# Pricing Congestion to Increase Traffic: The Case of Bogotá

Juan-Pablo Montero, Felipe Sepúlveda, and Leonardo J. Basso*

June 28, 2023

**Abstract**

In September 2020, the city of Bogotá introduced a major market-based reform to its odd-even driving restriction, better known as *Pico y Placa*. Drivers now have the option to pay a daily fee to be exempted from the restriction. Despite the increase in traffic—a 9% drop in average speed—we find substantial welfare gains from the reform, US$222 million per year. An important fraction of these gains—31%—comes from simply "abolishing" the restriction, i.e., setting the exemption fee equal to zero; the rest from setting a strictly positive fee, US$9 per day. The big winners of the reform are middle-income individuals who now use their cars more often (their gains amount to US$759 million), whereas the big losers are high-income individuals who now spend more time in traffic (their losses amount to US$506 million).

**Keywords**: congestion, driving restrictions, road pricing, air quality

**JEL Classification**: H23, L62, R41, R48, Q53.

*Montero (jmontero@uc.cl): Department of Economics, Pontificia Universidad Católica de Chile, and Sistemas Complejos de Ingeniería (ISCI); Sepúlveda (fasepu@ubc.ca): Department of Economics, University of British Columbia; and Basso (lbasso@ing.uchile.cl): Civil Engineering Department, Universidad de Chile, and ISCI. We are grateful to Laura Alvarez, Patrick Behrer, Marcelo Caffera, Agustina Calatayud, Germán Escovar, Carolyn Fischer, Andrés Gómez-Lobo, Josh Graff Zivin, Tomás Rau, Tomás Serebrisky, as well as seminar participants at different venues for many useful comments, to Dominga Selman and Sebastian Figari for superb research assistance, and to the Inter-American Development Bank (IADB) for financial and technical support, in particular for giving us access to the Waze database used in the empirical analysis. The opinions expressed in the paper, however, are not necessarily shared by the IADB. Montero also thanks financial support from the Chair Energy and Prosperity at Fondation du Risque.

## 1 Introduction

Congestion remains a serious problem in many cities around the world. According to the INRIX Global Traffic Scorecard, the city of Bogotá led the pre-covid-19 ranking of the most congested cities in the world, with 192 hours per capita lost in heavy traffic in 2019. It was followed closely by Rio de Janeiro, Mexico City, Istanbul, Sao Paulo and Rome. Chicago closed the top-10 list with 145 hours lost in congested roads.[1] Unfortunately, when authorities have decided to deal with this externality, they have rarely turned to pricing schemes.[2] Instead, they increasingly rely on rationing schemes, better known as driving restrictions or license-plate bans.

One of the most stringent driving restrictions today is precisely found in Bogotá, where restrictions were first introduced in 1998.[3] Since 2012 Bogota's driving restriction, better known as *Pico y Placa*, bans from circulation the vast majority of residential and commercial vehicles every other day of the week (excluding weekends) from 6:00 a.m. to 8:30 a.m. and then from 3:00 p.m. to 7:30 p.m. Buses, police cars, ambulances, fire trucks, government and diplomatic vehicles, school buses and vans, and electric and hybrid vehicles are exempt. To decide which half of the fleet is restricted in any given day, the program follows an odd-even schedule based on the last digit of the vehicle's license plate.[4] Compliance with the restriction is effectively enforced with a combination of different measures.[5]

These type of restrictions—which treat all cars the same—have been widely criticized for the perverse incentives they create on drivers to buy additional (often older and more polluting) vehicles, not only increasing the fleet size but also moving its composition toward higher-emitting vehicles, resulting in more congestion and pollution. The best documented evidence supporting this claim comes from Mexico City's *Hoy No Circula* program, as implemented in 1989 (e.g., Eskeland and Feyioglu 1997, Davis 2008, Gallego et al. 2013). In response not only to this "second-car" concern but also to help finance the public transport system, Bogotá's transport authority introduced a major reform to its *Pico y Placa* program in September 2020: since then drivers have the option to pay a fee to be exempted from the restriction, with the

[1]See https://inrix.com/scorecard/ for details on the rankings construction. In its November 23th 2021's edition, La Republica (https://www.larepublica.co/), Colombia's main business newspaper, also reports Bogotá as the "most congested city in the world."

[2]Notable exceptions include London, Stockholm, Singapore, Milan, and Gothenburg. Plans to introduce congestion pricing in New York City has been postponed until the end of 2023. For more see Baranzini et al (2021) and Calatayud et al (2021).

[3]Other restriction programs include, for example, Athens (where restrictions were first introduced in 1982), Santiago (1986), Mexico City (1989), Teheran (1991), São Paulo (1996), Manila (1996), Cali (2002), La Paz (2002), Medellín (2005), Beijing (2008), Tianjin (2008), several German cities (2008), Quito (2010), Hangzhou (2011), Chengdu (2012), Paris (2016), and Madrid (2019).

[4]Although much of our analysis covers up to December 2021, it is important to mention that the program has suffered some modifications after that. Since January 2022 the restriction runs uninterrupted from 6:00 a.m. to 9:00 p.m. and since January 2023 it no longer follows an odd-even schedule but a sequential one (e.g., plates ending in 1, 2,..., or 5 are restricted one day and those ending in 6, 7,..., or 0 are restricted the next, and so on).

[5]It includes a ground force of more than 1000 agents (divided between police patrols and city officials), a network of more than 200 traffic cameras, high penalties, and confiscation of the vehicle when caught in non-compliance by a ground agent. More details can be found in a series of district decrees (decretos distritales in Spanish), in particular, Decreto 575 (2013), Decreto 515 (2016), Decreto 846 (2019) and Decreto 208 (2020). These decrees are avaible at https://bogota.gov.co.

entire fee collection going to public transport.

Of all the possible variations on a driving restriction policy one might think of, the introduction of an exemption fee represents a radical departure from early designs. By allowing drivers to bypass the restriction not by purchasing a second car but by paying an exemption fee, driving restrictions with exemption fees have the potential not only to restore many socially valuable trips that were inefficiently rationed by the restriction in the first place but also to make drivers face the external cost of at least some of their trips.[6] Because the restoration of valuable trips comes at the cost of increasing traffic, the introduction of an exemption fee presents authorities with a clear tradeoff—increasing traffic vs. restoring valuable trips—that can be resolved differently for different income groups. Using Bogotá's 2020 reform as evidence, the objective of this paper is to study this tradeoff, both overall and for each income group in particular.

We initiate our analysis in Section 2 with a brief description of *Pico y Placa*'s recent history and its 2020 reform to continue with an empirical evaluation of the impact of the reform on traffic, for which we use a large Waze database including not only vehicle speed data from Bogotá but also from Medellín—Colombia's second largest city—which serves as control.[7] Our difference-in-differences estimates suggest a statistically significant increase in traffic due to the reform: a drop in city-level speed of about 9%.

Since at the time of the reform many drivers were expected to pay the exemption fee, this increase in traffic should not come as a surprise. Some may interpret this as the inevitable short-run sacrifice needed to finance and improve public transit. Doing so, the story goes, drivers could be persuaded to give up their cars in favor of public transit and attain a substantial reduction in congestion in the future. To others, the introduction of an exemption fee into an existing restriction program could facilitate the extension of the restriction, in digits and/or daily hours of application, to eventually replicate a standard congestion-pricing scheme, where car owners must pay a congestion fee whenever they use their cars.[8]

The main contribution of this paper is to show that there is no such short-run sacrifice, quite the contrary. A motivating piece of evidence supporting this conclusion comes from a simple model of homogeneous drivers developed in Section 3. If one views a driving restriction without an exemption fee as equivalent to proportional rationing,[9] where any car trip is equally likely to be rationed, an "unpleasant" result may emerge (Proposition 2): drivers may end up worse off with a restriction with no exemption fees unless congestion costs are sufficiently high. Our application to Bogotá confirms this unpleasant result: the gains from faster travel in days

[6]In the limit, when the introduction of the exemption fee is accompanied by an extension of the restriction to every hour of the day and day of the week, we converge to a full-fledged road pricing scheme.

[7]Salgado and Mitnik (2022) is another attempt at using Waze data to study traffic. There are also similar studies using Google Maps, for example, Hanna et al (2017), Akbar and Duranton (2018), and Akbar et al (2023).

[8]This seems to be Bogota's authorities ultimate goal (personal communication with Nicolás Estupiñán, Chief of Bogotá's Transport Authority, May 20th 2021). See also Secretaría Distrital de Movilidad de Bogotá (BMDS 2021), Segunda fase del permiso especial de acceso a áreas de restricción vehicular", August 2021.

[9]This view is also adopted by Barahona et al (2020). Proportional rationing contrasts with efficient rationing, which is the way a congestion charge works. See Tirole (1989) for more on different rationing rules.

of no restriction are not enough to compensate for the lost of socially valuable trips in days of restriction.

There is a fix to this unpleasant result, however, which is what Bogotá did in September 2020: to allow drivers to pay a (congestion) fee that exempts them from the restriction. Despite the increase in traffic, the exemption fee restores those socially valuable car trips that were inefficiently rationed in the first place. This is shown to be welfare enhancing (Proposition 4).[10]

Motivated by these theoretical results, in Section 4 we extend the model to a group of heterogeneous commuters with varying preferences for transport modes (private vs public transport) and remote working. The model is then calibrated to capture Bogotá's transport reality before the reform, in particular, the share between public and private transport and the demand for remote work.

The calibrated model is used in Section 5 to evaluate the welfare and distributional implications of the reform. Consistent with Proposition 4, we find substantial overall welfare gains from the reform, $222 million a year (the currency used throughout the paper is 2020 U.S. dollars).[11] An important fraction of these gains, 31%, corresponds to undoing the unpleasant result in Proposition 2, i.e., to hypothetically setting the exemption fee equal to zero (equivalent to abolish the restriction). The remaining 69% corresponds to the gains from raising the exemption fee from zero to its current level, $8.8 per day on average. Interestingly, and after accounting for the likely increase in remote work relative to its pre-covid-19 level, our model predicts an optimal exemption fee of around $15, not too far from the existing fee.[12]

When it comes to evaluate the impact of the reform across different income groups we find major differences. The big winners of the reform are middle-income individuals who now use their cars more often, restoring many of their socially valuable trips that before were rationed. Their gains amount to $759 million a year.

By contrast, the big losers of the reform are high-income individuals who now spend more time in traffic; their losses amount to $506 million. There are two reasons that explain these large losses. One is that many high-income individuals have access to more than one car, so they have more easily accommodated to the restrictions before the reform. And a second, closely related reason is that these individuals have greater access to remote work. Imagine an individual who faces a week with two days of restriction. He or she could completely prevent

[10] Bogotá initiated its reform in September 2020 with a lump-sum exemption fee, when drivers had only the option to purchase a six-month pass, and then, in September 2021, switched closer to a per-trip exemption fee, when drivers were also offered the option to purchase a daily pass. Although our empirical analysis focus on the impact of the reform from September 2021 onward, our motivating theory also serves to show that a per-trip fee (Proposition 4) is highly superior to a lump-sum exemption fee (Proposition 3).

[11] Following Bogotá's current practice, the entire fee collection is returned back to the public transport system. In our model, this is done in the form of lower public transit fares relative to the ones before the reform. If instead the entire fee collection were returned back to individuals in a lump-sum fashion, while preventing transfers across income groups, the gains would drop somewhat, to $179 million a year. In either case, the gain is equivalent to 20% of today's yearly budget that the city of Bogotá allocates to public transport.

[12] There are significant additional welfare gains to be made if the authority decides to extend the restriction to replicate a standard congestion-pricing scheme—an everyday restriction with the option to pay an exemption fee. If the congestion fee is set at its optimal level of $22, these additional welfare gains amount to $912 million per year.

the destruction of valuable car trips by combining the use of a second car to cope with one of the days of restriction and the work from home to cope with the other. For this individual the reform can only have a detrimental effect from the resulting heavier traffic.[13]

We are certainly not the first to study the impact of driving restrictions (including low emission zones) whether on traffic, air pollution, crime activity, fleet size and composition, consumer spending, or consumer welfare (see, e.g., Eskeland and Feyzioglu 1997, Davis 2006, Gallego et al 2013, Wolff 2014, Viard and Fu 2015, Zhang et al 2017, Blackman et al 2018, Carillo et al 2018, Bonilla 2019, Barahona et al 2020, Salgado and Mitnik 2022, Galdon-Sanchez et al 2023). We are the first, however, to look at the impact of introducing an exemption fee into an existing restriction program.[14] Despite the large number of existing restriction programs, Bogotá is one of the only two programs where exemption fees have been introduced. The other is Cali, also in Colombia.

This unusually low use of exemption fees is unfortunate but perhaps not surprising. It may be in part explained by the resulting increase in traffic. Here is where Bogotá's reform provides such a valuable policy lesson: despite the increase in traffic, exemption fees can always be made welfare enhancing. This is in addition to other benefits such as the possibility of raising extra funds for the public transport system or paving the way toward a full-fledged congestion-pricing scheme in the future.[15]

Natural candidates for the evaluation (and eventual introduction) of these exemption fees include a long list of existing programs, notably *Hoy no Circula* in Mexico City and *Rodízio* in São Paulo. In a similar vein, Bogotá's reform should also serve to call the attention of any authority considering the introduction of a restriction policy to fight traffic, as it is currently the case in Lima and Santiago. Absent of an exemption fee, no restriction may better than any restriction.[16]

The rest of the paper is organized as follows. Section 2 contains the empirical analysis. Theory results are in Section 3. The extension of the theory model to capture Bogotá's transport reality is in Section 4. The impact of the reform on different dimensions—traffic, overall welfare, equity, and air quality—are studied in Section 5. We extend the analysis in different directions (e.g., alternative uses of the fee collection, moving toward a full congestion-pricing scheme, considering higher levels of remote work, etc.) in Section 6. We conclude in Section 7. Additional results are collected in the Appendix.

[13] At the end of Section 5 we also discuss the impacts of the reform on air quality. Using information on pollution harm from SDG (2018), we estimate an increase in pollution costs of $31.2 million a year. As shown in Section 6, however, if the authority were to extend the restriction to replicate a standard congestion-pricing scheme, these changes in pollution would reverse and turn into pollution benefits.

[14] Daganzo (2000) and Basso et al (2021) also discuss, but at a more theoretical level, the potential benefits of restriction policies with exemption fees.

[15] If the increase in pollution is also a concern, one could follow the vintage exemptions in Barahona et al (2020) and make the exemption fee available only to cars with pollution rates below certain threshold or, alternatively, increase its price accordingly for the more polluting cars.

[16] Again, if the aim is primarily to fight air pollution, the restriction may abstract from the exemption fee but follow a vintage-specific design, as discussed by Barahona et al (2020).

## 2 Bogotá's Market-Based Reform

In this section we first briefly explain the evolution of Bogota's *Pico y Placa* and then offer an empirical evaluation of the impact of the reform on traffic.

### 2.1 Bogotá's *Pico y Placa*

Bogotá, Colombia's capital and home to more than 7 million people, has long suffered congestion problems. In response, it introduced in August 1998 a restriction program, better known as *Pico y Placa*, that placed a circulation ban on 20% of the fleet each day of the week (excluding weekends) from 7:00 a.m. to 9:00 a.m. and then from 5:30 p.m. to 7:30 p.m. Over the years *Pico y Placa* has gone through some modifications looking to extend its scope, in particular, with regard to the number of cars restricted on a single day. Since July 2012, *Pico y Placa* affects the vast mayority of residential and commercial vehicles every other day of the week (excluding weekends) from 6:00 a.m. to 8:30 a.m. and then from 3:00 p.m. to 7:30 p.m. Buses, police cars, ambulances, fire trucks, government and diplomatic vehicles, school buses and vans, and electric and hybrid vehicles are exempt. To decide which half of the fleet is restricted in any given day, the program follows an odd-even schedule based on the last digit of the vehicle's license plate.[17]

The 2012 design remained in place until March 19th 2020 when the authority ordered its complete suspension in response to the covid-19 pandemic. As the covid-19 crisis begun to recede, the program was reinstated in September 1st 2020 according to its 2012 design except for a major provision: the possibility to pay a congestion fee to be exempted from the restriction. At the time, the exemption fee made no distinction between different type of cars and, most importantly, was only available as a six-month pass. Both aspects of the 2020 reform were revised in September 1st 2021. Since then, exemption fees vary according to the car's characteristics—commercial value and pollution rate—and drivers have the flexibility to also pay them on a daily and monthly basis.

