Pricing Congestion to Increase Traffic: The Case of Bogotá

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Bogotá: The (pre-covid) most congested city in the world

Based on INRIX's 2020 and 2019 ranks

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Table 3: 10 Most Congested Cities in the World in 2019

2019 IMPACT RANK (2018 IMPACT)	URBAN AREA	COUNTRY	REGION	HOURS LOST IN CONGESTION (RANK 2019)	2018-2019 CHANGE	2017-2018 CHANGE	LAST MILE SPEED (MPH)	BIKE	TRANSIT
1 (2)	Bogota	Colombia	South America	191 (1)	3%	1%	9		
2 (1)	Rio de Janeiro	Brazil	South America	190 (2)	-5%	-1%	11		
3 (5)	Mexico City	Mexico	North America	158 (6)	2%	1%	12		
4 (9)	Istanbul	Turkey	Asia	153 (8)	6%	3%	11		
5 (10)	São Paulo	Brazil	South America	152 (9)	5%	1%	13		
6 (7)	Rome	Italy	Europe	166 (3)	1%	2%	11		
7 (4)	Paris	France	Europe	165 (4)	-4%	-5%	10		
8 (3)	London	United Kingdom	Europe	149 (12)	-9%	-4%	10		
9 (6)	Boston, MA	United States	North America	149 (12)	-5%	9%	12		
10 (13)	Chicago, IL	United States	North America	145 (14)	4%	4%	11		

Medellín also faces significant congestion problems

Both cities responded with "Pico y Placa" (driving restriction/license-plate ban)

Bogotá's 2020 market-based reform

- From September 2020 onward, drivers in Bogotá have the option to buy a pass (pay a fee) to be exempted from the restriction
  - Sep 2020 – Aug 2021, only 6-month passes available (lump-sum fee)
  - Since Sep 2021, monthly and daily (per-trip fee) passes also available
- Exemption fee is on average US$8.8 a day
- Since Sep 2021 it varies with car characteristics, commercial value and emissions rate
- Entire fee collection goes to public transport (in our model to reduce fares)

Pico y Placa over time: Bogotá (1998) vs Medellín (2005)

	Pre-Covid	**Covid-19**	**Transition**	**Post-Covid**
	Aug 2013 -- Mar 2020	Apr 2020 -- Aug 2020	**Sep 2020** -- Aug 2021	Sep 2021 -- Present
Bogotá	Pico y Placa in place (50%)	Confinement & P y P suspended	Confinement ends & P y P is back with 6-month pass	P y P daily and monthly passes also available
Medellín	Pico y Placa in place (40%)	Confinement & P y P suspended	Confinement ends & P y P still on hold	P y P is back (no exemption fee)

Difference-in-differences estimation

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

	(1) $\ln(v_1)$	(2) $\ln(v_2)$	(3) $\ln(v_3)$	(4) $\ln(v_4)$	(5) $\ln(v_4)$	(6) $\ln(v_4)$
Panel A: it includes all ZATs						
Post × *Bogota*	-0.292***	-0.294***	-0.090***	-0.091***	-0.089***	-0.086***
	(0.044)	(0.044)	(0.015)	(0.016)	(0.016)	(0.016)
Post	0.071***	0.064***	0.065***	0.066***	0.065***	0.063***
	(3.6e-13)	(3.6e-13)	(1.8e-13)	(8.9e-14)	(1.4e-13)	(1.0e-13)
Bogota	0.418***	0.419***	-0.023***	-0.079***	-0.079***	-0.079***
	(0.032)	(0.032)	(0.014)	(0.015)	(0.015)	(0.015)
Observations	1,463,536	1,463,536	1,669,357	1,669,354	1,660,892	1,325,420
Adjusted R^2	0.009	0.009	0.006	0.016	0.015	0.018

