PRICING CONGESTION TO INCREASE TRAFFIC: THE CASE OF BOGOTÁ

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RESUMEN

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, whereas the big losers are high-income individuals who now spend more time in traffic (their annual gains and losses amount to US$759 million and US$506 million, respectively).

1. INTRODUCTION

In September 2020, the city of Bogot´a 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. This will obviously increase traffic in the second most congested city in the world. In this paper we study empirically, theoritcally and trough a simulation model this market reform.
For space reasons related to the conference format, sections 2 and 3 have been drastically reduced. An extensions' section and references have been omitted. The full paper with all the details is available upon request from the authors.

2. BOGOTÁ'S MARKET-BASED REFORM

Bogot´a, 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. 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.

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.

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. We use data comprising the urban areas of Bogot´a and Medell´ın from January 2019 through December 2021. For space reasons we do not provide details here, but Results are consistent across specifications: the impact of the exemption fee was a reduction in the average speed at the city level of about 9 %. In highly-congested segments, this reduction was twice as much, consistent with a strictly convex congestion function.

3. MOTIVATING THEORY

In the full paper, availaible upon request, we provide a theoretical model that allows to shed light on the main trade-off. The resul and intuiton are as follow: in many instances the authority does not have this market-based instrument at her disposal, so must rely on altrnative 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 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.

Proposition 1. *A driving restriction that works as a proportional rationing scheme leads to welfare losses unless the congestion externality is sufficiently large.*

4. APPLICATION TO BOGOTA

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, 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 λ_i corresponds to i's marginal utility of income (i.e., the Lagrangian multiplier for the budget/income constraint), θ_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 λ_i, θ_i, ϑ_i and ξ_i.

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

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

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. 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 (ri = 2) would not need to spend on exemption fees if she is planning to use the car only three days (di = 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 γ_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, γ_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 γ_i^c and γ_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 ζ is a crowding penalty, y is the bus frequency, s is the average bus size, q is the duration of the peak period,[36] and L is length of the road network.[37]

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 $m \in \{c, b\}$, κ is an equivalence factor between buses and cars, K is the capacity ofa 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 αm and βm 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 di and hi or bi (recall that bi = 5−di −hi) so as to that maximize (14), while taken as given the equilibrium choice of the remaining individuals, that is, taken as given nc, nb and nh. 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.[38] We use $g = 1, ..., 5$ to denote the income group.

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.

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

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 $\bar{\gamma}_g^c/5$.

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 λ_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 with mean $\bar{\theta}_g$ and standard deviation σ_g^θ.[40] Fourth, based on PBGSD (2021), which documents that the demand for remote work has shown to be increasing with income,[41] we let $\xi_{i\in g} = \xi_0(6 - g)$, where ξ_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 σ_g^ϑ.

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	κ	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	ζ	0.2	Basso et al (2021)
Parameters of BPR function – cars	α_c	0.15	Basso et al (2021)
	β_c	1.8	Basso et al (2021)
Parameters of BPR functions – buses	α_b	0.225	Basso et al (2021)
	β_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.

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

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 π_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: λ_0, ξ_0, $\bar{\theta}_1$, ..., $\bar{\theta}_5$, $\bar{\vartheta}_1$, ..., $\bar{\vartheta}_5$, ω^θ, and ω^ϑ.

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

Parameters	Preference for car		Remote work	
Income group	$\bar{\theta}_g$	σ_g^θ	$\bar{\vartheta}_g$	σ_g^ϑ
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, $\xi_0 = 0{,}04$.

Tabla 4: Preference parameters

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.

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.[42] 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.

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. 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 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.

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

Tabla 6: Exemption-fee factors

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 %

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

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 %

Tabla 8: Car characteristics by income group

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 thevalidity of the exemption, but also drivers are acting less socially responsibly.

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, 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 zero (this would be consistent with scenario B in Figure 3).

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.