Probably, the six-month format as opposed to the daily format does not make much of a difference for drivers who are prepared to pay the exemption fee every time their cars are restricted. But for many others, those who are prepared to pay the fee only sporadically, say, once week, it does make a big difference. The six-month format comes closer a lump-sum fee while the daily format comes closer to a per-trip fee (it would be exactly a per-trip fee if cars were used exclusively for commuting purposes). Once the six-month pass is paid, it becomes a sunk investment that does not affect a driver's decision at the margin, i.e., as to whether use her or his car in a particular day. The distinction between these two formats has profound welfare implications. As we formally show in Section 3, a per-trip exemption fee is highly superior to a lump-sum exemption fee, so much that the latter may render useless in some contexts, even under homogeneous drivers.

[17] Although much of our analysis covers up to December 2021, it is important to mention that the program has suffered some modifications since then. See footnote 4.

Since September 2021, the exemption fee that applies to a particular car is the product of a base value, of about $8 per day, and a factor that increases with the commercial value of the car and its pollution rate, which weighs both local and global pollutants. Although this factor can be as high as 1.8 for some cars—for 0.1% of the fleet—the relevant factor for 92% of the fleet is 1.2 or less, leading to an average exemption fee of $8.8 per day. By April 2022, the first and only month for which we obtained detailed data from Bogotá's Mobility District Secretary, the total number of exemption fees issued by day in its different formats was anywhere between 25,291 and 60,692.[18]

## 2.2 The impact of the reform on traffic

For most cities, if not all, traffic after covid-19 did not returned to its pre-covid-19 level, even in the absence of any policy change. This is particularly true for the initial months following the crisis as cities gradually returned to their usual day-to-day activities. For this reason, we evaluate the impact of Bogota's reform on traffic following a Difference-in-differences approach that uses the city of Medellín as control.

Medellín, home to 2.6 million people, is the second largest city in Colombia. Despite their distance—a driving distance of 425 km—Medellín and Bogotá share similar trends in many aspects of economic activity, most importantly for our work, in traffic congestion. In fact, in February 2005 Medellín introduced its own *Pico y Placa* program, placing a circulation ban on 20% of the fleet each day of the week (excluding weekends) from 6:30 to 8:30 a.m. and then from 5:30 to 7:30 p.m. In August 2013, Medellín decided to extend its circulation ban to 40% of the fleet, while delaying its morning start in 30 min, to 7:00 am.

Medellín's program remained unaltered until March 19th 2020 when it was completely suspended in response to the covid-19 crisis. But unlike Bogotá, Medellín reinstated its *Pico y Placa* program not only a year later, in September 6th 2021, but more importantly without giving drivers the option to pay a congestion fee to be exempted from the restriction. The only difference with its 2013 design is that now the circulation ban applies to only 10% of the fleet, although during the entire working day, from 5:00 a.m. to 8:00 p.m. If anything, the 2021 design appears to be less restrictive than the pre-covid-19 design, so our results below may be an underestimation of the actual impact of Bogotá's reform on traffic.

In the rest of the paper we focus on the impact of the reform as of September 2021 onward. We do this not only because it captures the latest changes in Bogotá's reform but also because this is when the *Pico y Placa* programs in both cities were in operation once again, which is essential for our diff-in-diff estimation. In the rest of the section we first describe the data used in the analysis, then offer a justification for using Medellín as control, and finally present the empirical strategy and results.

[18] The available information only tells us that a particular license plate is associated to the payment of at least one exemption fee during the month, when in fact it could be associated to multiple payments during the month, up to 10 or 11 payments (the number of weekdays a car is restricted during a month).

### 2.2.1 Data

The data we use in our analysis comes from the Waze application, which collects speed data via the GPS signal of a driver's mobile device on which the application is installed.[19] We use data comprising the urban areas of Bogotá and Medellín from January 2019 through December 2021. Each city is divided into ZATs (*Zona de Análisis de Transporte* or Zone of Transport Analysis in English) and each ZAT includes several segments (e.g., streets, drives, avenues, etc) for which vehicle speeds are recorded. The city of Bogotá (or Bogotá D.C.) is made of 898 ZATs scattered in 20 counties and the city of Medellín is made of 342 ZATs scattered in 16 counties.[20]

Our unit of observation is the average speed at the ZAT level every 15-minute intervals. Because segments in each ZAT vary by length and whether they exhibit high levels of congestion at a given time interval, our unit of observation comes in four different formats: $\bar{v}_1$ is the average velocity or speed considering only highly-congested segments within the ZAT, and $\bar{v}_2$ is the average speed recorded on highly-congested segments but weighted by each segment's length. Analogously, $\bar{v}_3$ is the average speed of all segments, and $\bar{v}_4$ is the average speed of all segments but weighted by each segment's length. We are particularly interested in the results obtained from $\bar{v}_3$ and $\bar{v}_4$ since our analytical framework does not make any distinction between highly congested and less congested roads. It takes an aggregate view at the city level.

### 2.2.2 Medellín as control

There are good reasons that make Medellín a good control. As seen in Figure 1, one reason is that Medellín and Bogotá exhibit a similar evolution of income per-capita, an important driver of economic and traffic activity.[21]

Another reason is the parallel trend that we observe when estimating the following event-study model at the monthly level for each of the four speed formats separately:

$$y_{it} = \alpha + \sum_{j=2}^{20} \beta_j Lead_{jit} + \sum_{k=0}^{3} \gamma_k Lag_{kit} + \mu_i + \lambda_t + \varepsilon_{it}$$

The dependent variable $y_{it}$ is a city-level speed for city $i$ for a given at the hourly level in a given month. To construct it, we take the average of the natural logarithm of all ZAT records in a given format available in the city for each of the four hours between 6:00 and 10:00 a.m. of each weekday in any given month. As an example, our first observation would be the representative city-level speed in Bogotá for any Monday during the month of January 2019 from 6:00 am to 6:59 am. More generally, this would give us a total of 40 observations in each month, the

[19] According to the 2019 Bogotá's Mobility Survey (BMS 2019), Waze is by far the most popular navigation application, with a market share growing by income-group, from 32% to 58%.

[20] Figure A1 in Appendix A depicts ZATs in Bogotá.

[21] The information to construct the figure comes from different public sources including Banco de la República and the Departamento Administrativo Nacional de Estadística.

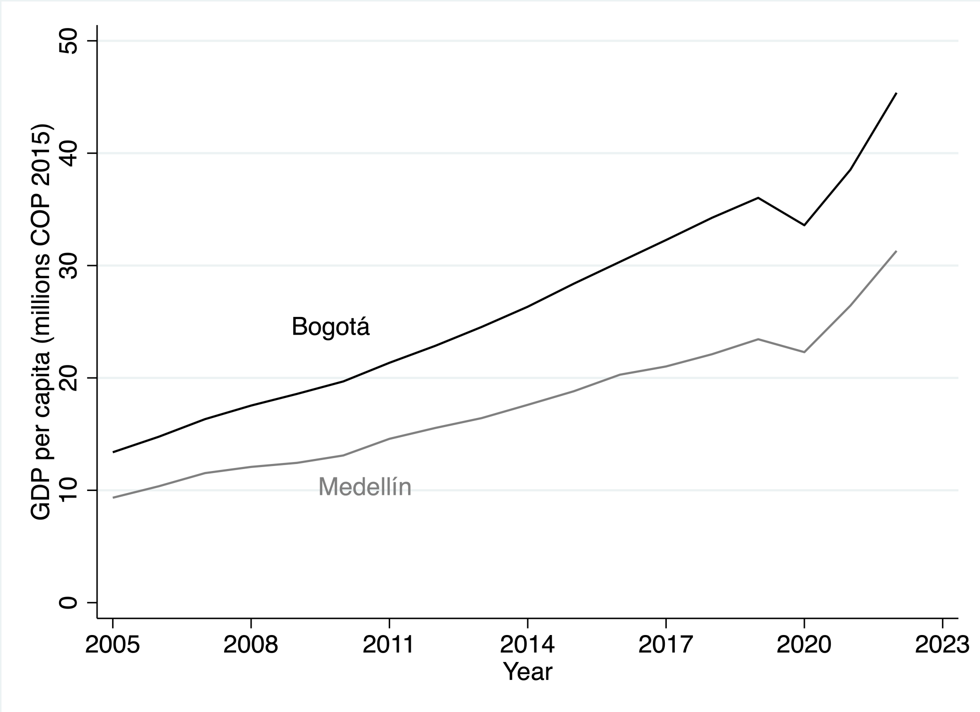


Figure 1: Evolution of GDP per capita in Bogotá and Medellín

product of 4 hours, 5 weekdays and two cities. Note that the 6:00–10:00 a.m. window that we consider in the estimation extends beyond the windows affected by the *Pico y Placa* programs. This should provide us with a wider picture of the morning traffic in each city.

As for the explanatory variables, $Lead_{jit}$ is a dummy variable that takes the value of 1 for observations coming from the $j$th month before the first "treated" month, which is September 2021, that is, the first month when both *Pico y Placa* programs were in operation again. Similarly, $Lag_{kit}$ is a dummy variable that takes the value of 1 for observations coming from the $k$th month after the first treated month. Since we remove from the analysis the months of September 2020 through August 2021, which is when Medellín's *Pico y Placa* was still on hold, we have 19 "leads" (from January 2019 to August 2020) and 4 "lags" (from September 2021 to December 2021) in the analysis. The specification also controls for city fixed effects, $\mu_i$, and time (day of the week and year) fixed effects, $\lambda_t$. The error term is denoted by $\varepsilon_{it}$.[22]

We are interested in the value of the *Lead* (i.e., $\beta_j$) and *Lag* (i.e., $\gamma_k$) coefficients, which capture the difference between the city-level speeds in Bogotá and Medellín relative to the omitted base month, August 2020. Figure 2 shows results for speed format $\bar{v}_3$.

On the one hand, estimations of the *Lead* coefficients suggest that traffic patterns in Medellín and Bogotá have followed, for the most part, parallel trends before their *Pico y Placa* programs were suspended. There is only one *Lead* coefficient that is statistically different from zero. Its smaller confidence interval as well as of the other *Lead* coefficients closer to the treated month

[22]In our estimation we use two-way clustered standard errors due to the existence of crosssectional and serial correlation. Specifically, we cluster standard errors at day-of-the-week and city level.

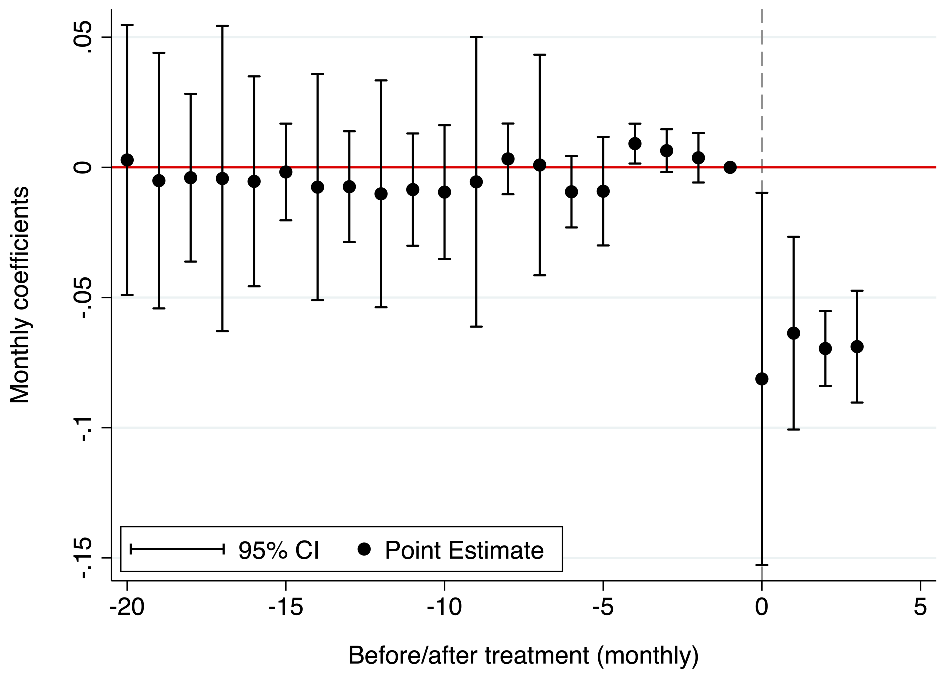


Figure 2: Results from event study comparing Bogotá and Medellín

are possibly explained by the sharp drop in traffic as a result of the city-wide lock-downs during the covid-19 pandemic.[23]

On the other hand, estimations of the *Lag* coefficients suggest that traffic patterns in Medellín and Bogotá have moved apart after their *Pico y Placa* programs were reinstated. Bogotá exhibits a relative drop in speed of around 7%, a number that is entirely in line with the difference-in-differences estimations that we describe next.

#### 2.2.3 Empirical strategy and results

For our estimation, we use speed records during the morning peak affected by both *Pico y Placa* programs, between 6:30 a.m. and 8.30 a.m., Monday through Friday. We estimate the following diff-in-diff equation for each of the four speed formats separately:

$$\ln(\bar{v}_{it}) = \beta_0 + \beta_1 Post_t + \beta_2 Bogota_i + \beta_3 Post_t \times Bogota_i + \beta_4' X_t \times Bogota_i + \mu_{it} \quad (1)$$

where $\bar{v}_{it}$ is the average speed in ZAT $i$ during time interval $t$, $Post_t$ is a dummy variable equal to 1 for time intervals when both *Pico y Placa* programs are active again, $Bogota_i$ is a dummy variable equal to 1 for ZATs located in Bogotá, $X_t$ is a vector of time fixed effects (i.e., the day of the week and month of the year), and $\mu_{it}$ is the error term. We are interested in the sign and magnitud of $\beta_3$, the impact of the exemption fee on traffic.

[23]Note also that because we have 40 observations to estimate each *Lead* and *Lag* coefficient, our confidence intervals are highly sensitive to small changes in speeds.

As shown in Table 1, we estimate equation (1) for different specifications.[24] Panel A shows results when we use ZAT as the unit of observation, as in (1), while Panel B shows results when we use the city as the unit of observation. The latter is constructed by taking the unweighted average of all the available ZAT observations at a given 15-min interval. The reason we include Panel B is precisely to control for the fact that ZAT-level data is not available for all ZATs and 15-min intervals.[25]

Given that Medellín reinstated its *Pico y Placa* program a year later than Bogotá did, specifications (1)–(4) drop from the analysis any data from September 1st 2020 to September 6th 2021, which is when $Post_t$ equals 1. In addition, because Medellín considered a "pedagogic/trial" period from September 6th to September 20th in which offenders to the restriction were offered the option to engage in a drivers education course instead of paying a fine, specification (5) drops, in addition to the data dropped in columns (1)–(4), any data from this pedagogic/trial period. Finally, specification (6) drops, in addition to the data dropped in (1)–(4), data during the 2020 covid-19 lock-downs, that is, from March 19th 2020 to September 1st 2020.

