
R^2	0.48	0.57	0.07	0.56
AIC	21714	20264	28454	16907
BIC	21955	20496	28696	17123
Calima	Yes	No	No	No
Biomass combustion	Yes	No	No	No
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	30 121	30 121	30 121	30 121

Notes: The table reports estimates from 20 separate RDiT-OLS regressions fitting Equation 2. The unit of observation is the daily median, and the sample for all regressions extends from January 1, 2019, to December 31, 2022. The dependent variables are the pollutants' concentration levels in logs, where PM_{10} is particulate matter, NO_2 is nitrogen dioxide, SO_2 is sulfur dioxide, and O_3 is ground-level ozone. According to the different panels, specifications also include a 1st-, 2nd-, 3rd-, 4th-, or 5th-order polynomial time trend interacted with the PTD policy, as well as current and 1-day lags of quartics in temperature, atmospheric pressure, humidity, and wind speed, plus the average number of measurements recorded by the monitoring stations. Time fixed effects include indicator variables for day of the week, day of the month, week of the year, month of the year, quarter of the year, and year, as well as interactions between week of the year and years and day of the week and months. Standard errors clustered at the city level appear in parentheses. Significance values: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Appendix B Additional Figures

Figure B.1: Map of short- and medium-distance railway services affected by the PTD policy



Notes: The yellow areas show the operational radius of short-distance railway services. The medium-distance connections operated by high-speed railway services are *Madrid—Segovia—Valladolid*, *Madrid—Ciudad Real—Puertollano*, *Madrid—Toledo*, *Salamanca—Segovia—Madrid*, *Albacete—Cuenca—Madrid*, *Barcelona—Tarragona—Lleida*, *Barcelona—Girona*, *Barcelona—Figueres Vilafant*, *Valencia—Requena Utiel*, *Calatayud—Zaragoza*, *Málaga—Córdoba—Sevilla*, *Granada—Málaga*, *Granada—Córdoba—Sevilla*, *Ourense—Santiago—A Coruña*. Source: Wikipedia.