Who drives, where, and when? An evaluation of behavioral responses to license-plated based driving restrictions

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16. Abstract In an effort to manage increasing pollution and congestion in cities, regions, and megaregions around the world, governments have implemented various types of driving restriction programs. This report examines the effects of these restrictions and is divided into two chapters. The first provides a critical review of the literature on license-plate-based driving restrictions with a focus on the academic origins and uses of the second-car hypothesis. This hypothesis posits that the policy backfires and leads to increased local pollution due to households purchasing second cars with different final license-plate digits to avoid the restriction. Reviewing 235 papers that reference license-plate- based driving restrictions, we only find nine papers that directly test the second-car hypothesis, generally as part of an appendix or secondary analysis. None presents strong empirical evidence that the second-car hypothesis substantially reduces the efficacy of license-plate-based driving restrictions. The second chapter draws on analysis of a large household travel survey, interviews, and a focus group to better understand these behavioral responses to Mexico City's Hoy No Circula. Purchasing a newer exempt vehicle is a popular approach for wealthier households whose members driver a lot. Two-thirds of vehicles on the road on weekdays and Saturdays have an exempt hologram type. These vehicles are more likely to be driven by wealthier residents during peak hours and in the most congested, central parts of the metropolitan area.		
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Chapter 1. Does Rationing Backfire? A review of the literature

1.1 Introduction

In response to increased urban air pollution and congestion, local and national governments have enacted a variety of programs to limit the amount, location, and type of private vehicles allowed on public roads. License-plate-based driving restrictions, first implemented in cities, such as Mexico City, Santiago, and São Paulo in the 1980s, have experienced a resurgence in popularity after helping reduce Beijing's air pollution in the lead-up to the 2008 Beijing Summer Olympics. These restrictions limit the number of days that vehicles are permitted to circulate in a city or metropolitan area based on the last digit of license plates. For example, Beijing's policy initially restricted automobiles from circulating on alternate days depending on whether the last number of the license plate was even or odd. After the Olympics, regulators adjusted the policy to restrict vehicles from circulating one day per week (L. Wang et al., 2014).

Academic studies examining the effectiveness of license-plate-based driving restrictions in reducing congestion or pollution have produced mixed results. Eskeland and Feyzioglu (1997) and Davis (2008) concluded that Mexico City's *Hoy No Circula* restriction may have even increased pollution by encouraging households to purchase a second, older, and higher polluting car with a different last license-plate digit to avoid the restriction. The notion that license-plate-based restrictions can or do "backfire"—what we henceforth refer to as the second-car hypothesis—has become pervasive throughout the empirical literature, including in studies of Chinese cities where additional public policies may make purchasing a second car difficult. In Beijing, for example, the right to purchase a car requires winning a low-probability lottery.

In addition to purchasing another car that is restricted on different days, drivers have a variety behavioral approaches to avoid the policy, such as adjusting daily or weekly driving schedules, avoiding highly policed areas, or purchasing unrestricted low-emissions vehicles (Gu et al., 2017; Guerra & Millard-Ball, 2017; L. Wang et al., 2014). These behavioral responses may be substantially easier and less burdensome than purchasing a second car, particularly for low- and moderate-income households. If license-plate-based car restrictions are not working, it is important for regulators to understand why and adjust policies accordingly.

This chapter provides the first systematic literature review of the empirical evidence for and prevalence of the second-car hypothesis in explaining the success or failure of license-plate-based driving restrictions. In doing so, we also provide the first formal review of the literature on license-plate-based driving restrictions more generally. Through this review, we emphasize how policy design, urban context, and behavioral factors likely influence whether and by how much license-plate-based restrictions might reduce driving and associated local pollution. The remainder of the paper is organized as follows. Section 1.2 describes our general approach to selecting, organizing, and summarizing academic papers that discuss license-plate-based restrictions and the second-car hypothesis. Section 1.3 traces the hypothesis' origins, diffusion, and use in the academic literature. Section 1.4 focuses on the empirical evidence supporting or contradicting the second-car hypothesis. Section 1.5 summarizes findings about the relationship between license-plate-based restrictions and local pollution. Section 1.6 provides a theoretical framework for how different behavioral responses to license-plate-based restrictions affect pollution and congestion and provides evidence from the literature on the nature and scale of these responses. The final section concludes with a summary of the results and key takeaways for researchers and policymakers.

1.2. Methodology

We take two overlapping approaches to identifying and selecting the studies reviewed in this paper. First, we begin with two seminal papers that present, test, and discuss the second-car hypothesis (Davis, 2008; Eskeland & Feyzioglu, 1997) and trace all of the papers citing them using *Google Scholar* and The University of Pennsylvania's online academic search system *Franklin*. Through this process, we identify 198 different references to Eskeland and Feyzioglu (1997) and 592 references to Davis (2008). We then exclude papers that do not reference the two seminal papers in the context of driving restrictions or have not undergone peer review. As an example, we exclude Carson (2010) because it cites Davis (2008) only as an example of someone investigating existing pollution mitigation strategies, with no reference to license-plate based restrictions. This filtering reduces the total number of citations to 117. We next conduct a general keyword search of any peer-reviewed papers that refer to “license plate restrictions” or “driving restrictions”. After excluding papers referring to different types of driving restrictions, this process adds another 118 papers to our database.