Results are consistent across specifications. The numbers in the first row of columns (3)–(6) of the table indicate that the impact of the exemption fee was a reduction in the average speed at the city level of about 9%. In highly-congested segments, columns (1) and (2), this reduction was twice as much, consistent with a strictly convex congestion function that is common to congested road systems (see, e.g., Small and Verhoef, 2007). As Medellín's post-covid-19 *Pico y Placa* design may appear less restrictive than its pre-covid-19 design, these results may be an underestimation of the true impact of Bogotá's reform on traffic.[26]

## 3 Motivating Theory

Consider a unit mass of a continuum of homogeneous drivers. Driver $i$'s net surplus from driving can be written as

$$S(x_i, x_{-i}) = B(x_i) - C(x_i) - T(x_i, x_{-i}) \tag{2}$$

where $x_i$ is $i$'s amount of driving in a given period, say a week, and $x_{-i}$ is the overall amount of driving by all the other drivers. The amount of driving can be measured by the number of trips made or kms traveled during the period.

With the goal of illustrating a fundamental tradeoff that motivates much of our work, in

[24]In Table A2 of Appendix A.2 we show results for the same specifications but under a more extended time window, including time intervals outside *Pico y Pico*, from 6:00 a.m. to 10 a.m. Not surprisingly, results show a slightly smaller impact of the reform.

[25]We do not know the exact criteria followed by Waze to provide no data in a given ZAT and 15-min interval. In Appendix A.1, however, we explain that ZATs with significant missing information corresponds to rural areas in the city's periphery and urban green spaces (e.g., parks, playing fields, cemeteries, golf courses, etc.). In Table A3 of Appendix A.3, we provide results of regressions that omit these "rural/green" ZATs altogether, which reduces the sample in almost 20%. We find drops in speed for formats $\bar{v}_3$ and $\bar{v}_4$ that are slightly smaller than those in Table 1, of around 7%.

[26]If we do not use Medellín as control and simply run a before-and-after regression for Bogotá, which is essentially running (1) without the Medellín data, we find the reform to have a much smaller effect on traffic, if at all (see Table A4 of Appendix A.4 for details).

Table 1: Difference-in-differences estimations (6:30-8:30 a.m.)

| | (1) $\ln(\bar{v}_1)$ | (2) $\ln(\bar{v}_2)$ | (3) $\ln(\bar{v}_3)$ | (4) $\ln(\bar{v}_4)$ | (5) $\ln(\bar{v}_3)$ | (6) $\ln(\bar{v}_3)$ |
|---|---|---|---|---|---|---|
| Panel A: ZAT level | | | | | | |
| $Post \times Bogota$ | -0.292*** | -0.294*** | -0.090*** | -0.091*** | -0.090*** | -0.089*** |
| | (0.022) | (0.022) | (0.003) | (0.003) | (0.003) | (0.003) |
| $Post$ | 0.071*** | 0.064*** | 0.065*** | 0.066*** | 0.065*** | 0.065*** |
| | (0.021) | (0.021) | (0.003) | (0.003) | (0.003) | (0.003) |
| $Bogota$ | 0.418*** | 0.419*** | -0.023*** | -0.078*** | -0.023*** | -0.023*** |
| | (0.024) | (0.023) | (0.003) | (0.003) | (0.003) | (0.003) |
| Constant | 1.986*** | 1.992*** | 3.262*** | 3.342*** | 3.263*** | 3.262*** |
| | (0.023) | (0.023) | (0.003) | (0.003) | (0.003) | (0.003) |
| Observations | 1,463,522 | 1,463,522 | 1,669,357 | 1,669,354 | 1,325,423 | 1,660,895 |
| $R^2$ | 0.009 | 0.009 | 0.006 | 0.016 | 0.008 | 0.006 |
| Panel B: City level | | | | | | |
| $Post \times Bogota$ | -0.223*** | -0.222*** | -0.087*** | -0.088*** | -0.087*** | -0.086*** |
| | (0.032) | (0.032) | (0.002) | (0.003) | (0.002) | (0.003) |
| $Post$ | 0.041 | 0.033 | 0.062*** | 0.063*** | 0.062*** | 0.061*** |
| | (0.030) | (0.030) | (0.002) | (0.002) | (0.002) | (0.002) |
| $Bogota$ | 0.354*** | 0.353*** | -0.026*** | -0.083*** | -0.026*** | -0.026*** |
| | (0.038) | (0.037) | (0.003) | (0.003) | (0.003) | (0.003) |
| Constant | 2.017*** | 2.023*** | 3.265*** | 3.346*** | 3.266*** | 3.265*** |
| | (0.036) | (0.036) | (0.003) | (0.003) | (0.003) | (0.003) |
| Observations | 7,872 | 7,872 | 8,159 | 8,159 | 6,063 | 7,999 |
| $R^2$ | 0.086 | 0.088 | 0.450 | 0.687 | 0.632 | 0.431 |

Clustered standard errors in parentheses.

All columns are estimated using time and city fixed effects and interactions between them.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

this section we adopt very simple forms for the different elements in (2). In the next section we extend these forms in different directions to better capture Bogotá's transport reality, most importantly, drivers' heterogeneity.

The benefit of driving is captured by a quadratic (concave) function, $B(x_i) = x_i - x_i^2/2$, so $i$'s inverse demand for driving is the linear $B'(x_i) = 1 - x_i$. Given that a driver always has the option to take the bus or work from home, $B'(x_i)$ must be interpreted as the net benefit of an extra car trip relative to the best alternative option, which could be either complete that trip by bus or cancel it and work from home.

The cost of driving has two components. One is the financial cost of travel, $C(x_i)$, which includes expenses on fuel, parking, lubricants, tires, repairs, and so on. This cost is captured by the linear function $C(x_i) = cx_i$, with $c < 1$. The other component is the time cost of travel, $T(x_i, x_{-i})$, measured in monetary terms. This cost, which is increasing in traffic $x_{-i}$, is also captured by a linear function, $T(x_i, x_{-i}) = \gamma x_{-i} x_i$.[27] One should interpret $\gamma$ as the road's congestion propensity.

In the absence of any government intervention, the amount of driving in equilibrium is given by the first-order condition

$$B'(x_i) - C'(x_i) - \partial T(x_i, x_{-i})/\partial x_i = 0 \tag{3}$$

Since all drivers are the same, in equilibrium $x_i = x_{-i}$. Plugging the latter into (3), our simple functional forms yield the following no-intervention amount of driving

$$x^{ni} = \frac{1-c}{1+\gamma}$$

and corresponding consumer welfare $S^{ni} \equiv S(x^{ni}, x^{ni}) = (1-c)^2/2(1+\gamma)^2$.

Given the congestion externality, the no-intervention amount of driving is obviously above the socially efficient (or first-best) level, which is given by

$$x^{fb} = \arg\max_x S(x, x) = \frac{1-c}{1+2\gamma}$$

**Proposition 1** *The authority can restore the first-best amount of driving with a congestion fee* $\tau$ *per trip equal to* $\tau^{fb} = \gamma x^{fb}$.

**Proof.** Faced with such congestion fee, $i$ solves $\max_{x_i}\{B(x_i) - C(x_i) - \tau^{fb} x_i - T(x_i, x_{-i})\}$, which yields $x_i = x_{-i} = x^{fb}$. ■

As well known, the reason the first-best is restored is because $\tau^{fb}$ is exactly equal to the externality that $i$ imposes upon the remaining drivers evaluated at the optimal level of driving. Depending on the value of $\gamma$, restoring the first-best may call for a significant reduction in traffic, $\gamma/(1+2\gamma)$ or 33% when $\gamma = 1$.

As discussed in the Introduction, however, in many instances the authority does not have this market-based instrument at her disposal, so must rely on alternative instruments. Among these, one that have received much support in practice is the rationing of driving according to the last digit of a vehicle's license plate, a so-called driving restriction. While a congestion fee is also intended to ration the amount of driving, it does it quite differently than a driving restriction. Under a congestion fee, drivers have a choice as to which trips to make and which

[27] We do not make any attempt, neither here nor in the application to Bogotá, to let $C(x_i)$ be affected by the amount of traffic. Fuel consumption may go up at lower speed levels but the probability of having an accident may go down.

to cancel (and take the bus or work from home). Obviously, they would cancel only those that report net benefits below the congestion fee, which is socially efficient provided the fee is set at its socially optimal level. Under a driving restriction, in contrast, drivers do not have that choice. At times, they would be forced to cancel highly valuable trips and at others allowed to make car trips of negative social value.

Thus, the main difference between a congestion fee and a driving restriction—leaving aside fiscal considerations—is that the former works as an efficient rationing scheme and the latter does not. One can certainly entertain different views about the extent of this inefficiency. If, following Barahona et al (2020), one adopts the view that a driving restriction works as a proportional rationing scheme—where all trips are equally likely to be canceled—then an "unpleasant" result may follow.

**Proposition 2** *A driving restriction that works as a proportional rationing scheme leads to welfare losses unless the congestion externality (i.e., $\gamma$) is sufficiently large.*

**Proof.** Let $R \in (0,1)$ denote the extent of the driving restriction, with $R \to 1$ the case of no restriction and $R \to 0$ the case of full restriction. If $x^r_{-i}$ is everybody else's amount of driving for a given level of restriction $R$, then the surplus that $i$ actually obtains under proportional rationing is equal to

$$S^r(x^u_i, x^r_{-i}; R) = R(B(x^u_i) - C(x^u_i) - T(x^u_i, x^r_{-i})) \tag{4}$$

where $x^u_i \equiv x^u_i(x^r_{-i})$ is the unrestricted amount of driving that $i$ would pursue when the rest is driving $x^r_{-i}$, i.e., $x^u_i(x^r_{-i})$ solves (3) for $x_{-i} = x^r_{-i}$. Taking the derivative of (4) with respect to $R$ and applying the envelope theorem leads to

$$\frac{\partial S^r(\cdot)}{\partial R} = (B(x^u_i) - C(x^u_i) - T(x^u_i, x^r_{-i})) - R\frac{\partial T(\cdot)}{\partial x^r_{-i}}\frac{\partial x^r_{-i}}{\partial R} \tag{5}$$

Using the fact that in equilibrium $x^r_i = Rx^u_i = x^r_{-i} = x^r$, our simple functional forms yield

$$x^r = \frac{(1-c)R}{1+\gamma R} < x^{ni}$$

and

$$\frac{\partial S^r(\cdot)}{\partial R} = \frac{(1-c)^2(1-\gamma R)}{2(1+\gamma R)^3} \tag{6}$$

It follows that a necessary condition for a driving restriction to increase welfare is $\gamma > 1$; otherwise is optimal to set $R = 1$, i.e., to have no restriction. ■

Expression (5) helps convey the intuition. Increasing $R$ (i.e., relaxing the restriction) has two effects on $i$'s welfare. Captured by the terms in parenthesis, one effect is the direct effect, which is positive. It amounts to the net benefit of marginally increasing $i$'s driving while keeping congestion unchanged. Working in the opposite direction is the indirect or congestion effect.

Since $\partial x^r_{-i}/\partial R > 0$ (and $\partial T(\cdot)/\partial x^r_{-i} > 0$), increasing $R$ leads to more congestion and, hence, to higher travel costs. According to expression (6), for the congestion effect to dominate the direct effect, we need $\gamma > 1$; otherwise, the restriction policy will lead to welfare losses, no matter $R$. Whether $\gamma > 1$ is a demanding condition is ultimately an empirical question to which we will come back in the next section. In our simple model $\gamma > 1$ calls for a first-best reduction of traffic of more than 33%.

Propositions 1 and 2 show not only that restrictions are a poor alternative to congestion fees but also that they can potentially reduce welfare. Does this imply that authorities should abandon driving restrictions as a tool to curb traffic, even though in many cases they appear to be the only available tool (other than improving public transport)? The answer is no, but subject to a fix. Following what Bogotá did, the fix is precisely to allow drivers to pay a fee that exempts them from the restriction.

As explained earlier, exemption fees can come in different formats, from lump-sum to per-trip based (and anything in between). Bogotá initiated its reform in September 2020 with a lump-sum fee, when drivers had only the option to purchase a six-month pass, and then, in September 2021, switched closer to a per-trip fee, when drivers were also offered the option to purchase a daily pass. Commuters in our application to Bogotá make on average 1.03 round trips per day according to Bogotá's 2019 Mobility Survey (BMS 2019), so a daily fee comes very close to a per-trip fee.[28]

Given their use in practice, we will study both types of exemption fees here, but in the application to Bogotá we will only consider the per-trip fee, which is today's relevant case. Although intuitive, the next two propositions show that a per-trip fee is highly superior to a lump-sum fee, so much that the latter may render useless in some contexts, as the following proposition indicates.

**Proposition 3** *Consider a driving restriction $R \in (0, 1)$ that allows drivers to use their cars in times of restriction upon payment of a lump-sum or fixed fee $F \geq 0$, independent of how much they drive. Assume that the entire fee collection is returned to drivers in a lump-sum fashion. If conditions (i) $\gamma > 1$ and (ii) $\gamma R < 1$ hold, then it is optimal to set the fee at*

$$F^* = (1 - R)(1 - c)^2 / 8 \tag{7}$$

*so a fraction*

$$z^* = \frac{1 - \gamma R}{\gamma(1 - R)} \in (0, 1) \tag{8}$$

*of individuals pay the fee. If, on the other hand, condition (i) holds but (ii) does not, then it is optimal to leave the restriction as it is, that is, to set the fee at*

$$F^* \geq \bar{F} \equiv (1 - R)(1 - c)^2 / 2(1 + \gamma R)^2$$

[28] According to Basso et al (2021), this number is 1.35 in Santiago.

*so that nobody pays it ($z^* = 0$). Finally, if condition (i) does not hold and, hence, (ii) does, then it is optimal to terminate the restriction, that is, to set the fee at*

$$F^* \leq \underline{F} \equiv (1 - R)(1 - c)^2 / 2(1 + \gamma)^2$$

*so that everybody pays it ($z^* = 1$).*

**Proof.** See Appendix B. ■

The proposition shows that the conditions under which the introduction of a fixed fee can improve upon a plain restriction are quite limited. Congestion (i.e., $\gamma$) must be neither too high nor too low for the fee to be of any help. The reason is that a fixed fee does not have the ability to sort out socially valuable trips from socially non-valuable trips. When congestion is too high, the (traffic) cost of adding non-valuable trips to the road is higher than the benefit of restoring valuable trips, so it is optimal to keep the restriction as it is. On the other hand, when congestion is not that high, the benefit of restoring valuable trips is higher than the cost of adding non-valuable trips to the road, so it is optimal to get rid of the restriction altogether.

A per-trip exemption fee works quite differently. It has the ability to sort out valuable from non-valuable trips. For this reason, it can always be designed in a way to improve welfare.