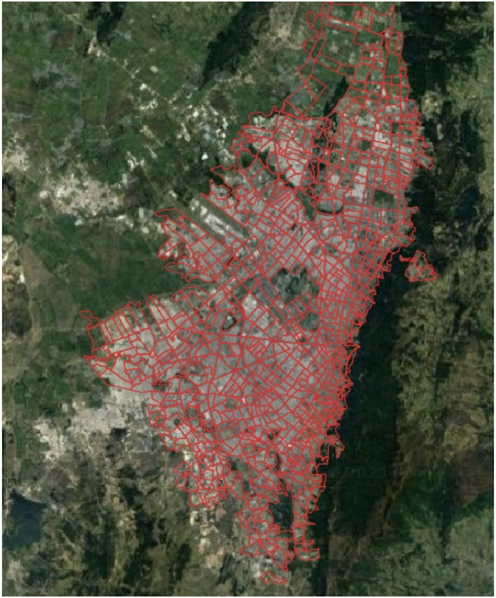
- IADB's Waze data, Jan 2019 – Dec 2021 (at the ZAT level, every 15 min)
- Vel 1&2: congested segments, unweighted and weighted by segment length
- Vel 3&4: all segments, unweighted and weighted

Difference-in-differences estimation by income group

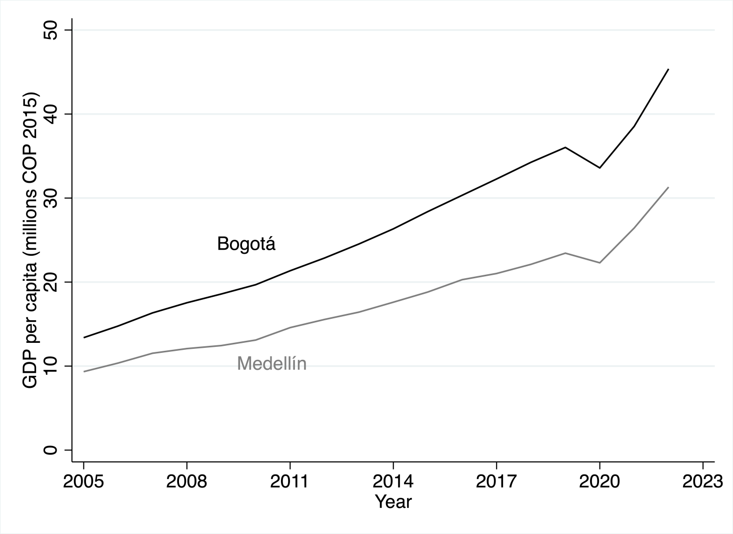
Table 2: Difference-in-difference estimations by income group (6:30-8:30 a.m.)

	(1) all groups	(2) Groups 1&2	(3) Group 3	(4) Group 4	(5) Group 5
Panel A: with expansion factors					
Post × *Bogota*	-0.091***	-0.055*	-0.103***	-0.052**	-0.048**
	(0.016)	(0.030)	(0.020)	(0.023)	(0.020)
Observations	1,669,354	347,336	930,587	534,748	147,468
Adjusted R^2	0.016	0.080	0.031	0.024	0.027
Panel B: without expansion factors					
Post × *Bogota*	-0.091***	-0.044	-0.111***	-0.062*	-0.020
	(0.016)	(0.029)	(0.017)	(0.032)	(0.021)
Observations	1,669,354	342,228	906,908	551,338	159,665
Adjusted R^2	0.016	0.087	0.031	0.025	0.028