Table 1.1 provides a summary of the 235 papers included in our review. In total, we identify 145 peer-reviewed papers that mention the second-car hypothesis and another 90 papers that mention license-plate-based restrictions but do not reference the second-car hypothesis. Most papers (152) only briefly mention license-plate restriction programs, generally to describe contextual conditions or provide an example of a general policy to influence driving or vehicle purchases. For example, Zhang et al. (2020) list exemptions from license-plate based restrictions as one of several possible policies to encourage the adoption of automated vehicles.

Table 1.1 Total papers reviewed by focus on license-plate-based restrictions and reference to the second-car hypothesis

Paper category	References second-car hypothesis	Does not reference second-car hypothesis	Total
Briefly mentions license-plate restriction programs	94	58	152
Examines effects of license-plate restriction on congestion or pollution	37	3	40
Simulation or examines effects on vehicle purchases, crime, or another outcome	14	29	43
Total	145	90	235

Of the remaining 83 papers, 40 provide empirically estimates of the effects of license-plate-based restrictions on pollution or congestion. We exclude simulations from this category since the findings depend on the simulation inputs. For example, Pu el al.’s (2015) finding that Hangzhou’s license-plate based restrictions reduced vehicle travel and pollution by 7% to 10% depends on the assumption that the policy reduced driving by 20% in the restricted zone at restricted times of day. The final category of papers includes simulations and papers studying the effects of restrictions on some other outcome, such as crime, transit use, or vehicle purchases. We discuss both categories of papers in greater detail in section 1.4 and section 1.5.

1.3. Origins, diffusion, and use of the second-car hypothesis

Eskeland and Feyzioglu (1997) provide the first peer-reviewed empirical study of Mexico City's license-plate based car restriction *Hoy No Circula*. Creating a predictive model of aggregate gasoline consumption prior to the policy and applying the model to data after the policy's enactment, Eskeland and Feyzioglu (1997) find that gasoline consumption increased significantly more after the policy than their model would have predicted. The authors attribute this increase to the second-car hypothesis. Two earlier working papers use similar language to discuss the likely effects of *Hoy No Circula* (Eskeland, 1992; Levinson & Shetty, 1992). Neither working paper provides empirical evidence to support the claim. Levinson and Shetty (1992) summarizes pollution-restriction programs in several cities and states that *Hoy No Circula* had "backfired....with families having purchased second cars, usually older and dirtier, rather than face time on Mexico City's crowded public transit system (Levinson & Shetty, 1992, p. 32)." Eskeland (1992) presents a similarly worded assertion and argues that a gasoline tax would be more efficient than a license-plate-based restriction. Between 1997 and 2007, two peer-reviewed papers cite Eskeland and Feyzioglu (1997) as evidence that second-car purchases make license-plate-based driving restrictions ineffective and share the same lead author (Eskeland et al., 1998; Eskeland & Xie, 1998).

Davis (2008), the second foundational paper, is the first to formally test and find evidence in support of the second-car hypothesis. The focus of the paper is a series of regression discontinuity designs examining whether local pollutants increased or decreased after *Hoy No Circula* was implemented in Mexico City. To explain why pollution did not decrease and possibly increased, the study also examines shifts in metro system use and second-hand car purchases. Presenting a regression discontinuity design on annual car sales, Davis (2008) concludes that *Hoy No Circula* led to a statistically significant uptick in car sales.

1.3.1. Diffusion and use of the second-car hypothesis

Starting in 2008, the number of papers citing the second-car hypothesis increases sharply (Figure 1.1). This increase likely corresponds to Davis (2008) but also to Beijing's implementation of a restriction policy in the lead-up to the 2008 Summer Olympics and the spread of license-plate-based restriction policies to a variety of additional Chinese cities. Of the total 145 peer-reviewed studies that reference the second-car hypothesis, 19 cite Eskeland and Feyzioglu (1997), 48 cite Davis (2008), and 42 cite both. Another 36 papers cite neither, but cover similar topics, refer to the same cities, and use similar language of backfiring when referencing the second-car hypothesis. Several studies cite a 2014 Guardian article (Mathiesen, 2014) about license-plate-based restrictions as evidence of a policy backfire (L. Li et al., 2020; Tan et al., 2017).