**Proposition 4** *Consider a driving restriction $R \in (0, 1)$ that allows drivers to use their cars in times of restriction upon payment of a per-trip fee $p \geq 0$. Assume that the entire fee collection is returned to drivers in a lump-sum fashion. Let $x^{rp}$ and $S^{rp}$ denote, respectively, the amount of driving and consumer welfare under this $(R, p)$ restriction. Despite the increase in traffic (i.e., $x^{rp} > x^r$), the introduction of a per-trip fee leads to welfare gains (i.e., $S^{rp} > S^r \equiv S^r(x^r, x^r; R)$) for any $p \in (\underline{p}, \bar{p})$, where $\underline{p} \geq 0$ and $\bar{p}$ is the choke price that eliminates the demand for exemptions.*

**Proof.** Let $x_i^p$ denotes $i$'s amount of driving with net value above the exemption fee $p$ when the total driving from the remaining drivers adds to $x_{-i}^{rp}$. This valuable driving is obtained from the first-order condition

$$B'(x_i^p) - C'(x_i^p) - \partial T(x_i^p, x_{-i}^{rp})/\partial x_i^p - p = 0 \tag{9}$$

Thus, $i$'s welfare, $S_i^{rp}(x_i^p, x_i^u, x_{-i}^{rp}; R, p)$, can be written as

$$S_i^{rp}(\cdot) = R(B(x_i^u) - C(x_i^u) - T(x_i^u, x_{-i}^{rp})) + (1 - R)(B(x_i^p) - C(x_i^p) - T(x_i^p, x_{-i}^{rp})) \tag{10}$$

where $x_i^u$ is, as in Proposition 2, the unrestricted amount of driving that $i$ would pursue given $x_{-i}^{rp}$. The second term in (10) is new; it captures the extra surplus from valuable trips (i.e., with net benefit above $p$) that were previously rationed. Taking the derivative of (10) with respect to $p$ and applying the envelope theorem (twice) yield

$$\frac{\partial S_i^{rp}(R,p)}{\partial p} = -R\frac{\partial T(x_i^u, x_{-i}^{rp})}{\partial x_{-i}^{rp}}\frac{\partial x_{-i}^{rp}}{\partial p} - (1-R)\frac{\partial T(x_i^p, x_{-i}^{rp})}{\partial x_{-i}^{rp}}\frac{\partial x_{-i}^{rp}}{\partial p} + (1-R)p\frac{\partial x_i^p}{\partial p} \tag{11}$$

Using (3) and (9) to obtain, respectively, $x_i^u = 1 - c - \gamma x_{-i}^{rp}$ and $x_i^p = 1 - c - \gamma x_{-i}^{rp} - p$, (11) reduces to

$$\frac{\partial S_i^{rp}(R,p)}{\partial p} = -\gamma x_i^u \frac{\partial x_{-i}^{rp}}{\partial p} - (1-R)p \tag{12}$$

where, after using $x_i^{rp} = Rx_i^u + (1-R)x_i^p$ and the fact that in equilibrium $x_i^{rp} = x_{-i}^{rp}$,

$$x_{-i}^{rp} = x^{rp} = \frac{1 - c - (1-R)p}{1+\gamma} \tag{13}$$

for $p \leq (1-c)/(1+\gamma R) \equiv \bar{p}$. At $\bar{p}$, $x_i^p = 0$, so $x^{rp} = x^r$ for any $p \geq \bar{p}$. On the other hand, $\partial x^{rp}/\partial p < 0$ from (13), so $x^{rp} > x^r$ for any $p < \bar{p}$, which concludes the first part of our proof (somewhat obvious because an exemption fee leaves drivers with a milder restriction). For the rest of the proof, that $S^{rp} > S^r$ for any $p \in (\underline{p}, \bar{p})$, note that (i) $S_i^{rp}(R,p)$ is concave in $p$, i.e., $\partial^2 S_i^{rp}(R,p)/\partial p^2 < 0$ for all $p < \bar{p}$ (ii) $\partial S_i^{rp}(R, p = 0)/\partial p > 0$, and (iii) $\partial S_i^{rp}(R, p \to \bar{p})/\partial p = -(1-R)p/(1+\gamma) < 0$. It remains to determine the value of $\underline{p}$. If $\gamma$ is not high enough so that $S^r < S^{ni}$ (see Proposition 2), then $\underline{p} = 0$. Conversely, if $\gamma$ is high enough so that $S^r > S^{ni}$, then $\underline{p} > 0$ solves $S^r = S^{rp}(R, \underline{p})$. Figure 3 below illustrates these two possibilities. ■

This homogeneous-driver setting provides us with two important results that motivate much of our analysis. The first is that uniform restrictions, like the one introduced in Bogotá in the late 1990s, can potentially lead to welfare losses (Proposition 2). And the second is that despite the increase in congestion, these uniform restrictions can be fixed, as Bogotá did in 2020, with the introduction of an exemption fee, ideally per-trip based (Proposition 4) as opposed to lump-sum based (Proposition 3).[29]

The work of the exemption fee $p$ is illustrated in Figure 3 for two scenarios, A and B. For graphical convenience, we have assumed that the choke levels of the exemption fee, $\bar{p}$, are the same for both scenarios and that $S_A^r = S_B^r$. The main difference between scenarios is that in A a restriction $R < 1$ with no exemption fee is better than no restriction ($S_A^r > S_A^{ni}$) while in B no restriction is better than a restriction $R < 1$ with no exemption fee ($S_B^{ni} > S_B^r$). In either case, $S^{rp} > S^r$ as long as $p \in (\underline{p}, \bar{p})$.

Another aspect of Figure 3 that deserves attention is the level of the optimal exemption fee for a given level of restriction, say, $p^*(R)$. It is not obvious how this value compares to the Pigouvian level $\tau^{fb}$ (see Proposition 1), which corresponds to the optimal price under full restriction, i.e., $p^*(R = 0) = \tau^{fb}$. The reason is because there are two forces at work. When only a fraction trips can be priced, the regulator would like to set the exemption fee above the first-best level in order to bring the overall level of congestion closer to the first-best level. But

[29] It is not difficult to see that Propositions 4 extends beyond the linear-quadratic setting. An exemption fee $p$ equal or above the existing traffic externality—$\gamma x^{rp}$ in our case—can only increase welfare.

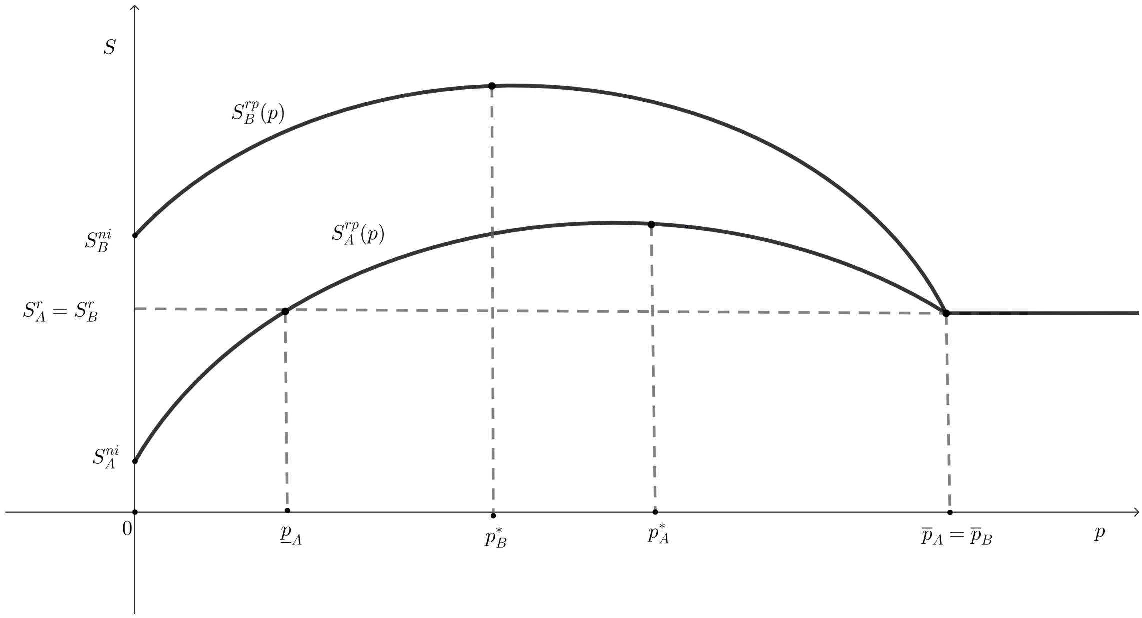


Figure 3: Welfare gains from introduction of an exemption fee

since only a fraction of cars face a price, this lower level of congestion would encorauge drivers of unrestricted cars to increase their trips, some of which are non-valuable from a social point of view. In our simple setting, the second force dominates so the optimal exemption fee is below the Pigouvian level, as the next lemma indicates.[30]

**Lemma 1** *The optimal exemption fee in a* $(R, p)$ *restriction is given by*

$$p^*(R) = \frac{\gamma(1-c)}{(1+2\gamma+\gamma^2 R)} < \tau^{fb}$$

*for any* $R \in (0, 1)$.

**Proof.** Make (12) equal to zero, replace $x_{-i}^{rp} = x_i^{rp} = x^{rp}$ by (13), use $x_i^u = 1 - c - \gamma x_{-i}^{rp}$, and then solve. ■

Having established the superiority of a per-trip fee over a lump-sum fee, for the rest of the paper we will concentrate exclusively on the former, which is today's revelant case in Bogotá. In exploring how much of the potential welfare gain of Proposition 4 applies to Bogotá, many questions arise.

How much of the gain, if any, is due to moving from $p \to \infty$ to $p = 0$ (the difference between $S^{ni}$ and $S^r$) and how much to moving from $p = 0$ to $p > 0$ (the difference between $S^{rp}(p)$ and $S^{ni}$)? How far is the existing $p$ from $p^*(R)$? How is the welfare gain allocated among different

[30]It is outside the scope of this paper to prove the generality of the lemma. However, it seems to hold quite generally. In the context of the simple setting, it also holds for highly convex (e.g., $B'(x) = (1-x)/x$ with $x \in [0, 1]$) and concave (e.g., $B'(x) = \ln(2-x)$ with $x \in [0, 1]$) demands. It also does in the application to Bogotá, a context of heterogeneous individuals (see Figure 7).

individuals, many of whom may not even own a car? Has the reform left everyone better off? What are the implications of the increase in traffic for air quality? What are the efficiency and distributional implications of letting $p$ to vary according to a car's value and pollution rate? What is the additional gain of deepening Bogotá's reform so as to replicate a full congestion pricing scheme, that is, of moving toward a "restriction scheme" where $R = 0$ and, ideally, $p = p^*(R = 0) = \tau^{fb}$. To answer these and other questions we need to extend our model to more closely capture Bogotá's transport reality.

## 4 Application to Bogotá

Our homogeneous-driver setting certainly abstracts from elements that may prove relevant in a practical application. The most important is the presence of heterogeneous commuters. One source of heterogeneity is that the demand for driving depends on preferences over and availability of different transportation modes (e.g., car, public transport, etc.) and also on the possibility to work remotely. Other sources of heterogeneity include the extent of the restriction, $R$, and the cost of being stuck in traffic, $\gamma$. As documented by Gallego et al (2013) for Mexico City, high-income households tend to be less affected by the restriction (they perceive a higher $R$) than middle and low-income households given their access to more than one car. Similarly, high-income drivers tend to value travel time more than their lower-income counterparts, as widely documented in the transportation literature (see, e.g., Small and Verhoef 2007, Basso et al 2021). These sources of heterogeneity may well explain why the introduction of an exemption fee could affect different individuals in opposing directions.

A second element absent in our simple setting is air pollution associated to vehicle travel, whether at the local or global level. Unlike the restriction policies introduced in Santiago and Mexico City in the late 1980s, which were mainly triggered by ever-more-frequent episodes of local air pollution, Bogotá's policy has mostly responded to congestion concerns. It is easy to see that our result in Proposition 4 may not look as favorable in the presence of air pollution (for the same reason that the result in Proposition 2 may not look as negative). The increase in traffic prompted by the the exemption fee ($x^{rp} > x^r$) may lead to higher levels of air pollution that can dissipate, at least partially, some of the gains in consumer surplus ($S^{rp} > S^r$). At the end of Section 5, we attend these air pollution considerations and show that the increase in vehicle emissions have had a rather modest effect on welfare, not affecting our results.[31]

We use the rest of this section to explain first, how our simple setting can be extended to accommodate for commuter heterogeneity and then, how this extended model is calibrated to

[31] Yet another element absent in our setting is the possibility of buying a second (often older and more polluting) car to bypass the restriction, something that has been documented in other restriction programs (see, e.g., Davis 2008). In policies without an exemption fee (i.e., where $p \to \infty$), this possibility does not change the result in Proposition 2. It basically amounts to a costly investment that only affects the extent of the restriction (higher $R$), certainly undoing some of the initial gain in traffic (and pollution) reduction (see, e.g., Gallego et al 2013). By contrast, in restriction policies that include an exemption fee, the incentive to buy a second car is significantly reduced, if not completely eliminated (see, e.g., Basso et al 2021). For this reason, in what follows we abstract from this "second-car" possibility.

Bogota's transport reality. We leave the evaluation of Bogotá's reform for the following section.

### 4.1 Heterogeneous commuters, public transport and remote work

We consider a standard origin-destination transport model with income and time constraints (see, e.g., Small and Verhoef 2007). On a daily basis, a large number of individuals, say $n$, must decide whether to commute to the city center to work/study either by car or public transport, or to work/study from home.

Since car owners will transition between weeks with two and three days of restriction, we consider the week to be the relevant planning horizon. Call $d_i$ the number of days of the week (excluding weekends) that $i = 1, ..., n$ commutes by car, $h_i$ the number of days that works from home, and $b_i = 5 - d_i - h_i$ the number of days that $i$ uses public transport, i.e., buses; since all public-transport in Bogotá runs on buses, whether as part of the Bus Rapid Transit (BRT) system or zonal buses.

In a model where individuals face income and time constraints, the net surplus that individual $i = 1, ..., n$ obtains after a week of travel can be written as

$$S_i(d_i, h_i, b_i) = B_i(d_i, h_i, b_i) - C_i(d_i, b_i; r_i) - T_i(d_i, b_i; n_c, n_b) \tag{14}$$

where $r_i = 0, ..., 5$ measures the extent of the restriction, i.e., the number of days $i$'s car, provided she owns one, is restricted from circulation during the week,[32] $n_c$ is number of individuals that commute by car in any given day and $n_b$ is the number of individuals that commute by bus, so $n_h = n - n_c - n_b$ is the number of individuals that work from home. Given the large number of individuals, the partition $(n_c, n_b, n_h)$ is invariant to the day of the week. Unlike the previous section, the functions $B_i(\cdot)$, $C_i(\cdot)$ and $T_i(\cdot)$ now vary across individuals.

The benefit of travel depends on $i$'s intrinsic (relative) preferences for each transport mode and remote work as follows

$$B_i(d_i, h_i, b_i) = \lambda_i^{-1}[d_i + \theta_i b_i + H_i(h_i)]$$

where $\lambda_i$ corresponds to $i$'s marginal utility of income (i.e., the Lagrangian multiplier for the budget/income constraint),[33] $\theta_i$ captures $i$'s preference for public transport relative to private transport, and $H_i(h_i)$ corresponds to the benefit of remote work relative to private transport, which we capture with the linear demand $H_i'(h_i) = \vartheta_i - \xi_i h_i$. In the next section we explain how to obtain values for the parameters $\lambda_i$, $\theta_i$, $\vartheta_i$ and $\xi_i$.

In turn, $i$'s weekly financial travel cost is given by

[32] In an odd-even restriction, half of the cars will face two days of restriction in a given week and the other half three days of restriction in that week.

[33] Note that by including $i$'s marginal utility of income we are assuming that transport-related expenditures have non-trivial income effects. This is well documented, particularly for lower-income individuals (see, e.g., Small and Verhoef 2007).

$$C_i(d_i, b_i; r_i) = c_i d_i + p_i \max\{0, d_i + r_i - 5\} + f b_i \tag{15}$$

where $c_i$ is the daily cost of using a car (set to infinity for those individuals who do not own one), $p_i$ is the exemption fee (set to infinity before the reform) and $f$ is the daily expense on public transit (i.e., the product of single-ride fare and the average number of daily rides), which is the same across individuals. In contrast, we let individuals to face different exemption fees to account for the fact that they may vary by vehicle type. Values for all these financial-cost parameters are obtained from external sources.

Two observations regarding how the driving restriction enters into (15) are in order. The first is that we allow the extent of the restriction to vary accross individuals with different access to cars. In particular, and following the evidence documented by Gallego et al (2013), we let individuals in households with two or more cars to face a milder restriction, more precisely, one less day of restriction a week than the nominal level.[34]

The second observation is that individuals have ample flexibility to accommodate to the restriction. For example, an individual that faces a week with two days of restriction ($r_i = 2$) would not need to spend on exemption fees if she is planning to use the car only three days ($d_i = 3$); the days of restriction would be those in which she either works from home or takes public transit. Note that this flexibility, if anything, would work against the result in Proposition 2 that a restriction without an exemption fee may be welfare decreasing.