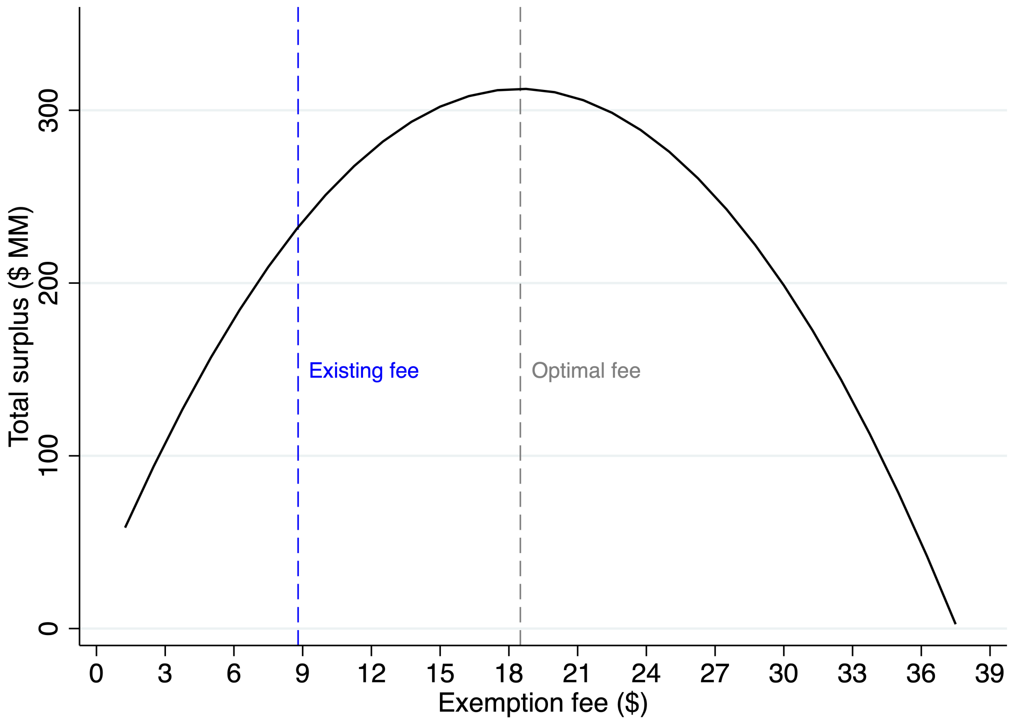

Figura 4: Welfare gains from the reform

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.

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 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.

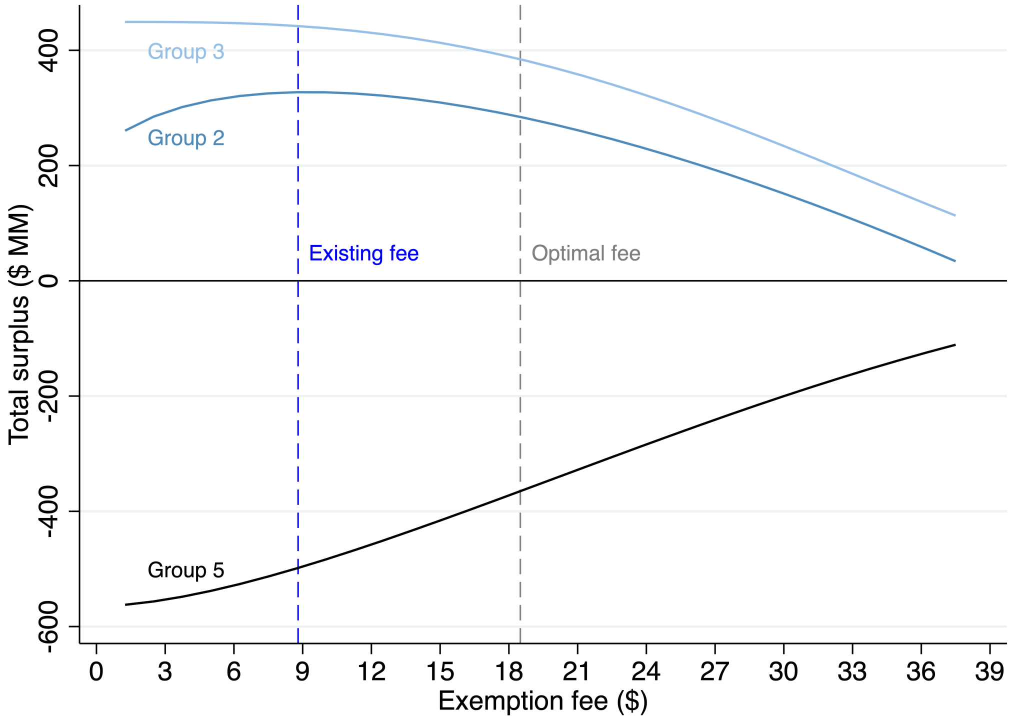

Figura 5: Welfare impact of the reform for different income groups

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.

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 %

Tabla 9: Fraction of exemption fees actually paid

Air quality implactions are also studied un the ful-version paper.

6. 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 Bogot ´a'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 Bogot´a'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.

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