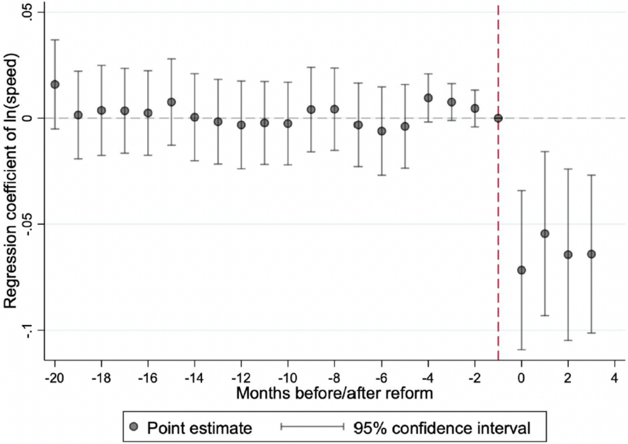
ZATs in Bogota



Is Medellín a good control? Similar GDP trends

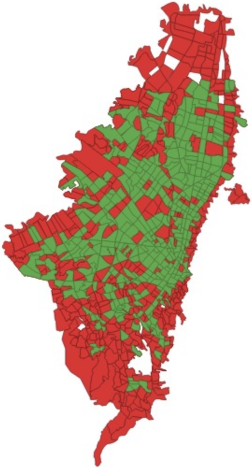


Is Medellín a good control? Parallel trends before the event

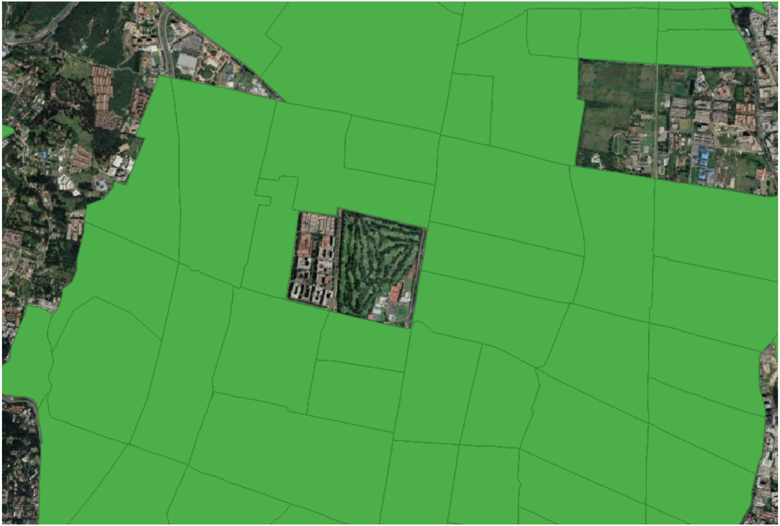


Many ZATs with missing data

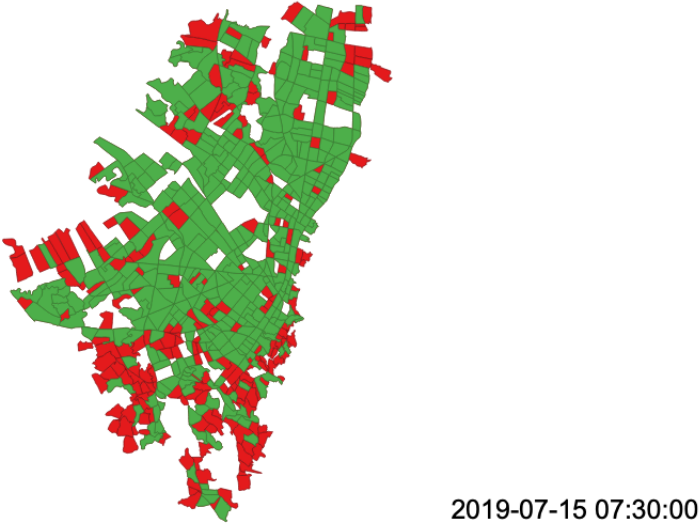
- not sure about criteria followed by Waze to report missing data
- No problem if missing data happens at random
- But what if drivers turn on their Waze app when there is more traffic?



Example of ZAT with missing data



Dropping ZATs with significant missing data (16% of obs.)



Diff-in-diff estimation after dropping marginal ZATs

Table A3: Diff-in-Diff estimations after excluding ZATs with restaurants and cafes (6:30-8:30 a.m.)