Finally, $i$'s time cost of travel per week is expressed as follows

$$T_i(d_i, b_i; n_c, n_b) = \lambda_i^{-1} \left[ \gamma_i^c t^c(n_c) l d_i + \left( \gamma_i^b(n_b) t^b(n_c) l + \gamma_i^w w^p \right) b_i \right] \tag{16}$$

where $\gamma_i^m$ is $i$'s marginal utility of time (i.e., the Lagrangian multiplier for the time constraint) when using transport mode $m \in \{c, b\}$, $t^m(n_c)$ is the time per unit of distance spent on transport mode $m$ on any given day, $l$ is the average distance traveled in a round trip from home to work including any shorter trips during the day, $\gamma_i^w$ is the marginal utility of time when waiting at the bus station, and $w^p$ is the average waiting time at the station. Following Basso and Silva (2014), we assume that that $\gamma_i^w = 2\gamma_i^c$.

We allow $\gamma_i^c$ and $\gamma_i^b$ to differ and also to control for any inconvenience that may result from increasing public-transport use without the corresponding adjustment in service frequency. Following Tirachini et al (2017) we let

$$\gamma_i^b(n_b) = \gamma_i^c \left( 1 + \zeta \frac{n_b l}{ysqL} \right) \tag{17}$$

where $\zeta$ is a crowding penalty, $y$ is the bus frequency, $s$ is the average bus size, $q$ is the duration

[34] In the case of Bogotá, such individuals would alternate between weeks of 1 and 2 days of restrictions, while the rest of individuals between weeks of 2 and 3 days of restriction.

of the peak period,[35] and $L$ is length of the road network.[36]

To model travel times $t^c$ and $t^b$ we adopt a standard Bureau of Public Roads (BPR) function (see, e.g., Small and Verhoef, 2007, p.76)

$$t^m(n_c) = t_f^m \left(1 + \alpha_m \left(\frac{y\kappa + n_c l/aqL}{K}\right)^{\beta_m}\right) \tag{18}$$

where $t_f^m = 1/v_f^m$ is the free-flow travel time of mode $m \in \{c, b\}$, $v_f^m$ is the free-flow speed of mode $m \in \{c, b\}$, $\kappa$ is an equivalence factor between buses and cars, $K$ is the capacity of a road lane (maximum number of cars per hour a road lane can absorb without affecting travel time and taking into account traffic signals), $a$ is the car occupancy, and $\alpha_m$ and $\beta_m$ are positive parameters. With the exception of $K$, which is estimated (but separately from the preference parameters), values for all the other travel-time-cost parameters, including marginal utilities of time, are obtained from external sources.

The decision problem of individual $i$ is to chose $d_i$ and $h_i$ or $b_i$ (recall that $b_i = 5 - d_i - h_i$) so as to that maximize (14), while taken as given the equilibrium choice of the remaining individuals, that is, taken as given $n_c$, $n_b$ and $n_h$. According to David and Fourcat (2014), a game like ours, with network externalities, may accept multiple equilibria. There are two reasons, however, this potential multiplicity is less of a problem here than in David and Fourcat (2014). One is the fact that public-transit quality is exogenous (i.e., determined outside the game), so Morhing's (1972) positive externality from public-transit use is absent in our setting. And the second reason is that in our model public transit become less attractive (i.e., more crowded) as more people switch to it. We only share with David and Fourcat (2014) the fact that buses run faster as more people switch to public transport, leaving behind less congested roads. Whether this network externality alone is enough to generate multiplicity is something that none of our simulations supports.

### 4.2 Parameter values and calibration

The model is parameterized to capture Bogotá's traffic and air pollution reality by 2019, before covid-19, using the most recent available data. Most importantly, this reality accounts for the fact that in any given week half of Bogotá's commuters face two days of restriction and the other half three days of restriction.

Since most of the relevant information for calibration (including car ownership, use of private vs public transport, amount of remote work, value of time, etc.) is available at the income-group level, we follow the characterization in Bogotá's 2019 Mobility Survey (BMS 2019) and cluster our individuals according to their income levels in five income groups: (1) low, (2) middle-low, (3) middle, (4) middle-high and (5) high.[37] We use $g = 1, ..., 5$ to denote the income group.

[35] Since $l$ is the round-trip average distance, $q$ includes duration of both morning and evening peaks.

[36] The difference between $\gamma_i^b$ and $\gamma_i^c$ is similar to the difference in Basso and Silva (2014), i.e., about two times larger.

[37] The only difference with BMS (2019) is that we collapse its high-income groups 5 and 6 into a single high-

As shown in Table 2, groups are of different sizes (they are not quintiles). Not surprisingly, the table shows substantial heterogeneity in several dimensions. For instance, cars are significantly used only by the higher income groups, while the majority of individuals in the lower income groups rely heavily on public transport.

Table 2: Individual characteristics by income group

| Income group | Fraction of total | Income per-capita | Car ownership | More than one car | Average marginal utility of time ($/hr) |
|---|---|---|---|---|---|
| 1. Low | 11% | 100 | 11% | 1% | 0.70 |
| 2. Middle-low | 40% | 157 | 21% | 2% | 1.59 |
| 3. Middle | 34% | 273 | 39% | 6% | 3.01 |
| 4. Middle-high | 10% | 588 | 66% | 16% | 5.36 |
| 5. High | 5% | 850 | 82% | 36% | 14.42 |

Notes: This table contains household characteristics following the income division in BMS (2019). To elaborate the table we use information from different sources: BMS (2019), Bogota's Mobility District Secretary (BMDS 2021) and Santiago's Transport Planning Secretary (SECTRA 2013). To facilitate the comparison, we have normalized the average income of the low-income group to 100.

The marginal utility of time shown in the last column of the table corresponds to the average value of the marginal utility of time when driving a car for each income group $g = 1, ..., 5$, say $\bar{\gamma}_g^c$. In the absence of detailed data for Bogotá, we adopt the numbers developed by SECTRA (2013) and later updated by Basso et al (2021) for the city of Santiago, which exhibits an income disparity similar to Bogotá's. The numbers in the table correct for the fact that GDP—a main driver of marginal utility of time—is lower in Bogotá than in Santiago, 37.5% lower. Also following SECTRA (2013), we let $\gamma_i^c \equiv \gamma_{i\in g}^c$ to be drawn independently from a uniform distribution with mean $\bar{\gamma}_g^c$ and standard deviation $\bar{\gamma}_g^c/5$.[38]

Values for the remaining financial- and travel-time-cost parameters of the model are summarized in Table 3. The one parameter in the table that deserves further explanation is $K$, the capacity of the road lane. It is estimated using equation (18) for $m = c$, the value of $n_c$ that is in BMS (2019), 45%, and the 2019 city-level average car speed, $v^c(n_c) = 1/t^c(n_c)$, that is in BMDS (2021), 20.4 km/h.

Values for the remaining parameters of the model, namely, marginal utilities of income and preferences for transport modes and remote work, are estimated jointly as follows. First, we let the income distribution of our simulation sample of $n = 10,000$ commuters—half of which face a week with two days of restriction and the other half with three days of restriction—replicate the actual income distribution observed in BMS (2019). Second, we let $\lambda_i = \lambda_0/Y_i$, where $Y_i$ is $i$'s income and $\lambda_0$ is a scaling factor to be estimated together with the preference parameters.

Third, we let $\theta_i \equiv \theta_{i\in g}$ to be drawn independently from a (truncated) normal distribution

income group.

[38] Since it is clear from Proposition 2 that results are sensitive to the value that individuals assign to time, we run some sensitivity analysis around the $\gamma$ numbers shown in the table. We will see that results remain qualitatively unchanged.

Table 3: Summary of financial- and travel-time-cost parameters

| Parameter (units) | Symbol | Value | Source |
|---|---|---|---|
| Trip length (km) | $l$ | 27.8 | BMS (2019)[(a)] |
| Network length (km) | $L$ | 2,171 | Transmilenio[(b)] |
| Passenger car equivalence factor for buses | $\kappa$ | 2.06 | Basso and Silva (2014) |
| Public transport fare ($/day) | $f$ | 1.5 | BMDS (2021) |
| Average waiting time at station (min) | $w^p$ | 2 | Basso and Silva (2014) |
| Car operating cost ($/day) | $c$ | 16.4 | Basso et al (2021)[(c)] |
| Car occupancy | $a$ | 1.5 | BMDS (2021) |
| Lane capacity (car/h) | $K$ | 400 | Own estimation[(d)] |
| Free-flow speed – cars (km/h) | $v_f^c$ | 43 | BMDS (2021) |
| Free-flow speed – buses (km/h) | $v_f^b$ | 30 | BMDS (2021) |
| Bus frequency (bus/h) | $y$ | 13.4 | BMDS (2021) |
| Bus average size (m$^2$) | $s$ | 26.4 | BMDS (2021) |
| Crowding penalty | $\zeta$ | 0.2 | Basso et al (2021) |
| Parameters of BPR function – cars | $\alpha_c$ | 0.15 | Basso et al (2021) |
| | $\beta_c$ | 1.8 | Basso et al (2021) |
| Parameters of BPR functions – buses | $\alpha_b$ | 0.225 | Basso et al (2021) |
| | $\beta_b$ | 1.05 | Basso et al (2021) |

Notes:
[(a)]The value considers two trips per day of approximately 12.5 km each.
[(b)]Transmilenio 2021: Estadísticas de oferta y demanda del Sistema Interconectado de Transporte Público (SITP).
[(c)]This is the operating cost of a car in the middle-value range. The costs in the low- and high-value ranges are 10% lower and higher, respectively.
[(d)]See text for details on the estimation.

with mean $\bar{\theta}_g$ and standard deviation $\sigma_g^\theta$.[39] Fourth, based on PBGSD (2021), which documents that the demand for remote work has shown to be increasing with income,[40] we let $\xi_{i\in g} = \xi_0(6-g)$, where $\xi_0$ is a constant to be estimated. In addition, we let $\vartheta_i \equiv \vartheta_{i\in g}$ to be drawn independently from a (truncated) normal distribution with mean $\bar{\vartheta}_g$ and standard deviation $\sigma_g^\vartheta$.

Fifth, we reduce the number of preference parameters to be estimated following Basso et al's (2021) in that the variance of the distribution of these parameters is assumed to be inversely related to the number of people owning a car in the group. Otherwise, it would hard to explain why some individuals in low-income groups are so keen to use their cars. Thus, we let $\sigma_g^\theta = \omega^\theta/\pi_g^c$ and $\sigma_g^\vartheta = \omega^\vartheta/\pi_g^c$, where $\pi_g^c$ is the fraction of individuals owning a car in group $g$—as indicated in the fourth column of Table 2. This reduces the number of parameters to be estimated to fourteen: $\lambda_0$, $\xi_0$, $\bar{\theta}_1, ..., \bar{\theta}_5$, $\bar{\vartheta}_1, ..., \bar{\vartheta}_5$, $\omega^\theta$, and $\omega^\vartheta$.

Finally, commuters are assigned to the different income groups according to the proportions

[39]Distributions are truncated at the 5 and 95% levels.

[40]In fact, PBGSD (2021) shows that approximately 35% of workers in the IT and financial sectors often telework, in contrast to only 10% of workers in the manufacturing sector. These numbers are consistent with those obtained in a survey conducted by the UC Berkeley in Bogotá (Rodriguez et al 2021), indicating that 81% of lower-income individuals believe they will not be teleworking once the covid-19 pandemic is over, in contrast to the 40% of higher-income individuals.

Table 4: Preference parameters

| Parameters | Preference for car | | Remote work | |
|---|---|---|---|---|
| Income group | $\bar{\theta}_g$ | $\sigma_g^{\theta}$ | $\bar{\vartheta}_g$ | $\sigma_g^{\vartheta}$ |
| 1. Low | -5.19 | 2.27 | -7.53 | 0.01 |
| 2. Middle-low | -3.19 | 1.19 | -2.81 | 0.02 |
| 3. Middle | -1.55 | 0.64 | -1.30 | 0.04 |
| 4. Middle-high | 0.01 | 0.37 | -0.12 | 0.04 |
| 5. High | 0.05 | 0.30 | -0.08 | 0.06 |

The estimation also includes values for the scaling factor for the marginal utility of income, $\lambda_0 = 0.05$, and the slope of remote working demand, $\xi_0 = 0.04$.

and characteristics of Table 2 and their corresponding distribution functions. The estimation of these 14 parameters is done by minimizing the sum of the square of the difference between what the model predicts and the actual observation of both public vs private transport use (modal share) and remote work at the income-group level and overall. Information on modal share comes from BMS (2019) and on remote work from PBGSD (2021). We utilize an unweighted minimizing function, only normalized by the actual observation in each of the 12 differences. The estimated parameters are in Table 4 and how they fit the model to the actual data is in Table 5.

Table 5: Model fit

| | Public transport use | | Remote work | |
|---|---|---|---|---|
| Income group | Observed | Model Prediction | Observed | Model Prediction |
| 1. Low | 91% | 93% | 0% | 0% |
| 2. Middle-low | 80% | 81% | 3% | 4% |
| 3. Middle | 61% | 64% | 13% | 8% |
| 4. Middle-high | 37% | 34% | 26% | 12% |
| 5. High | 12% | 12% | 35% | 36% |
| Overall | 67% | 68% | 10% | 8% |

Note: The table shows how our model matches observed/surveyed data for the calibrated parameters. The first and second columns contrast (pre-covid-19) observed modal shares of public transport to the predictions of our model. The third and the fourth columns do the same for remote working.

It is interesting to observe in Table 4 that while higher-income individuals have on average stronger preferences for cars, estimations for lower-income individuals exhibit a much larger standard deviation. This is an indication that some lower-income individuals value their cars more than their higher-income counterparts.

### 4.3 Policy implementation

An important difference between our homogeneous-driver model and its extension to Bogotá is that the latter considers an exemption fee that varies with car characteristics, namely, with the value of the car and its pollution rate. For each of these dimensions, authorities have classiffied all cars registered in Bogotá in three ranges: low, medium and high.[41] Cars with a commercial value up to $12,500 are classified in the low-value range while cars with a commercial value of $27,500 and above are classified in the high-value range. Similarly, cars with a pollution rate up to 0.25 are classified in the low-pollution range while cars with a pollution rate of 0.4 and above are classified in the high-pollution range.

Based on these classifications, the exemption fee corresponding to each car in the fleet is the product of a baseline exemption fee of $8 and the factor in Table 6. Thus, exemption fees vary from $8, for the cleanest and cheapest cars, to $15, for the most polluting and expensive cars. As shown in Table 7, however, there are very few drivers that face such high exemption fees. The large majority of drivers face exemption fees of $9.6 or less, which results in an average exemption fee of $8.8.

Table 6: Exemption-fee factors

| Commercial value \ Pollution rate | Low | Medium | High |
|---|---|---|---|
| Low | 1.00 | 1.10 | 1.20 |
| Medium | 1.25 | 1.38 | 1.50 |
| High | 1.50 | 1.65 | 1.80 |

Table 7: Fraction of cars in each value-pollution category

| Commercial value \ Pollution rate | Low | Medium | High |
|---|---|---|---|
| Low | 55.31% | 23.93% | 12.48% |
| Medium | 5.96% | 1.41% | 0.36% |
| High | 0.25% | 0.30% | 0.01% |

The pollution rate of a car is important not only to determine its exemption-fee factor but also to estimate its contribution to the air pollution costs borne by society before and after the reform. To estimate these pollution costs we use the same pollution rates used by the authority to classify cars in Tables 6 and 7. These pollution rates are based on a composite of local and global pollutants weighted by their pollution harm according to the responses of a group of 10 experts consulted by the authority.[42] In this composite, (fine) particulate matter weighs 50.4% while carbon dioxide 18.5%; the remaining 31.1% corresponds to the contribution of other local pollutants such as carbon monoxide and nitrogen oxides.