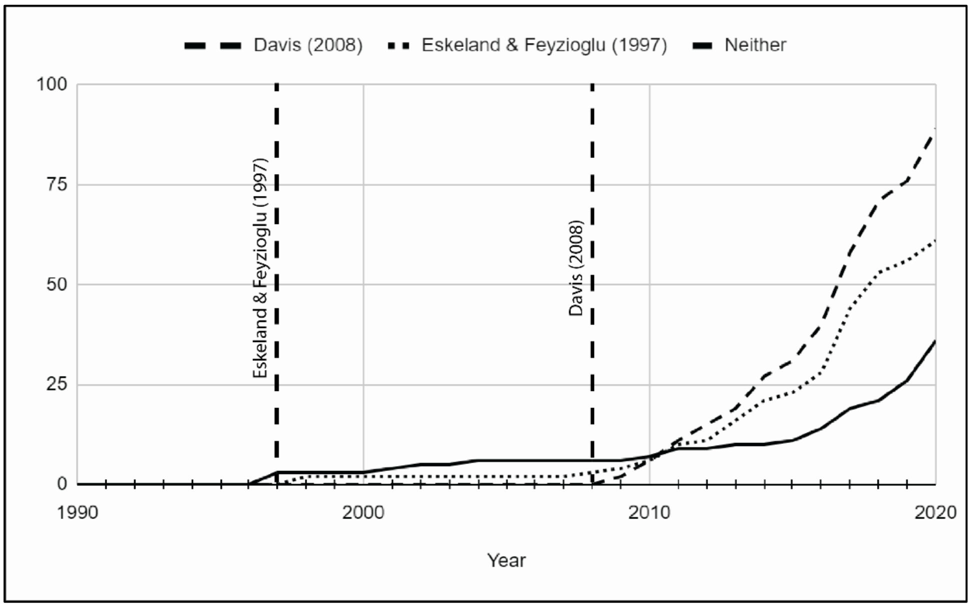


Figure 1.1 Cumulative total number of peer-reviewed publications referencing the second-car hypothesis and seminal papers from 1995 to 2020.

1.3.2. Referencing the second-car hypothesis

The 145 academic papers that discuss the second-car hypothesis examine a variety of geographies (Figure 2) and topics. The vast majority (141) examine some type of environmental regulation. About a third (51) study restriction policies directly and are mostly based in Latin America or China. Mexico City and Beijing's programs have received particular academic attention.

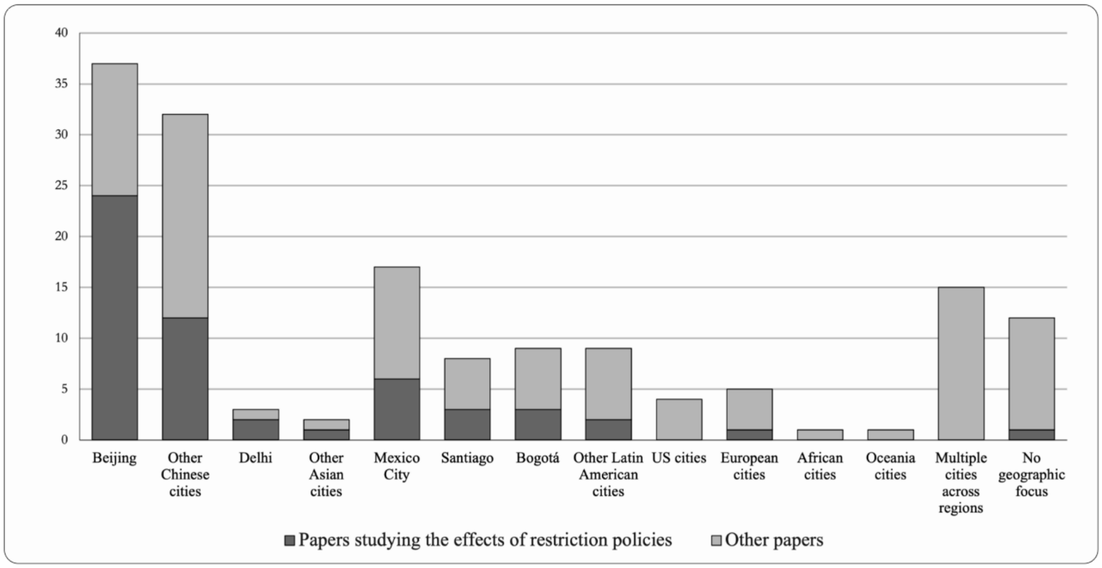


Figure 1.2 Geographical distribution of papers referencing the second-car hypothesis by focus on license-plate based restrictions. Papers with multiple study cities are counted multiple times.

The remaining two-thirds (94 papers) are from all over the world and cover a wide range of research topics, including travel credits (X. Wang et al., 2012), car lotteries (Yang et al., 2014), and subway expansion (S. Li et al., 2019). Four papers do not discuss environmental policies at all. For example, Durango (2011) focuses on identifying the areas of Bogota and Medellin most impacted by traffic congestion and potential congestion mitigation strategies. Matlock et al. (2019), thematically the least related to driving restrictions, examine ways to provide public-health communications about Valley Fever, a fungal respiratory disease, in central California.