	(1)	(2)	(3)	(4)	(5)	(6)
	$\ln(v_1)$	$\ln(v_2)$	$\ln(v_3)$	$\ln(v_4)$	$\ln(v_4)$	$\ln(v_4)$
Panel A: it excludes ZATs in Bogotá in top 25% of food-density ranking						
$Bogota \times Post$	-0.287***	-0.290***	-0.094***	-0.093***	-0.091***	-0.088***
	(0.046)	(0.047)	(0.018)	(0.019)	(0.019)	(0.019)
Observations	1,159,458	1,159,457	1,344,616	1,344,614	1,337,434	1,064,570
Adjusted R^2	0.010	0.010	0.004	0.012	0.011	0.014
Panel B: it excludes ZATs in Bogotá and Medellín in top 25% of food-density ranking						
$Bogota \times Post$	-0.231***	-0.234***	-0.092***	-0.086***	-0.084***	-0.081***
	(0.046)	(0.047)	(0.018)	(0.019)	(0.019)	(0.019)
Observations	1,154,653	1,154,652	1,318,482	1,318,480	1,311,557	1,042,375
Adjusted R^2	0.008	0.008	0.006	0.015	0.015	0.018

Before and after

Table A1: Before-and-after estimations (6:30-8:30 a.m.)

	(1) $\ln(v_1)$	(2) $\ln(v_2)$	(3) $\ln(v_3)$	(4) $\ln(v_4)$	(5) $\ln(v_4)$	(6) $\ln(v_4)$
Panel A: Long pre-treatment period (20 months)						
Post	-0.219***	-0.227***	-0.025***	-0.025***	-0.024***	-0.024***
	(0.007)	(0.007)	(0.001)	(0.001)	(0.001)	(0.001)
Observations	1,439,324	1,439,324	1,565,126	1,565,123	1,558,238	1,237,718
Adjusted R^2	0.009	0.009	0.001	0.001	0.001	0.001
Panel B: Short pre-treatment period (4 months)						
Post	-0.445***	-0.443***	-0.041***	-0.043***	-0.043***	.
	(0.032)	(0.032)	(0.004)	(0.004)	(0.004)	.
Observations	235,417	235,417	286,095	286,095	279,210	.
Adjusted R^2	0.037	0.037	0.005	0.004	0.004	.

Has Bogotá got it right despite the increase in traffic?

- Bogotá's market-based reform constitutes a major innovation in public policy
- The second city in the world to consider such a reform (the first was Cali, also in Colombia)
- The reform also differentiates the daily fee by car characteristics:
  - market value
  - pollution rate (including both local and global pollutants)
- It shows the way to reform existing programs (Mexico City, Sao Paulo) and design future ones (Lima, Santiago)
- It should also be viewed as a first step toward a full-fledged road pricing scheme (with the fee collection going to public transport)

SOME THEORY: AN UNPLEASANT RESULT

A simple model

- Consider a unit mass of a continuum of homogeneous drivers.
- The net surplus that driver i obtains from x_i kms of driving in a given period, say a week, is given by (Barahona-Gallego-Montero, 2020):

$$S_i(x_i, x_{-i}) = B(x_i) - C(x_i) - T(x_i, x_{-i})$$

- where:
  - x_{-i} : total amount of driving excluding i
  - $B'(x_i) = 1 - x_i$ (net benefit vs. bus or remote work)
  - $C'(x_i) = c$
  - $T(x_i, x_{-i}) = \gamma x_{-i} x_i$ (γ is i's **value of time**, i.e., importance of congestion)

The no-intervention outcome: Too much traffic

- i's equilibrium amount of driving in the absence of government intervention solves:

$$\frac{\partial}{\partial x_i} S_i(x_i, x_{-i}) = 0 \tag{1}$$

- Imposing symmetry, $x_i = x_{-i}$, yields the no-intervention amount of driving

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

  and its consumer welfare $S^{ni} = S(x^{ni}, x^{ni})$

- Given the congestion externality, x^{ni} is obviously above the socially efficient (or first-best) level:

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

Restoring the first-best

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

- Driver i solves $\max_{x_i}\{B(x_i) - C(x_i) - \tau^{fb}x_i - T(x_i, x_{-i})\}$, which yields $x_i = x_{-i} = x^{fb}$.
- τ^{fb} is exactly equal to the externality that i imposes upon the remaining drivers evaluated at the socially optimal level of driving.
- In many instances, however, the authority does not have this market-based instrument at her disposal...
- ...she must rely on alternative instruments, such as driving restrictions.