In our policy analysis we do not use the pollution rate estimated for each type of car but rather the average pollution rate of its pollution range, that is, 0.1, 0.3 or 0.5. The fact that cars in the high-pollution range are 5 times more polluting than cars in the low-pollution range is amply consistent with the evidence in Kahn (1996), Barahona et al (2020) and Jacobsen et

[41] The information used by authorities is in BMDS (2021).

[42] More detail can be found in BMS (2021).

al (2023), for example. They document that this wide range is mostly explained by the high pollution rates of older vehicles.

The last piece of information we need for our policy analysis is the type of cars owned by individuals in the different income groups. This is important to determine not only how individuals with different transport-mode and remote-work preferences decide whether to pay the exemption fee but also how this decision affects the estimation of pollution costs. Using information from BMDS (2021) we construct Table 8 with the fraction of each type of car by income group. Perhaps surprisingly, these fractions are not that different across income groups, showing a great concentration of cars in the low-value, high-pollution range.

Table 8: Car characteristics by income group

| Commercial value | Low (L) | | | Medium (M) | | | High (H) | | |
|---|---|---|---|---|---|---|---|---|---|
| Pollution rate | L | M | H | L | M | H | L | M | H |
| Group 1 | 17.1% | 32.8% | 47.8% | 0.1% | 0.5% | 1.5% | 0.0% | 0.1% | 0.1% |
| Group 2 | 14.4% | 28.0% | 54.3% | 0.2% | 0.6% | 2.2% | 0.0% | 0.2% | 0.1% |
| Group 3 | 13.1% | 23.9% | 56.6% | 0.3% | 1.1% | 4.6% | 0.0% | 0.3% | 0.2% |
| Group 4 | 10.1% | 20.8% | 57.8% | 0.4% | 1.7% | 8.5% | 0.0% | 0.3% | 0.3% |
| Group 5 | 10.6% | 21.8% | 49.9% | 0.8% | 3.4% | 12.2% | 0.0% | 0.6% | 0.7% |

## 5 Policy Evaluation

In our policy evaluation we assume that the entire fee collection goes to the public transport system, as Bogotá currently considers. There are certainly different forms to allocate these resources into the system. In our model, we assume that all of them are used to reduce existing public-transport fares. In the Extension section we discuss alternative uses of the fee collection, in particular, to return them back to individuals as lump-sum transfers.

### 5.1 Impact on traffic

Our model predicts city-level speed to fall by 11% with the reform, from its pre-reform level of 20.4 km/h to a post-reform level of 18.2 km/h This drop in average speed is very close to the diff-in-diff estimations in Table 1 when we consider records from all segments (i.e., $\bar{v}_3$ and $\bar{v}_4$), whether at the ZAT or city-level. This close match does not extend, however, to the number of daily exemption fees actually issued, anywhere between 25,291 and 60,992, and those predicted by the model, 80,861.

Other than a miscalibration of the model, we can think of two (complementary) explanations for the discrepancy between the number of actually issued and predicted exemptions. One is an increase in non-compliance activity. Our model assumes—in its calibration and predictions—full compliance with the restriction policy. According to conversations with Bogotá's Mobility

District Secretary full compliance is a reasonable assumption for the pre-covid-19 period but perhaps less so for the post-covid-19 period. Not only detecting non-compliance has become more demanding, as enforcement agents must also verify the validity of the exemption, but also drivers are acting less socially responsibly.[43]

Compliance with the program would nevertheless be relatively high according to our model. For instance, our model predicts 818,389 vehicles in circulation in any given day when the exemption fee is set to zero and 649,065 vehicles when is set at its current level of $9. The difference, 169,324, corresponds to the number of drivers in compliance with *Pico y Placa*: 80,861 by paying the exemption fee and the remaining 88,463 by leaving their cars at home.

Suppose the number of exemptions actually issued in any given day is 50,000. If we fully attribute the "exemption gap" of 30,861 exemptions (the difference between 80,861 and 50,000) to non-compliance with the program, this would give us a non-compliance rate of 18% (the ratio between 30,861 and 169,324). Given this rate and the current non-compliance fine of almost $100,[44] our model would suggest that two in ten (risk-neutral) drivers assign a probably of being caught in non-compliance of 9% or less. For the remaining eight drivers that probability would be higher than 9%.

A second explanation for the exemption gap is a genuine lower demand for exemptions. As we elaborate further in the Extension section, if we believe that covid-19 has enhanced remote working, then the demand for exemptions must necessarily drop. Using the results of a survey elaborated and conducted in 2021 by PBGSD (2021), which suggests the overall amount of remote work to have doubled because of covid-19, from 10 to 20%, our model predicts the demand for exemptions (assuming full compliance) to drop from 80,861 to 51,644, closing the exemption gap significantly, if not entirely. In the end, the exemption gap is probably explained by both, some level of non-compliance and more remote work. Without more information, our model is not prepared to properly weigh the two explanations any further.

### 5.2 Overall welfare

Despite the increase in traffic, and consistent with Proposition 4, our model predicts a substantial gain in overall welfare from the reform, $222 million a year. As shown in Figure 4 an important fraction of these gains, $69 million or 31%, corresponds to the gains from "abolishing" *Pico y Placa*, that is, from setting the exemption fee equal to cero (this would be consistent with scenario B in Figure 3).[45]

[43]We have also seen a surge in evasion in several public-transport systems.

[44]See https://www.valoraanalitik.com/2022/12/26/pico-y-placa-estas-son-las-sanciones-por-infringir-en-bogota-en-2023/.

[45]These results are particularly sensitive to the value of the marginal utility of time. For instance, if we were to adopt the point estimate provided by BMDS (2021) while maintaining the dispersion observed in the last column of Table 2, the gains from abolishing the restriction would jump to $201 million as well as the overall gains from the reform, they would jump to $316 million. The point estimate in BMDS (2021) is 20% lower than the comparable estimate in Table 2, so, if we were to use a point estimate 20% higher than the one in the table, while maintaining the dispersion in the table, the gains from abolishing the restriction would now turn into losses, $127 million, and the gains from the reform would be much smaller, $63 million (this would be consistent

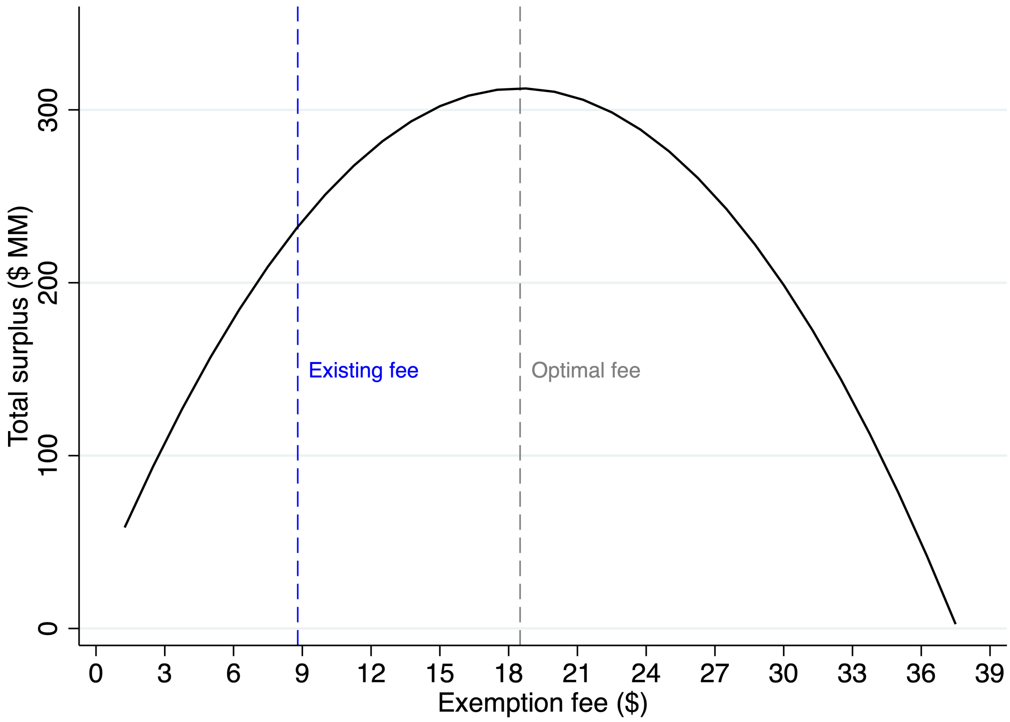


Figure 4: Welfare gains from the reform

One can decompose the $69 gain into the loss from higher traffic, $42.5 million, and the (private) gain from more car trips at the pre-reform average speed, $111.5 million. Interestingly, the latter figure—after accounting for fleet size and the extent of the restriction—is comparable to the estimation by Blackman et al (2018) for a one-day-a-week restriction in Mexico City.

Figure 4 also shows that doubling the exemption fee to reach its optimal level of $19 would report $90 million in additional welfare gains, that is, extra gains of 41%. These numbers suggest that it is not essential to aim for the optimal exemption fee to pocket a significant fraction of the potential welfare gains from the introduction of such fee.

### 5.3 Distributional implications

When it comes to evaluate the impact of the reform across different income groups we find major differences. The big winners of the reform are middle-income individuals (groups 2 and 3) who now use their cars more often, restoring many of their socially valuable trips that before were rationed. As shown in Table 5, their welfare gains amount to $759 million a year. By contrast, the same figure shows that the big losers of the reform are high-income individuals (group 5) with losses that amount to $506 million.[46]

There are two reasons that explain the large losses suffered by high-income individuals. One is that many high-income individuals have access to more than one car (see Table 2), so they

with scenario A in Figure 3). Rich individuals weigh more now, which explains the big loss from abolishing the

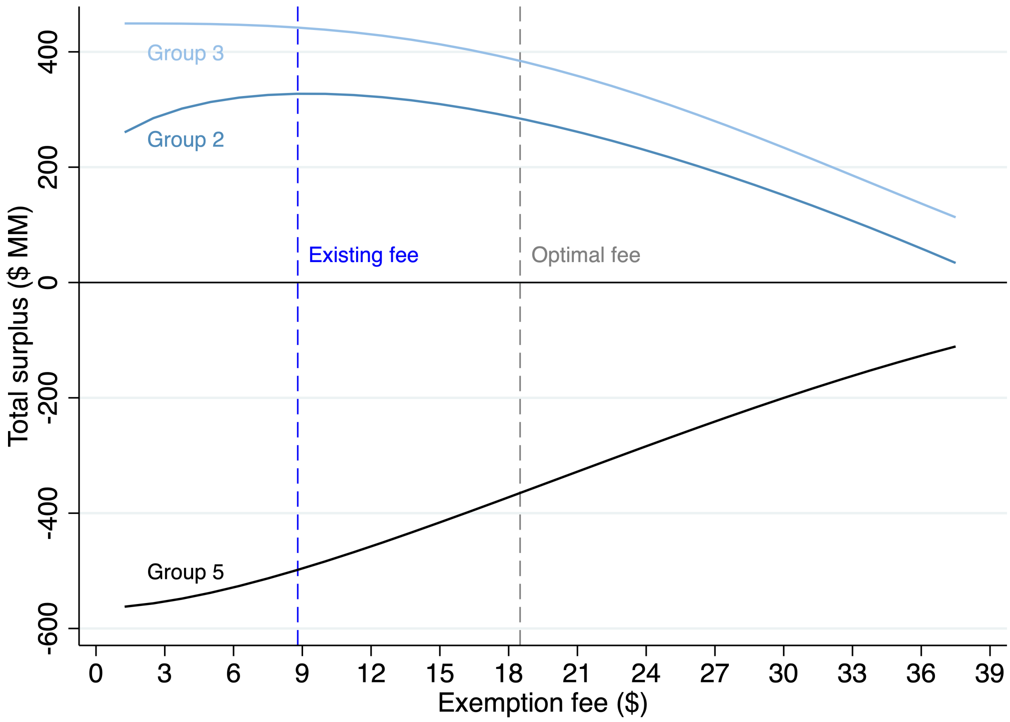


Figure 5: Welfare impact of the reform for different income groups

can more easily accommodate to the restrictions. And a second, closely related reason is that these individuals have greater access to remote work. Imagine an invidual who faces a week with two days of restriction. He or she could completely prevent the destruction of valuable car trips by combining the use of a second car during one of the days of restriction and work from home during the other.

Support for this explanation is found when looking at the number of exemption fees paid by the different groups as a fraction of their number of cars in circulation. According to our model, middle-income individuals purchase almost five times as many exemption fees as high-income individuals, 18.8% against 4.2%. Unfortunately, we cannot contrast these numbers with the numbers of exemption fees actually paid by drivers from different income groups. While we have information on the number of exemptions fees actually paid in April 2022 under the different factors of Table 6, see Table 9 below, there is not much we can infer from these numbers given the symmetric allocation of cars across the different income groups that we observe in Table 8.

restriction.

[46]The impact on the remaining groups is smaller: individuals in group 1 experience a gain of $51 million, and in group 4 a loss of $93 million.

Table 9: Fraction of exemption fees actually paid

| Commercial value \ Pollution rate | Low | Medium | High |
|---|---|---|---|
| Low | 60.45% | 11.34% | 3.03% |
| Medium | 17.66% | 3.31% | 0.57% |
| High | 1.85% | 1.78% | 0.02% |

### 5.4 Air quality implications

So far we have omitted from the analysis any impact of the reform on air pollution, whether at the local or global level. There is a reason for this. Unlike the restriction policies introduced in Santiago and Mexico City in the late 1980s, which were mainly triggered by ever-more-frequent episodes of critically high local air pollution, Bogotá's policy has mostly responded to congestion concerns. The numbers that follow confirm that.

According to SDG (2018) the social cost of fine particulate matter in Bogotá from all light vehicles (this excludes commercial and industrial trucks) amounts to \$68.4 million a year before the reform. On the other hand, and as depicted in Figure 6, our model predicts that the reform has increased emissions, as measured by our composite pollution index, by 23%. Since the weight of particular matter in this composite index is 50.4%, we estimate the reform to have increased pollution costs in \$31.2 million a year, 14.1% of the \$222 million in transport-related welfare gains reported above.

## 6 Extensions

In the previous section we focused on the impact of the actual reform on different policy dimensions. Here we extend the analysis to other policy-design considerations that may prove useful for restriction programs elsewhere or for eventual adjustments to today's *Pico y Placa* in the future.

### 6.1 Alternative uses of the fee collection

One of these considerations is the transfer scheme that determines the use of the revenue collected from the exemption fees. The existing scheme allocates the entire fee collection to the public transport system, which in our model takes the form of lower transport fares. To evaluate the merit (or the lack thereof) of the existing scheme within the limits of our model, let us consider an alternative use of the fee collection, such as lump-sum transfers to individuals. In particular, consider a scheme that prevents transfers between income groups, that is, the revenue collected from group $g = 1, ..., 5$ is returned in a lump-sum fashion to individuals in that same group.