Across studies, the second-car hypothesis is frequently referenced to describe a failed environmental policy or to discuss the risk of a policy having unintended consequences. Most (94) reference the second-car hypothesis in their introduction, literature, or background sections to motivate the study under consideration. Most treat the second-car hypothesis as an established fact. For example, Parry (2012) references the second-car hypothesis to dismiss license-plate-based driving restrictions as a potential congestion-mitigation strategy and to help motivate the importance of GPS-based congestion charges. Matlock et al. (2019, p. 11) reference the second- car hypothesis as a caveat about a public-health policy centered on identifying high-risk Valley Fever days and communicating these to the public: “An unintended consequence of a Valley Fever ‘bad day’ could involve individuals conducting risky behaviors on a ‘good day’ that still falls within the Valley Fever exposure season.”

Twenty-one additional papers use terms, such as backfiring, counterproductive, or unintended consequences when discussing the second-car hypothesis in relationship to environmental regulation. For example, Jakob (2017, p. 97) discusses Ecuador's policies to reduce greenhouse-gas emissions and uses the license plate-based driving restriction as “...a salient example of a policy that is relevant to climate change...” but one that is “...unlikely to achieve its goal and might even result in exacerbating the problem it intends to address.”

Although the existing literature tends to frame the second-car hypothesis as a universal phenomenon, most papers (80) reference Mexico City’s policy specifically. Even the term backfiring has a direct connection to Eskeland and Feyzioglu’s (1997) paper title. Moreover, studies that do not mention Mexico City directly often reference findings from Mexico City. Of the papers that cite neither Eskeland and Feyzioglu (1997) nor Davis (2008), twelve mention *Hoy No Circula* or Mexico City when discussing the second-car hypothesis. Nevertheless, the existing literature uses the second-car hypothesis to discuss a variety of environmental policies in cities and countries throughout the globe (Figure 2).

Papers that examine the effects of license-plate-based driving restrictions reference the second-car hypothesis for a wider range of reasons, such as explaining null results (Ye, 2017), describing why findings might differ across places (Gu et al., 2017; Xie et al., 2017), motivating a specific research design (Gu et al., 2017; Guerra & Millard-Ball, 2017), or explaining why short-run and long-run policy effects might differ (Ma & He, 2016; M. Xu et al., 2017). For example, Ma and He (2016) consider the second-car purchases a policy adaptation that could make pollution worse in the long run despite initial improvements. Most, however, simply present the second-car hypothesis as an established fact or typical finding in the paper introduction or literature review. Xiao et al. (2019, p. 299), for example, reference Eskeland and Feyzioglu (1997) before attributing an increase in Beijing’s private vehicle fleet to “…the fact that some consumers purchased additional cars to circumvent the driving restriction policy.”

1.4. Strength of the second-car hypothesis

For all its prominence in the academic literature and popular press, the second-car hypothesis remains lightly studied and has relatively weak empirical support. Just nine studies formally test whether license-plate-based restrictions increase second car purchases. These empirical tests produce mixed results and are generally included in appendices or supplementary materials rather than in a position of central interest. Moreover, the original papers examining the second-car hypothesis do not present strong weak evidence in its support. In revisiting this evidence, we do not intend to criticize the authors or their papers. Eskeland and Feyzioglu (1997) produced the seminal academic paper on license-plate-based driving restrictions and Davis (2008) wrote the most cited and likely best-regarded paper on license-plate-based driving restrictions. Instead, we intend to demonstrate the weaknesses of the second-car hypothesis' foundations before reviewing more recent empirical evidence. While some households may indeed purchase a second car in response to restriction policies, there is little to suggest that this causes the policies to backfire.

Eskeland and Feyzioglu (1997) present the second-car hypothesis as a way to explain a statistically significant increase in fuel expenditures in the years immediately after *Hoy No Circula.* The authors test this explanation by developing a household-level model of car purchases. Strikingly, the authors find that although some households would likely purchase a second car to avoid the policy, "a somewhat greater number of households would want to reduce their number of cars (Eskeland & Feyzioglu, 1997, p. 400)." The authors dismiss these empirical findings, however, with an observation that aggregate used car sales increased in Mexico City after *Hoy No Circula* and an anecdotal assertion that "…most observers believe that the opposite occurred (Eskeland & Feyzioglu, 1997, p. 393)." The initial finding that fuel expenditures increased due to *Hoy No Circula* is also relatively weak. The research design relies on the assumption that differences in fuel expenditures are entirely attributable to *Hoy No Circula*. The policy's implementation, however, coincides with the end of a nearly decade-long recession that had substantially reduced household income and almost certainly reduced car purchases and household driving. The only economic controls in the model of fuel expenditures are the quarterly number of international phone calls, which is used as a proxy for household prosperity. Davis (2008, p. 64) conducts a similar test of gasoline sales using a regression discontinuity design and concludes that *Hoy No Circula* is associated with, "a small and statistically insignificant change in gasoline sales." Employing another series of regression discontinuity designs, Davis (2008, p. 68) reports that *Hoy No Circula* is associated with an increase in the number of registered vehicles that "is statistically significant at the 1 percent level." The analysis, however, includes only 30 data points that overlap with multiple additional exogenous shocks, such as a major recession and a redesign of the policy to exempt cars with catalytic converters. Moreover, a shifting linear trend in increased vehicle sales (Davis, 2008, fig. 9, 2008, fig. 10) begins in 1986, three years prior to *Hoy No Circula*.