Driving restriction as a proportional rationing scheme

- 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.
- how inefficient?
- for now we adopt the view that a driving restriction works as a proportional rationing scheme (Barahona-Gallego-Montero, 2020)
- proportional rationing: all trips are equally likely to be rationed
  - some highly valuable trips must be canceled
  - some trips of negative social value are taken

An "unpleasant" result

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

- Now, a driver's surplus is given by:

$$S_i^r(x_i^r, x_{-i}^r; R) = R(B(x_i^u) - C(x_i^u) - T(x_i^u, x_{-i}^r)) \tag{2}$$

  where:
    - $R \in [0,1]$ is extent of restriction: $R = 1$ no restriction, $R = 0$ full restriction
    - x_{-i}^r is the total amount driving given R
    - $x_i^u \equiv x_i^u(x_{-i}^r)$ is i's unrestricted amount of driving, so $x_i^r = Rx_i^u$

- Using the envelope theorem:

$$\frac{\partial S^r(\cdot)}{\partial R} = \frac{(1-c)(1-\gamma R)}{2(1+\gamma R)^3} > 0$$

  when $\gamma < 1$ (i.e., when destroying valuable trips > having less congestion)

Never use a lump-sum exemption fee, as in 2020-21

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

$$F^* = (1-R)(1-c)^2/8$$

so a fraction

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

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

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

so that nobody pays it ($z^* = 0$).

cont. **Proposition 3**....

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 ($z^* = 1$).

Key takeaway: a lump-sum fee can only help when γ is neither too high nor too low — very restrictive conditions. A **per-trip fee always works**.

The "unpleasant" result can be fixed: use a per-trip fee

Proposition 4. *The authority can improve upon a driving restriction R with the introduction of a per-trip exemption fee $p \geq 0$ that allows drivers to use their cars in times of restriction: $S^{rp} > S^{r}$ (despite $x^{rp} > x^{r}$) for any $p \in (\underline{p}, \bar{p})$.*

- "rp" denotes a (R, p) restriction
- $x^{rp} > x^{r}$ is intuitively obvious: more trips are now allowed
- The fee sorts out valuable from non-valuable trips — something a lump-sum fee cannot do
- **Always welfare-improving**, unlike Proposition 3 which requires $\gamma > 1$ and $\gamma R < 1$

▸ Lemma 1

The exemption fee is welfare improving

- We know that:
  - $S^{rp}(R, p = 0) = S^{ni}$
  - $S^{rp}(R, p \geq \bar{p}) = S^{r}$
- In addition, it can be shown that $S^{rp}(R, p)$ is concave in p,

$$\left.\frac{\partial}{\partial p} S^{rp}(R, p)\right|_{p=0} > 0$$

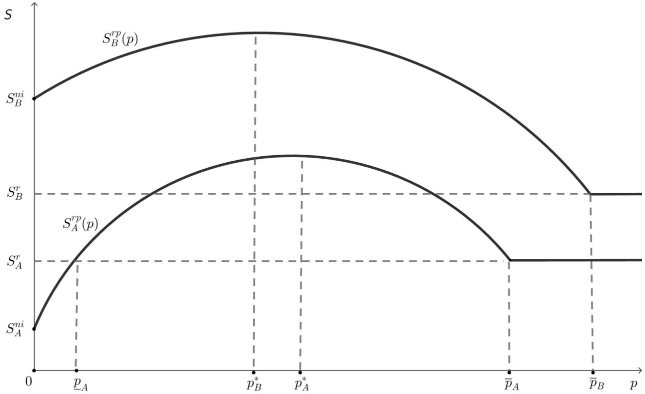
and

$$\left.\frac{\partial}{\partial p} S^{rp}(R, p)\right|_{p \to \bar{p}} < 0$$

- therefore $S^{rp}(R, p) > S^{r}$ for any $p \in (\underline{p}, \bar{p})$, where $\underline{p} \geq 0$ solves