Despite having no impact on traffic, this neutral-transfer scheme reports less overall welfare than the existing scheme, 19% less. In a world with income effects and marginal utilities of

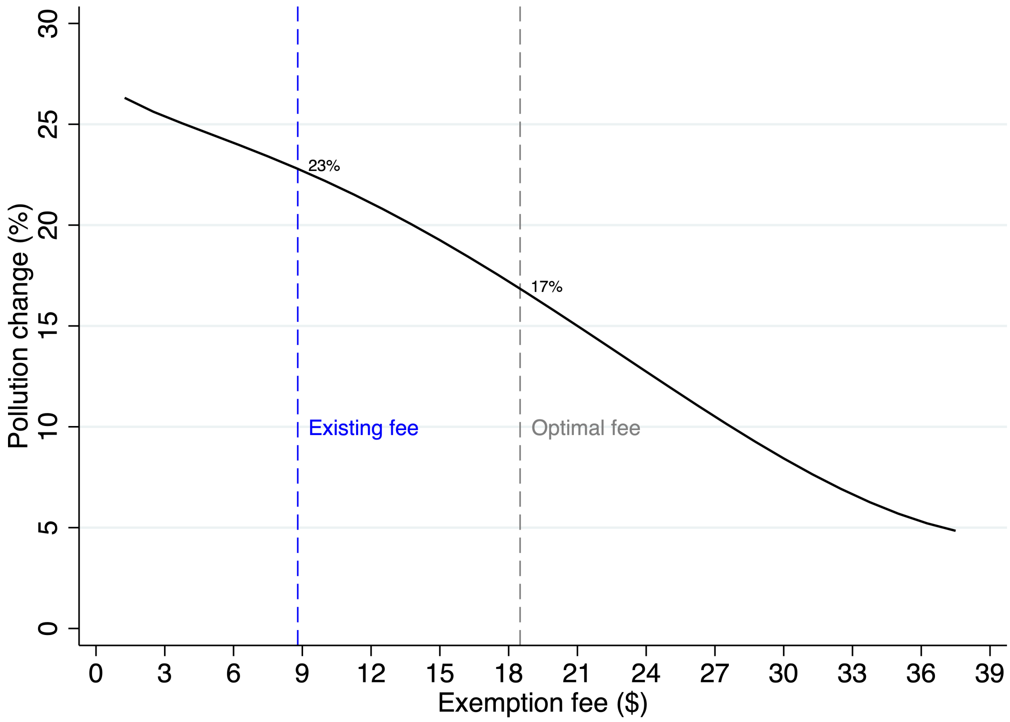


Figure 6: Impact of the reform on pollution

income decreasing with income, using exemption fees to lower public-transport fares appears to be an effective way to transfer resources from higher-income individuals to their lower-income counterparts, who are heavier users of public transport.

### 6.2 Gains from varying exemption fees

In September 2021 two adjustments were introduced to the September 2020 reform. Since then, exemptions fees vary according to the car's commercial value and pollution rate and their owners have the flexibility to also pay these fees on a daily, weekly and monthly basis. Because all passenger vehicles contribute the same to traffic, regardless of their commercial value or pollution rate, it is not obvious why one would like to introduce exemption fees that vary with the vehicle's value when curbing heavy traffic is the main policy goal. It is not only understandable but also desirable to let them vary with the vehicle's pollution rate when controlling air pollution is also a goal.[47]

In fact, our model predicts that the introduction of these varying fees have had minor welfare effects, of 4%. This is the result of two opposing effects. An equivalent uniform exemption fee of $8.8 would have led to higher (transport-related) welfare, to $231 million as opposed to $222 million, but to higher pollution, to an increase of 22.9% as opposed to 22.7%. Thus, the net

[47]The congestion-pricing scheme in London is another example in which congestion fees vary with the car's pollution rate.

effect of introducing varying fees has resulted, according to our model, in a welfare loss of $9 million per year. While varying fees have contributed to less pollution, as anticipated, they have also reduced the net transfers (in the form of lower transport fares) from higher- to lower-income individuals. This was not easy to anticipate given the fleet symmetry across income groups observed in Table 8.

Perhaps the main policy lesson here is that the use of varying fees can facilitate the introduction of fees without compromising their welfare goals. Communicating that more expensive and polluting cars will face higher exemption fees and that the entire fee collection will be allocated to the public-transport system appears to be an effective way to persuade the public to support these fees in the first place.

### 6.3 Moving toward full congestion pricing

To some, one of the greatest benefits of the 2020 reform is that it could facilitate the extension of the *Pico y Placa* restriction, in digits and/or daily hours of application, to eventually replicate a full congestion-pricing scheme, where car owners must pay a congestion fee whenever they use their cars. Figure 7 reports the extra benefits of moving toward a full congestion-pricing scheme. While maintaining the assumption that the entire fee collection goes to the public-transport system in the form of lower fares, the figure considers two congestion-pricing schemes, one with a uniform congestion fee and the other with varying fees based on the factors of Table 6. In both of them, the optimal congestion fee is around $22, higher than the optimal fee under the existing *Pico y Placa* format (this is consistent with Lemma 1).

Even if these congestion-pricing schemes keep the fee at the *Pico y Placa*'s current level, i.e., $9, the extra gains are substantial, $444 million or 186%. Part of these gains are explained by a return to the pre-reform average speed levels. In contrast to our previous finding, when fees are at their optimal level, varying fees report 1% more (transport-related) welfare than uniform fees. The use of varying fees is further reinforced when we look at their impact on pollution levels. As shown in Figure 8, when fees are set at their optimal levels uniform fees lead to 3% less pollution compared to the pre-reform level while varying fees lead to 7% less compared to the same pre-reform level.

Moving toward a full congestion-pricing scheme not only reports substantial gains overall but also group-wise. In fact, the welfare of high-income individuals jumps by $88 million, or $172 if fees are kept uniform. All this indicates that moving toward a congestion-pricing scheme (with the fee collection going to the public-transport system) should enjoy wide support.

### 6.4 Higher levels of remote work

There is no question that covid-19 has increased the amount of remote work. Our evaluation of the reform was done under the assumption that the demand curves for (not the amount of) remote work remained at their pre-reform levels. It is likely that covid-19 produced an outward shift of these demands. The survey elaborated and conducted in the middle of 2021 by PBGSD

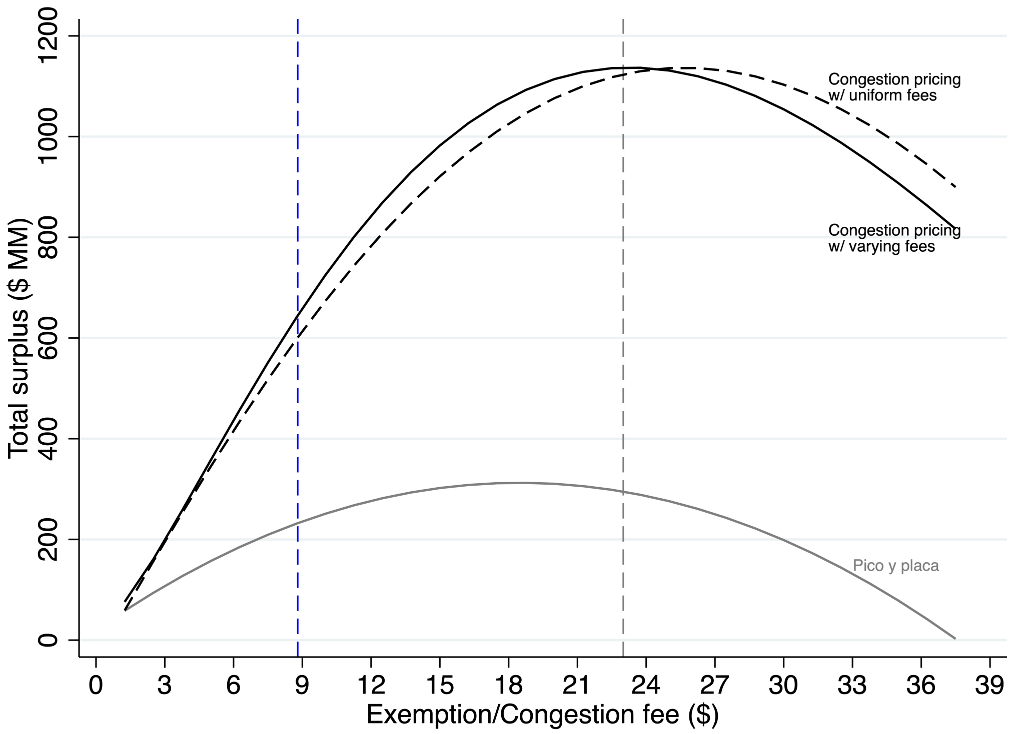


Figure 7: Welfare gains from congestion pricing

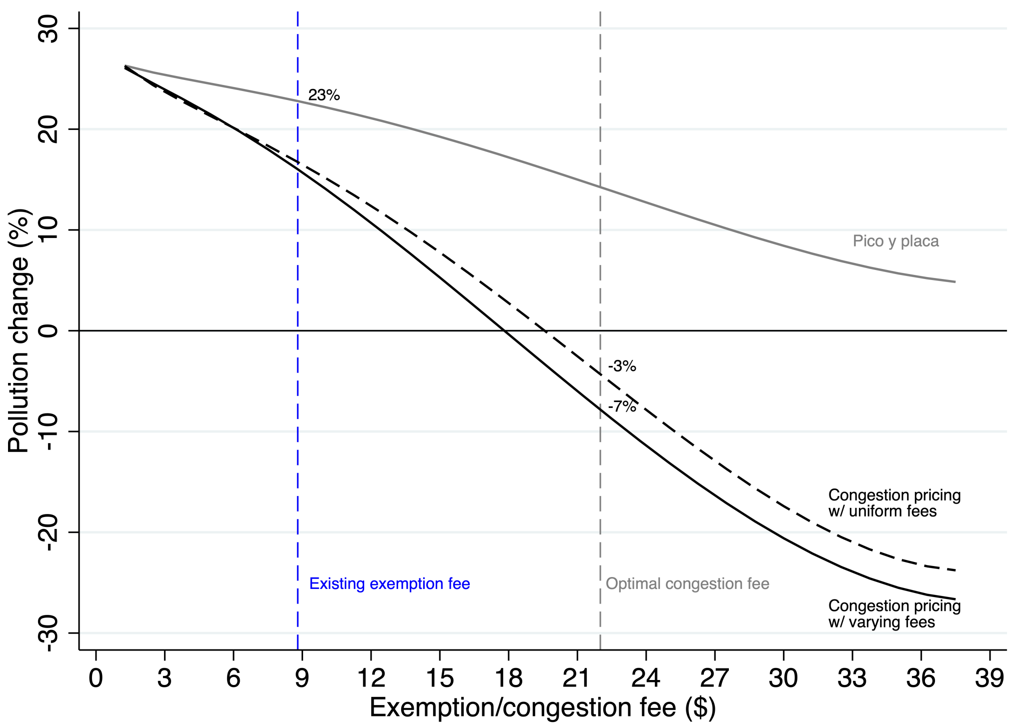


Figure 8: Air quality changes from congestion pricing

(2021) suggests that the overall amount of remote work has doubled because of covid-19, from 10 to 20%. To capture this shift in the demand for remote work in our model, we let constant $\xi_0$ of the demand curves, which is the same for all income groups by assumption, to increase so that the overall amount of remote work in equilibrium under the existing *Pico y Placa* program is 20%. This change in remote work would lead to a drop not only in the number of exemption fees paid in equilibrium, to 51,644 as mentioned earlier, but also in the level of the optimal exemption fee, to \$10. Since PBGSD's (2021) survey was conducted while covid-19 was still affecting the daily life of many individuals, the post-reform optimal exemption fee probably lies somewhere between this new estimation and the previous estimation of \$19. If so, the existing fee would not be that far from its optimal level.

## 7 Final Remarks

Bogotá's market-based reform has provided valuable policy lessons that should prove useful for existing or under-consideration restriction programs elsewhere and for eventual adjustments to its own *Pico y Placa* program in the future. First and foremost, it has shown that the introduction of an exemption fee into an existing driving restriction, even if not done at its optimal level, can report large overall welfare gains. This is in spite of an unavoidable increase in traffic. The welfare losses from this increase in traffic (and in pollution) are more than offset by the welfare gains from restoring many socially valuable car trips that were inefficiently rationed in the first place. We have also learned that these large overall gains do not imply that everyone is better off with the reform, quite the contrary. The big winners of the reform are middle-income individuals who now use their cars more often, whereas the big losers are high-income individuals who now spend more time in traffic.

In closing the paper, it is worth mentioning some aspects that escaped our analysis, three in particular. One is a more comprehensive analysis of the use of exemption fees that vary with vehicle characteristics. In our analysis we only considered the varying fees adopted by Bogotá's authority but did not explore whether there is room to improve upon them. A second aspect is a more comprehensive study of the use of the revenue collected from the exemption fees. We only considered the case in which the entire fee collection is used to lower public-transport fares but probably a better use of these resources is to combine some fare reduction with improvements in service quality, e.g., in higher frequency.

Both of these aspects can be tackled within the limits of our model, although we would require more supply and demand information regarding the public-transport system. There is a third aspect that falls outside the limits of our model, which is the analysis of any longer-term impact of the reform on fleet size and composition. If we believe that driving restrictions like Bogotá's pre-reform have invited individuals to purchase additional cars to bypass the restriction, then our welfare estimations provide a lower bound, as they do not include the benefit of selling some of these additional cars. Another dynamic aspect worth exploring is the impact of varying fees on fleet composition.

# Appendix A Additional Results from Section 2

## A.1 Zones of Transport Analysis (ZATs) in Bogotá

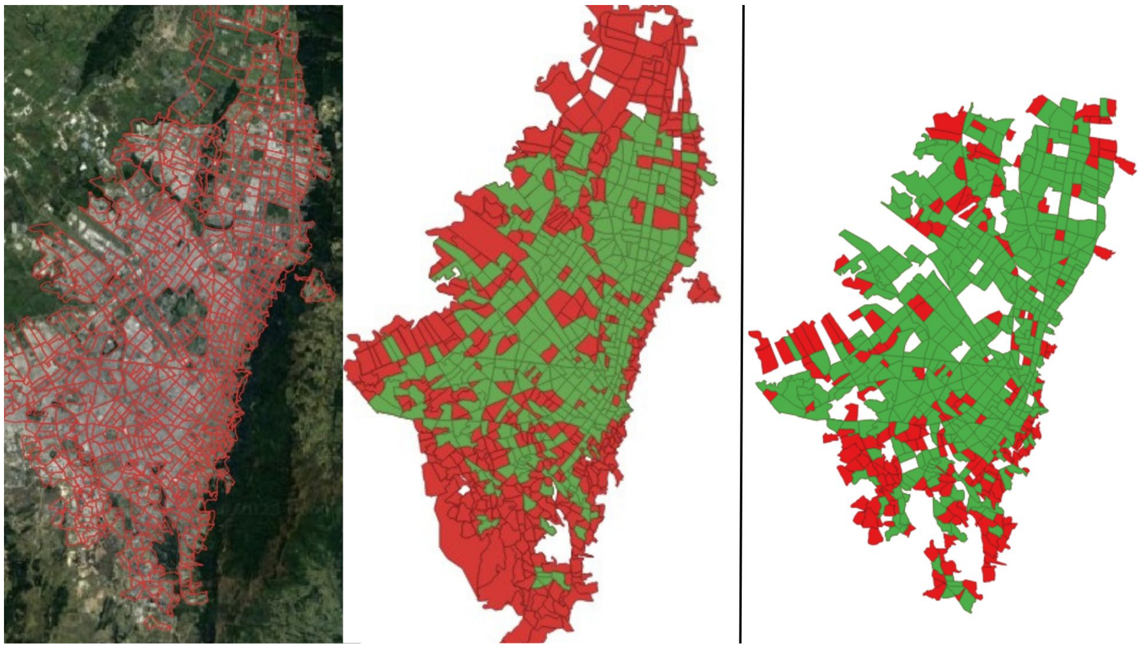

Figure A1: ZATs in Bogotá

The picture on the left shows the 898 ZATs that make the city of Bogotá. The picture in the middle shows the number of ZATs, pictured in green (or light gray in a black-and-white display), with available data at a given 15-min interval, in this case at 7:30 a.m. on July 15th, 2019. By looking at these two pictures, we can see that many of the ZATs with missing data correspond to rural areas in the city's periphery and urban green spaces (e.g., parks, playing fields, cemeteries, golf courses, etc.). Discarding these "rural/green" ZATs, we are left with the ZATs depicted in the picture on the right, which reduces the sample in almost 20%. In section A3 of this appendix, we provide results of regressions using this smaller dataset.