To test whether the reported results depend on the specification, we download the INEGI data on vehicle sales and re-estimate models of vehicle sales in Mexico City, other nearby states, and the entire country (Table 1.2.) For convenience, we report the original parameter estimates (Davis 2008, Table 10), which differ slightly from our own estimates, likely due to INEGI making minor revisions to the 2004 and 2005 data. We choose to present the model with the fifth order polynomial time trend. The fourth and sixth order time trends produce consistent results.

Table 1.2 Regression discontinuity estimates of the relationship between Hoy No Circula and annual vehicle registrations (natural log) using a 5th order polynomial time trend

	Parameter Estimates		**Standard errors**		
Geography	**Davis (2008)**	**Re-Estimate**	**Unadjusted**	**Newey West[1]**	**Bootstrapped[2]**
Mexico City	0.189	0.198	0.097.	0.094*	0.147
Mexico State	NA	0.220	0.225	0.233	0.986
Aguascalientes	NA	0.186	0.063**	0.050**	0.186
Puebla	NA	0.160	0.105	0.081.	0.160
Queretaro	NA	0.166	0.088.	0.078.	0.146
Country	NA	0.164	0.035***	0.076*	0.131

Notes: Significance codes '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1; [1]Newey West standard errors apply one-year lag. [2] Bootstrapped standard errors estimated over 50,000 iterations.

These robustness checks indicate that increased vehicle sales in Mexico City are not related to *Hoy No Circula*. First, *Hoy No Circula* appears to have had a similarly sized effect on vehicle registrations in Mexico City as it did throughout the country and in multiple states without license-plate based restrictions. In the case of Aguas Calientes, Queretaro, Puebla, and the country, the parameter estimates are statistically different from zero at the 10 percent level when applying

Newey West standard errors. By contrast, vehicle registrations do not appear to increase in Mexico State, much of which is subject to *Hoy No Circula*. Second, the confidence level of 1 reported in the paper is likely a typo and should be a confidence level of 10 (Davis 2008, Table 10). The Newey West correction for serial correlation, moreover, decreases rather than increases the size of the standard errors. Using bootstrapping to account for the random ways that other exogenous shocks might drive the findings, the standard errors increase substantially. Third, reducing the sample to an equal number of years before and after the discontinuity does not produce statistically significant results at the 10 percent level for Mexico City using any of the reported higher order polynomial time trends. Thus, although the study provides the first empirical evidence supporting the second-car hypothesis, the evidence is not strong. In an updated analysis that examines a shift in the restrictions to apply on Saturdays, Davis (2017) makes no mention of second-car purchases.

1.4.1 Other evidence for and against the second-car hypothesis

Four additional studies test the second-car hypothesis by comparing shifts in aggregate total or used vehicle sales before and after the policy implementation. Although all but one of these studies find modest increases in registrations, these studies also rely on time-series data with few observations immediately before and after policy implementation. As with Davis (2008), Bonilla (2019) observes a modest increase in used vehicle sales after the tightening of Bogota's license plate restriction and concludes that the study provides mild evidence that the new policy increased used vehicle sales. Gallego et al. (2013) and Chen et al. (2020) provide additional spatial controls and find modest, statistically significant increases in car sales and registrations in Santiago and eleven Chinese cites with restrictions relative to other Chilean and Chinese municipalities and cities without restrictions. Guerra and Millard-Ball (2017) include controls for other Mexican metropolitan areas and conclude that vehicle registrations in metropolitan Mexico City's increased no more quickly than in the rest of Mexico.

Five papers, including Eskeland and Feyzioglu (1997), rely on household-level data and generally find a weak relationship between the policy and household's second car purchases. For example, Guerra and Millard-Ball (2017) find that households with a restricted vehicle are no more likely to own a second car than similar households with a similarly aged but unrestricted vehicle. Gu et al. (2017) look at the travel behavior of households with one restricted and one unrestricted car compared to households with two unrestricted cars. Although the data sample is small, it appears that these households with one restricted car increase the share of trips by car as one household member picks up and drops off others.

Barahona et al. (2020) report that although more households own cars in Santiago than the rest of Chile, higher incomes and household structure explain this difference, not the car-restriction policy. Moncada et al. (2018) employ a similar methodology to look at changes in households' probability of purchasing a second vehicle in Bogota and Villavicencio, Colombia, using household travel surveys from 1996 and 2011 in Bogota and 2008 and 2012 in Villavicencio. Including controls for working age adults, children, household motorcycles, and inconsistent linear income categories, the authors find a 20% increase in the probability of purchasing an additional vehicle for residents of Bogota relative to residents of Villavicencio. Despite comparing a capital city of 7.5 million residents to a city of 500,000 at different time periods, the authors attribute the entirety of this 20% increase to Bogota's 1998 restriction policy and the policy's tightening a decade later.