$$S^{rp}(R, \underline{p}) = S^{r}$$

Restrictions with exemptions are always welfare enhancing



A (γ_A high): plain restriction is *good* ($S_A^r > S_A^{ni}$); **B** (γ_B low): plain restriction is *bad* ($S_B^r < S_B^{ni}$). In **both** cases, $S^{rp} > S^r$ for an appropriate p.

Lemma 2

APPLICATION TO BOGOTA

Policy analysis and questions

- Our Dff-in-diff estimations already showed, not surprisingly, that $x^{rp} > x^{r}$
- Next, we want to test for our second prediction, that $S^{rp} > S^{r}$
- This requires to extend the model to the presence of **heterogeneous commuters**....
- ....with different preferences over available "transportation" modes (e.g., car, public transport, remote working)
- How much of the gain 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} and S^{ni})?
- How far is the existing p from p^{*}?
- Distributional implications: how to allocate the exemption-fee collection?

Heterogeneous commuters

Table 3: Individual characteristics by income group

Income group	Fraction of total	Income per-capita	Car ownership	More than one car	Marginal utility of time ($/hr)
1. Low	11%	100	11%	1%	0.70
2. Middle-low	40%	160	21%	2%	1.82
3. Middle	34%	285	39%	6%	3.57
4. Middle-high	10%	569	66%	16%	7.48
5. High	5%	846	82%	36%	14.13

Calibration

- Ideally one would like to estimate/calibrate:
  - (i) preferences for public vs private transport
  - (ii) preferences for remote working
  - (iii) value of time (i.e., marginal utility of time)
- We estimate (i) and (ii) using pre-treatment (i.e., 2019) data
- We could potentially estimate (iii) using post-treatment data
  - for example, with number of drivers paying the exemption fee
  - we have this information only at the aggregate level, not by income level
  - solution: we consider different levels of marginal utilities of time.
  - our mains results do not qualitatively change

Calibration Results

Table 8: Model calibration — first stage

	Public transport use		Remote work	
Income group	Observed	Model Prediction	Observed	Model Prediction
1. Low	95%	97%	1%	3%
2. Middle-low	80%	84%	3%	5%
3. Middle	66%	67%	13%	15%
4. Middle-high	42%	42%	26%	26%
5. High	22%	21%	35%	34%
Overall	70%	72%	10%	12%

Some Model Predictions

- our model predicts a drop in average speed of **6.2%**, close to the diff-in-diff estimate of 6–9%
- however, our model predicts more drivers buying the exemption fee (62,983 per day) than the approximately 55,000 used in calibration
  - the gap can be explained by less than perfect compliance: non-compliant drivers assign a probability of being caught (and paying $100) of 9% or less
  - the gap can also be explained, fully or partially, by higher levels of remote work after covid-19

Results I: Major gains from introducing an exemption fee into the restriction

Table 11: Welfare impact of the reform and alternative policies[a]

	Exemption fee[b]			Road pricing[c]	
Income group	Existing	Free	Optimal	Public Transport	Neutral
1. Low	25.78	-0.07	24.70	78.00	-0.08
2. Middle-low	73.87	111.25	65.04	176.44	-36.95
3. Middle	59.04	157.05	41.77	27.12	148.29
4. Middle-high	-36.07	-88.10	-29.64	-62.82	-25.41
5. High	-80.57	-244.34	-53.76	-5.08	124.22
Total	42.05	-64.21	48.11	213.66	210.08

Result II: Clear winners and losers from the reform

Table 11: Welfare impact of the reform and alternative policies[(a)]