## A.2 Regression results for a more extended time window

Table A2: Difference-in-differences estimations (6:00-10:00 a.m.)

| | (1) $\ln(\bar{v}_1)$ | (2) $\ln(\bar{v}_2)$ | (3) $\ln(\bar{v}_3)$ | (4) $\ln(\bar{v}_4)$ | (5) $\ln(\bar{v}_3)$ | (6) $\ln(\bar{v}_3)$ |
|---|---|---|---|---|---|---|
| Panel A: ZAT level | | | | | | |
| *Post* × *Bogota* | -0.122*** | -0.118*** | -0.060*** | -0.059*** | -0.060*** | -0.061*** |
| | (0.010) | (0.010) | (0.002) | (0.002) | (0.002) | (0.002) |
| *Post* | 0.069*** | 0.065*** | 0.064*** | 0.065*** | 0.064*** | 0.065*** |
| | (0.009) | (0.009) | (0.002) | (0.002) | (0.002) | (0.002) |
| *Bogota* | 0.263*** | 0.261*** | -0.035*** | -0.090*** | -0.036*** | -0.035*** |
| | (0.012) | (0.011) | (0.002) | (0.002) | (0.002) | (0.002) |
| Constant | 2.148*** | 2.158*** | 3.267*** | 3.344*** | 3.268*** | 3.267*** |
| | (0.012) | (0.011) | (0.002) | (0.002) | (0.002) | (0.002) |
| Observations | 3,937,627 | 3,937,627 | 4,418,843 | 4,418,838 | 3,496,997 | 4,386,703 |
| $R^2$ | 0.005 | 0.004 | 0.005 | 0.016 | 0.007 | 0.005 |
| Panel B: City level | | | | | | |
| *Post* × *Bogota* | -0.214*** | -0.211*** | -0.073*** | -0.073*** | -0.074*** | -0.074*** |
| | (0.020) | (0.020) | (0.002) | (0.002) | (0.002) | (0.002) |
| *Post* | 0.063*** | 0.057*** | 0.065*** | 0.067*** | 0.065*** | 0.066*** |
| | (0.019) | (0.018) | (0.001) | (0.002) | (0.001) | (0.001) |
| *Bogota* | 0.295*** | 0.291*** | -0.035*** | -0.092*** | -0.037*** | -0.035*** |
| | (0.021) | (0.021) | (0.002) | (0.002) | (0.002) | (0.002) |
| Constant | 2.078*** | 2.089*** | 3.268*** | 3.347*** | 3.268*** | 3.268*** |
| | (0.020) | (0.020) | (0.002) | (0.002) | (0.002) | (0.002) |
| Observations | 19,731 | 19,731 | 20,398 | 20,398 | 15,158 | 19,998 |
| $R^2$ | 0.068 | 0.069 | 0.439 | 0.676 | 0.596 | 0.427 |

Clustered standard errors in parentheses

All columns are estimated using time and city fixed effects and interactions between them

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

### A.3 Regression results after removing "rural/green" ZATs

Table A3: Difference-in-differences estimations (6:30-8:30 a.m.)

| | (1) $\ln(\bar{v}_1)$ | (2) $\ln(\bar{v}_2)$ | (3) $\ln(\bar{v}_3)$ | (4) $\ln(\bar{v}_4)$ | (5) $\ln(\bar{v}_3)$ | (6) $\ln(\bar{v}_3)$ |
|---|---|---|---|---|---|---|
| Panel A: ZAT level | | | | | | |
| $Post \times Bogota$ | -0.296*** | -0.298*** | -0.074*** | -0.073*** | -0.074*** | -0.073*** |
| | (0.022) | (0.022) | (0.003) | (0.003) | (0.003) | (0.003) |
| $Post$ | 0.071*** | 0.064*** | 0.065*** | 0.066*** | 0.065*** | 0.065*** |
| | (0.021) | (0.021) | (0.003) | (0.003) | (0.003) | (0.003) |
| $Bogota$ | 0.390*** | 0.393*** | -0.052*** | -0.109*** | -0.053*** | -0.052*** |
| | (0.024) | (0.023) | (0.003) | (0.003) | (0.003) | (0.003) |
| Constant | 1.986*** | 1.992*** | 3.262*** | 3.342*** | 3.263*** | 3.262*** |
| | (0.023) | (0.023) | (0.003) | (0.003) | (0.003) | (0.003) |
| Observations | 1,217,803 | 1,217,804 | 1,399,052 | 1,399,049 | 1,108,570 | 1,392,067 |
| $R^2$ | 0.010 | 0.010 | 0.020 | 0.040 | 0.024 | 0.020 |
| Panel B: City level | | | | | | |
| $Post \times Bogota$ | -0.222*** | -0.223*** | -0.071*** | -0.070*** | -0.072*** | -0.071*** |
| | (0.032) | (0.032) | (0.002) | (0.003) | (0.002) | (0.002) |
| $Post$ | 0.041 | 0.033 | 0.062*** | 0.063*** | 0.062*** | 0.061*** |
| | (0.030) | (0.030) | (0.002) | (0.002) | (0.002) | (0.002) |
| $Bogota$ | 0.323*** | 0.322*** | -0.054*** | -0.112*** | -0.055*** | -0.054*** |
| | (0.038) | (0.037) | (0.003) | (0.003) | (0.003) | (0.003) |
| Constant | 2.017*** | 2.023*** | 3.265*** | 3.346*** | 3.266*** | 3.265*** |
| | (0.036) | (0.036) | (0.003) | (0.003) | (0.002) | (0.003) |
| Observations | 7,872 | 7,872 | 8,159 | 8,159 | 6,063 | 7,999 |
| $R^2$ | 0.074 | 0.077 | 0.609 | 0.772 | 0.742 | 0.599 |

Clustered standard errors in parentheses.

All columns are estimated using time and city fixed effects and interactions between them.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

## A.4 Results from before-and-after regressions

Table A4: Before-and-after estimations

| | (1) $\ln(\bar{v}_1)$ | (2) $\ln(\bar{v}_2)$ | (3) $\ln(\bar{v}_3)$ | (4) $\ln(\bar{v}_4)$ | (5) $\ln(\bar{v}_3)$ | (6) $\ln(\bar{v}_3)$ |
|---|---|---|---|---|---|---|
| Panel A: ZAT level | | | | | | |
| *Post* | -0.219*** | -0.227*** | -0.025*** | -0.025*** | -0.025*** | -0.024*** |
| | (0.007) | (0.007) | (0.001) | (0.001) | (0.001) | (0.001) |
| Constant | 2.431*** | 2.438*** | 3.239*** | 3.262*** | 3.239*** | 3.239*** |
| | (0.005) | (0.005) | (0.001) | (0.002) | (0.001) | (0.001) |
| Observations | 1,439,324 | 1,439,324 | 1,565,126 | 1,565,123 | 1,237,721 | 1,558,241 |
| $R^2$ | 0.009 | 0.009 | 0.001 | 0.001 | 0.001 | 0.001 |
| Panel B: City level | | | | | | |
| *Post* | -0.067*** | -0.075*** | 0.018*** | 0.019*** | 0.018*** | 0.019*** |
| | (0.017) | (0.017) | (0.002) | (0.003) | (0.002) | (0.002) |
| Constant | 2.092*** | 2.098*** | 3.250*** | 3.302*** | 3.250*** | 3.251*** |
| | (0.043) | (0.043) | (0.003) | (0.005) | (0.003) | (0.003) |
| Observations | 7,872 | 7,872 | 8,159 | 8,159 | 6,063 | 7,999 |
| $R^2$ | 0.051 | 0.054 | 0.046 | 0.027 | 0.088 | 0.047 |

Clustered standard errors in parentheses.

Fixed effects: month, day, hour, day×month, day×hour.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

## Appendix B Proof of Proposition 3

Consider a fixed $F$ under which a fraction $z \in (0,1)$ of individuals pay the fee in equilibrium. Since in equilibrium individuals must be indifferent between paying the fee and not, $F$ must be equal to the surplus gain from unrestricted driving, that is,

$$F = (1-R)(B(x_i^u(x_{-i}^{rF})) - cx_i^u(x_{-i}^{rF}) - \gamma x_i^u(x_{-i}^{rF})x_{-i}^{rF}) \tag{19}$$

where $x_{-i}^{rF}$ is the total amount of driving under the restriction $(R, F)$ and $x_i^u(x_{-i}^{rF})$ is $i$'s unrestricted amount of driving given $x_{-i}^{rF}$. In equilibrium it must also hold that the total amount of driving, $x^{rF}$, is the weighted average between the equilibrium amount of travel of those who pay the fee, $x^u$, and those who do not, $Rx^u$:

$$x^{rF} = zx^u + (1-z)Rx^u \tag{20}$$

Using (20) and the first-order condition $x_i^u(x_{-i}^{rF}) = 1-c-\gamma x_{-i}^{rF}$ we can obtain the equilibrium amounts of travel $x^u$ and $x^{rF}$ as a function of $R$ and $z$ that plugged into (19) leads to

$$F = \frac{(1-R)(1-c)^2}{2(1+R\gamma+z\gamma(1-R))^2} \tag{21}$$

Expression (21) allows us to solve for $z$ as a function of $F$ and, hence, write the equilibrium amounts of travel as a function of $R$ and $F$, that is $x^u(R,F)$ and $x^{rF}(R,F)$.

Plugging $x^u(R,F)$ and $x^{rF}(R,F)$ into the welfare function $S^{rF}(R,F) = B(x^u(R,F)) - cx^u(R,F) - \gamma x^u(R,F)x^{rF}(R,F)$ is easy to see that (7) is the fee that maximizes $S^{rF}$ and leads to (8) individuals paying the fee, which is valid as long as $z(F^*) \in (0,1)$, that is, as long as conditions (i) and (ii) hold. If either condition fails to hold the optimum is either to set $z=0$, which from (21) is done by setting $F=\bar{F}$ or higher, or to set $z=1$, which is done by setting $F=\underline{F}$ or lower.

## References


[1] Akbar, P., V. Couture, G. Duranton, and A. Storeygard (2023). Mobility and congestion in Urban India, *American Economic Review* 113, 1083-1111.

[2] Akbar, P., and G. Duranton (2018). Measuring congestion in a highly congested city: Bogotá, Mimeo.

[3] Barahona, N., F. Gallego, and J.-P. Montero (2020). Vintage-specific driving restrictions, *Review of Economic Studies* 87, 1646-1682.

[4] Baranzini, A., S. Carattini, and L. Tesauro (2021). Designing effective and acceptable road pricing schemes: Evidence from the Geneva Congestion Charge, *Environmental and Resource Economics* 79, 417-482

[5] Basso, L., J.-P. Montero, and F. Sepúlveda (2021), A practical approach for curbing congestion and air pollution: Driving restrictions with toll and vintage exemptions, *Transportation Research Part A* 148, 330-352.

[6] Basso, L., and H. Silva (2014), Efficiency and substitutability of transit Subsidies and other urban transport policies, *American Economic Journal: Economic Policy* 6, 1-33.

[7] Blackman, A., F. Alpízar, F. Carlsson, and M.R. Planter (2018). A contingent valuation approach to estimating regulatory costs: Mexico's Day without driving program. *Journal of the Association of Environmental and Resource Economists* 5, 607-641.

[8] BMS (2019), 2019 Bogotá's Mobility Survey, https://www.movilidadbogota.gov.co/web/sites/default/files/Paginas/22-04-2020/20191216_presentacion_encuesta_v2.pdf (accessed: March 1, 2021).

[9] BMDS (2021), Bogotá's Mobility District Secretary, Segunda fase del permiso especial de acceso a areas de restricción vehicular. August, 2021.

[10] Bonilla, J.A. (2019), The more stringent, the better? Rationing car use in Bogota with moderate and drastic restrictions, *The World Bank Economic Review* 33, 516-534.

[11] Calatayud, A., S. Sánchez González, F. Bedoya-Maya, F. Giraldez, and J.M. Márquez (2021). Urban road congestion in Latin America and the Caribbean: Characteristics, costs, and mitigation, Inter-American Development Bank, Transportation Division, Washington DC.

[12] Carillo, P., A. Lopez-Luzuriaga, and A. Malik (2018), Pollution or crime: The effect of driving restrictions on criminal activity, *Journal of Public Economics* 164, 50-69.

[13] Daganzo, C. (2000). Taking turns: Rx for congestion, *Access* 17, 14-19.

[14] David, Q. and R. Foucart (2014), Modal choice and optimal congestion, *Regional Science and Urban Economics* 48, 12-20.

[15] Davis, L. (2008), The effect of driving restrictions on air quality in Mexico City, *Journal of Political Economy* 116, 38-81.

[16] Eskeland, G. S. and T. Feyzioglu (1997), Rationing can backfire: The day without a car in Mexico City, *The World Bank Economic Review* 11, 383-408.

[17] Gallego, F., J.-P. Montero and C. Salas (2013), The effect of transport policies on car use: Evidence from Latin American cities, *Journal of Public Economics* 107, 47-62.

[18] Galdon-Sanchez, J.E., R. Gil, F. Holub, and G. Uriz-Uharte (2023), Social benefits and private costs of driving restriction policies: The impact of Madrid Central on congestion, pollution, and consumer spending, *Journal of the European Economic Association*, forthcoming.

[19] Hanna, R., G. Kreindler and B. Olken (2017), Citywide effects of high-occupancy vehicle restrictions: Evidence from "three-in-one" in Jakarta, *Science* 357 (6346), 89-93.

[20] INRIX (2020), INRIX Global Traffic Scorecard, Kirkland WA, U.S.

[21] Jacobsen, M., J. Sallee, J. Shapiro, and A. Van Benthem (2023), Regulating untaxable externalities: Are vehicle air pollution standards effective and efficient? *Quarterly Journal of Economics*, forthcoming.

[22] Kahn, M. (1996), New evidence on trends in vehicle emissions, *The RAND Journal of Economics* 27, 183-196.

[23] Mohring, H. (1972), Optimization and Scale Economies in Urban Bus Transportation, *American Economic Review* 62, 591-604.

[24] PBGSD (2021), Gestión de Demanda en un Escenario Post COVID: Teletrabajo y Cambios en la Demanda de Viajes, ProBogota and GSD+, Bogotá, June 2021.

[25] Rodriguez, D., Lazarus, J. and M. Toledo (2021), Consultoría para el desarrollo del modelo de elección modal para evaluar el impacto de las medidas de gestión de la demanda de vehiculos particulares en Bogota. Bogotá, January, 2021.

[26] Salgado, E. and O. Mitnik (2022), Spatial and Time Spillovers of Driving Restrictions: Causal Evidence from Lima's Pico y Placa, working paper, Inter-American Development Bank.

[27] SDG (2018), Estructuración técnica del sistema de cobro por distancia recorrida para vehículos motorizados privados que circulan en Bogotá. Report No. 23180101 prepared by Steer Davies Gleave (SDG) for the Secretaría Distrital de Movilidad de Bogotá.

[28] SECTRA (2013), Plan Maestro de Transportes de Santiago 2025, Santiago, Secretaría Interministerial de Planificación de Transporte (SECTRA), Santiago, Chile.

[29] Small, K. and E. Verhoef (2007), *The Economics of Urban Transportation.* Routledge, London.

[30] Tirole, J. (1988), *The Theory of Industrial Organization.* MIT Press, Cambridge, Massachusetts.

[31] Viard, V. B. and S. Fu (2015), The effect of Beijing's driving restrictions on pollution and economic activity, *Journal of Public Economics* 125, 98-115.

[32] Wolff, H. (2014), Keep your clunker in the suburb: Low-emission zones and adoption of green vehicles, *Economic Journal* 124, F481-F512.

[33] Zhang, W., C.-Y.C. Lin Lawell, and V.I. Umanskaya (2017), The effects of license plate-based driving restrictions on air quality: Theory and empirical evidence, *Journal of Environmental Economics and Management* 82, 181-220.