In addition to the empirical analyses, Gu et al. (2017), Guerra and Millard-Ball (2017), and Barahona (2020) also describe the small share of households that potentially avoid the policy through the second-car hypothesis. In Beijing, only 2.2% of households own more than one car (Gu et al., 2017). In Mexico City, only 1.2% of households own at least two cars that are both likely to be subject to the driving restriction (Guerra & Millard-Ball, 2017). In Santiago, less than 5% of households own more than one car and many own newer, exempt vehicles (Barahona et al., 2020). Although Moncada et al. (2018) do not present statistics on their dependent variable, just 3.3% of households reported having two or more cars or pickups on Bogota's 2011 household travel survey (Secretaría Distrital de Movilidad de Bogotá, 2013). In all three cities, most households with two or more cars are wealthy and would likely own two or more cars regardless of the driving restrictions. In short, even if some households purchase second cars to avoid the policy, the second-car hypothesis is unlikely to be the most prominent cause of restriction programs' outcome.

1.5. The effect of license-plate-based driving restrictions on pollution and congestion

This section summarizes the results of the 40 papers that examine the effects of license-plate based driving restrictions on pollution and congestion. The second-car hypothesis originated to explain findings that Mexico City's *Hoy No Circula* increased gasoline consumption (Eskeland & Feyzioglu, 1997) and failed to reduce pollution (Davis, 2008). Thus, whether license-plate-based restrictions increase or decrease pollution is essential to the theoretical and empirical importance of the second-car hypothesis. Better understanding the range of findings about the relationship between license-plate-based driving restrictions, congestion, and pollutions is also of general academic and policy interest.

Across the papers reviewed, we find a wide range of results. Twenty papers report that license-plate-based driving restrictions decreased pollution or congestion, nine find no effect or an inverse effect, and eleven present mixed results (Table 1.3). In addition to the wide range of findings, the papers use a variety of research approaches in places with differently designed policies to examine a variety of outcomes. We discuss these differing outcomes and designs throughout this section and the next.

Table 1.3 Summary findings of 40 papers examining the results of license-plate-based driving restrictions

Publication	Location	Main research approach	Main findings
Studies finding license-plate based restrictions reduced pollution or congestion			
Viard and Fu (2015)	Beijing	Before and after (odd-even and one-day per week) examination of daily air quality index and hourly television viewership (regression discontinuity design)	Reduced pollution and increased television viewership (assumption related to less time spent commuting)
Y. Liu et al. (2016)	Beijing	Before and after (odd-even and one-day per week) examination of daily air quality index and hospitalizations (regression discontinuity design)	Reduced pollution and hospital admissions
X. Lu (2016)	Beijing	Before and after examination of reducing policy hours and later increasing penalty for violations on air quality index (regression discontinuity design)	Strengthening the policy associated with improved air quality. Weakening the policy associated with reduced air quality
Gu et al. (2017)	Beijing	Compares household behaviour on restricted days to household behaviour on unrestricted days using travel diaries	Decreased car trips on restricted days
Q. Liu et al. (2017)	Beijing	Compares daily hospital admission for respiratory issues on high restriction and low-restriction days using #4 death license-plate (roughly 14% instead of 21% banned)	Reduced hospital admissions on days with more cars banned

W. Zhang et al. (2017)	Beijing	Examine unique subway card data to identify users that only use the subway on one consistent day per week, assume these switched from driving due to policy, and estimate pollution reduction from removing trip	A small shift in trips from private cars to metro (0.12%) with a corresponding decrease in CO2 emissions
Zhong et al. (2017)	Beijing	Compares daily/hourly air quality index, traffic congestion index, and daily ambulance call data using "death" plate to compare high and low restriction days	Lower pollution, congestion, and hospital admissions on days with more vehicles banned
Yang et al. (2018)	Beijing	Compares daily public transit use, taxi use, and congestion using "death" plate to compare high and low restriction days	Reduced congestion and increased taxi and transit use on days with more restricted vehicles
S. Chen, Qin, et al. (2020)	Beijing	Examines shift in traffic congestion index using #4 death plate design by geography and compares to shifts in travel speeds.	Finds that traffic congestion index increases by 0.5 to 0.7 on days with fewer cars restricted.
Z. Liu and Kong (2021)	Beijing	Compares differences in changes in air pollution index on weekdays and weekends in Beijing relative to Tianjin using a differences-in-differences approach.	Finds a 3%-5% reduction in pollution from the license-plate policy with another 8% to 12% reduction attributable to other policies.
Rajabov et al. (2020)	Beijing	Compares multiple particulates using "death" plate to compare high and low restriction days	Finds reductions in AQI, PM2.5, PM10, CO, and NO2, but no difference in O3
Yang et al. (2020)	Beijing	Examines shift in vehicle density using #4 death plate design by geography and compares to shifts in travel speeds	Statistically significant increase in vehicle density and decrease in travel speeds on days when fewer cars are restricted. Effects most pronounced in central locations
B. Zhang et al. (2020)	Beijing	Compares household mode choice at restricted unrestricted hours on weekdays and weekends using travel diaries	Residents traveling at restricted hours less likely to use a car relative to differences between the same time periods on unrestricted weekends
M. Zhang et al. (2020)	Beijing, Tianjin	Before and after examination of daily air quality index (regression discontinuity design)	Modest air quality improvement in both cities
Rao et al. (2017)	Delhi	Intercept survey asking respondents about effects of restriction on current and recalled travel behaviour	Increased speeds, shorter travel times, and shift from cars to transit
Mishra et al. (2019)	Delhi	Compares PM1.0 and PM2.5 on six days during temporary odd-even restriction to three days in weeks preceding restriction on three major arterials.	Particulate matter decreased by an average of 5% on arterials during restricted hours
Han et al. (2020)	Jinan	Compares daily CO, PM10, and mortality rates before and after temporary restrictions	Reduction in CO (46.6%), PM10 (33.1%), and morality (0.313 per million people per percent of PM10)
Z. Liu et al. (2018)	Langfang	Before and after (every other day vs. one day per week) comparison of non-compliance, travel speed, and traffic volumes by space and time-of-day (regression discontinuity design)	Traffic speeds increased with more frequent restriction
Carrillo et al. (2016)	Quito	Before and after examination of hourly CO in restricted zones and times relative to unrestricted times and zones	Improved air quality at restricted times and locations
Barahona et al. (2020)	Santiago	Compares the share of high-polluting vehicles in the fleet in Santiago relative to other municipalities over time (regression discontinuity design)	Santiago has significantly fewer older cars without catalytic converters and these emit less pollution on average
Studies with negative or null findings			
L. Wang et al. (2014)	Beijing	Compares residents' mode choice on days when household vehicle is restricted using travel diaries	No significant change in probability of traveling by car instead of transit, bike, or foot
Xiao et al. (2019)	Beijing	Before and after examination of daily air quality	No evidence of improved air quality