	Exemption fee[(b)]			Road pricing[(c)]	
Income group	Existing	Free	Optimal	Public Transport	Neutral
1. Low	25.78	-0.07	24.70	78.00	-0.08
2. Middle-low	73.87	111.25	65.04	176.44	-36.95
3. Middle	59.04	157.05	41.77	27.12	148.29
4. Middle-high	-36.07	-88.10	-29.64	-62.82	-25.41
5. High	-80.57	-244.34	-53.76	-5.08	124.22
Total	42.05	-64.21	48.11	213.66	210.08

Result III: Remote work explains why high-income individuals lose

- High-income individuals had already adapted to the restriction:
  - access to **multiple cars** (alternate odd/even plates)
  - greater access to **remote work**
- For them, the reform only brought heavier traffic — no restored trips, only slower commutes
- Calibration: baseline remote work = 15% (PBGSD 2021), assumed 50% higher post-reform than 2019 (covid effect)
- Remote work also partly explains the gap between model (62,983 fees/day) and observed ($\sim$55,000)
- **Sensitivity**: if post-reform remote work only 30% above 2019 $\Rightarrow$ welfare gains rise from $42M to $55M (same winners and losers)

Result IV: Minor air pollution implications

- Pre-reform social cost of PM from passenger vehicles: $68.4 million/year (SDG 2018)
- Reform $\uparrow$ emissions by 6.5% $\Rightarrow$ **+$8.8 million/year** in damages — minor relative to $42M in welfare gains
- Full road pricing: emissions $\downarrow$ 12.3% $\Rightarrow$ **$16.7 million in air quality benefits**

Result V: Significant additional gains from full road-pricing

Table 13: Alternative policy designs[(a)]

	Per-trip fees[(b)]		Lump-sum fees[(c)]	
Income group	*Pico y Placa*	Road Pricing	*Pico y Placa*	Road Pricing
1. Low	26.48	80.39	20.90	91.66
2. Low-middle	80.86	177.69	71.98	239.45
3. Middle	69.73	10.20	47.21	65.72
4. Middle-high	-40.58	-61.11	-32.04	-129.24
5. High	-98.24	17.16	-78.74	-104.85
Total	38.25	224.33	29.30	162.75

Conclusions

- Theory and evidence shows that Bogotá got it righ: The introduction of an exemption fee was welfare enhancing (**$42 million per year**), despite the increase in traffic ($\sim$**5–6% drop in average speed**)
- There were winners and losers, no matter how the fee collection is used
- Higher air pollution played a relatively minor role ($8.8 million in extra damages vs. $42 million in gains)
  - big winners (groups 2 and 3): middle-income individuals (**$133 million**)
  - big losers (groups 4 and 5): high-income individuals (-**$117 million**)
- The reform also funds public transport and differentiates fees by pollution rate
- **Full road-pricing potential**: benefits could **quintuple** to **$214 million**, plus $17 million in air quality gains

APPENDIX

Lemma 1: Optimal fee is below the Pigouvian level

- The optimal per-trip exemption fee in a (R, p) restriction is:

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

- The optimal fee is always **below the Pigouvian (first-best) level** τ^{fb}
- Intuition: pricing only restricted cars encourages unrestricted drivers to make more non-valuable trips, so setting p too high is counterproductive
- In Bogotá: existing avg. fee ($8.8) is close to the estimated optimal ($10.2)

Lemma 2: Welfare gain is decreasing in the value of time

- **Lemma**: The welfare gain $S^{rp}(R, p^*(R)) - S^r(R)$ is **decreasing in** γ
- Intuition: the fix is *more valuable* when γ is low
  - Low γ (Scenario B): restriction causes welfare *losses* $\Rightarrow$ any exemption fee helps
  - High γ (Scenario A): restriction is already somewhat efficient $\Rightarrow$ fee only helps if set sufficiently high
- Direct implication: overestimating the value of time *understates* the welfare gains from the reform