Bonilla (2019)	Bogota	Before and after examination of two phases (peak hours only and 6am-8pm restrictions) on hourly CO (regression discontinuity design)	No evidence of improved air quality
S. Chen, Zheng, et al. (2020)	Chinese cities (11)	Before and after comparison of annual PM10 and car registrations in eleven cities with restrictions compared to 100 without restrictions	Air quality worsened and car registrations increased in cities with restrictions

Ye (2017)	Lanzhou	Before and after examination of hourly air quality index (regression discontinuity design)	No evidence of improved air quality. Some evidence of worsened air quality
Eskeland and Feyzioglu (1997)	Mexico City	Before and after comparison of quarterly gasoline consumption	Increased gasoline consumption
Davis (2008)	Mexico City	Before and after examination of hourly, daily, and weekly air quality (regression discontinuity design)	No evidence of improved air quality. Some evidence of worsened air quality
Davis (2017)	Mexico City	Before and after examination of policy change to include Saturday restrictions on air quality (regression discontinuity design)	No evidence of improved air quality
Guerra and Millard-Ball (2017)	Mexico City	Compares the daily vehicle travel of households with a single banned car that of similar households with a single car that is likely exempt by vehicle age using travel diaries	No evidence of reduced driving from households with a banned car
Studies with mixed findings			
Sun et al. (2014)	Beijing	Compares peak travel speeds and daily PM10 using "death" plate to compare high and low restriction days	Traffic speeds increased on days with more restricted vehicles, but no air quality improvement
Ma and He (2016)	Beijing	Before and after examination of hourly air quality index	Air quality improved in short run but worsened in the long run
Xie et al. (2017)	Beijing	Before and after examination of daily air quality index	Air quality improved in short run but not in the long run
W. Zhang et al. (2017)	Bogota	Before and after examination of hourly air quality measures (regression discontinuity design)	Decrease in NO but increases in NO2, NOx, and O3.
Z. Chen et al. (2021)	Chinese cities (15)	Compares change in PM2.5 over time relative to 158 control cities using a differences-in-differences approach with propensity score matching.	No evidence of reduced pollution across the full sample but variation in results across regions and city types with an 11% reduction in air pollution outside of provincial capitals.
Chowdhury et al. (2017)	Delhi	Compares satellite-based PM2.5 estimates during a 15-day odd-even restriction to time-periods immediately before and after the restriction.	Reduces PM2.5 by 4% to 6%, which is within the 10% uncertainty range of the satellite-based estimates and therefore a null finding.
Mohan et al. (2017)	Delhi	Compares PM2.5, traffic speeds, and congestion measures immediately before, during and after implementation of two-week odd-even scheme	Car volumes reduced by 7% to 19% but increase in exempt auto rickshaws, two-wheelers, and buses. Speeds up around 5% on average and no measurable change in pollution.
Joshi et al. (2020)	Delhi	Compares PM2.5 measures immediately before and after implementation of odd-even scheme	Pollution decreased immediately after policy implementation with a subsequent increase, likely due to forest fires.
Huang et al. (2017)	Lanzhou	Before and after examination of hourly air quality measures (regression discontinuity design)	Air quality improved in short run but not in the long run
Gallego et al. (2013)	Mexico City, Santiago	Before and after examination of daily air quality measures (regression discontinuity design) with municipal comparison groups in Chile but not Mexico	Air quality improved in short run but worsened within a year
de Grange and Troncoso (2011)	Santiago	Before and after examination of long-term policy and short-term emergency measures on hourly vehicle flows and daily transit ridership	Long-term policy of excluding cars with catalytic converters not associated with reduction in driving. Short-term emergency measures extending the ban to all vehicles associated with reduced driving and increased metro use

For the twenty papers with positive findings, the most common research design is to examine measures of air quality from air quality monitoring stations before and after policy implementation while controlling for other temporal predictors of pollution, such as the weather and time-of-day. Regression discontinuity designs, with the year or month of policy implementation identified as the discontinuity, are particularly common. Several papers include additional control groups. For example, Carrillo et al. (2016) use a differences-in-differences approach instead of a discontinuity design and conclude that Quito's license-plate based restrictions reduced carbon emissions by 9% to 11% during peak traffic hours from monitoring stations within the restriction zone compared to monitoring stations outside of the zone. Z. Liu and Kong (2021) use a differences-in-differences approach comparing Beijing to Tianjin to try to net out the effect of the license-plate-based restrictions from other policies to reduce local pollution. The authors conclude that this approach leads to a smaller estimated reduction in pollution than Viard and Fu's (2015) estimates. While both studies find a 15% to 20% reduction in Beijing's local pollution, Z. Liu and Kong (2021) only attribute the license-plate-based restriction with a 3% to 5% reduction in pollution.

The next most common research approach relies on a location-specific aversion to license-plates ending in the number 4, which is associated with the Chinese word for death. On days that restrict the numbers 4 and 9 from circulating, Yang et al. (2018) report that just 14% of Beijing's cars are banned compared to 20% to 22% on other days. Days with fewer restricted vehicles are associated with a 3% to 20% increase in ambulance calls for heart and fever-related symptoms, 22% higher congestion, and 12% higher daily NO2 concentrations (Zhong et al., 2017). The "death" plate method has recently also been used as an exogenous instrument to tease out causal relationships between congestion and travel speed (Yang et al., 2020) and congestion and pollution (S. Chen, Qin, et al., 2020). Other general approaches include comparing household-level travel behavior on banned days (Gu et al., 2017), at banned times of day (B. Zhang et al., 2020), and before and after the policy (A. M. Rao et al., 2017).

The nine papers that produce null or inverse findings use similar methodological approaches. The majority employ a before-and-after approach, generally a regression discontinuity design. Several also include additional controls using a differences-in-differences approach instead of a discontinuity design. For example, S. Chen, Zheng et al. (2020) find that pollution, car registrations, and pollution per car increased rather than decreased in eleven Chinese cities with license-plate based driving restrictions compared to 100 cities without restrictions. Two papers use household-level survey data. Guerra and Millard Ball (2017) find no substantial drop in vehicle travel for households with just one banned car compared to households with a similarly aged car that is eligible to be exempted from the policy after passing a tailpipe emissions check. L. Wang et al. (2014) use a similar approach to Gu et al. (2017) but do not find a statistically significant change in the probability of traveling by car on days when Beijing's residents are banned from driving.

The eleven papers with mixed results also generally use regression discontinuity designs or similar approaches to examine air quality before and after policy implementation. The most common mixed finding is that air quality improved immediately after the policy intervention but not in the long run (Gallego et al., 2013; Huang et al., 2017; Ma & He, 2016; Xie et al., 2017). However, the timing of restriction policies often coincides with other, sometimes substantial, temporal changes that are also likely associated with pollution and congestion. Claims about long-run influences of driving restrictions are not well-suited to regression discontinuity designs. The further the pollution data move from the days, weeks, and months immediately before or after policy implementation, the less likely that differences in pollution have anything to do with driving restrictions.

Several studies find improvements along one dimension but not along another. For example, Sun et al. (2014) employ the "death" plate design and find increased traffic speeds but no change in emissions on days with more restricted vehicles. Types of pollutants may also matter. W. Zhang et al. (2017) use a regression discontinuity design on pollutants in Bogota and find the policy associated with decreases in NO but increases in NO2, NOX, and O3. Rajabov et al. (2020) find Beijing's policy associated with statistically significant decreases in most pollutants and an overall air quality index but not in O3. Total pollution likely also matters. For example, Chowdhury et al. (2017) find Delhi's policy reduces PM2.5 by 4% to 6%, but that this is within the 10% uncertainty of the satellite-based estimates and therefore a null finding. However, Mohan et al. (2017) report that cars contribute just 5% of Delhi's total PM2.5 and these reductions are offset by increases in unrestricted auto rickshaws, motorized two-wheelers and taxis. A recent study of Covid-19 restrictions across 325 Chinese cities finds that lockdowns reduce overall pollution by 12% relative to the cities without lockdowns, but that differences vary substantially by pollutant (M. Wang et al., 2021). For example, PM2.5 and PM10 decreased by 13% to 15%, but SO2, NO2, and CO only decreased by 3% to 4%.

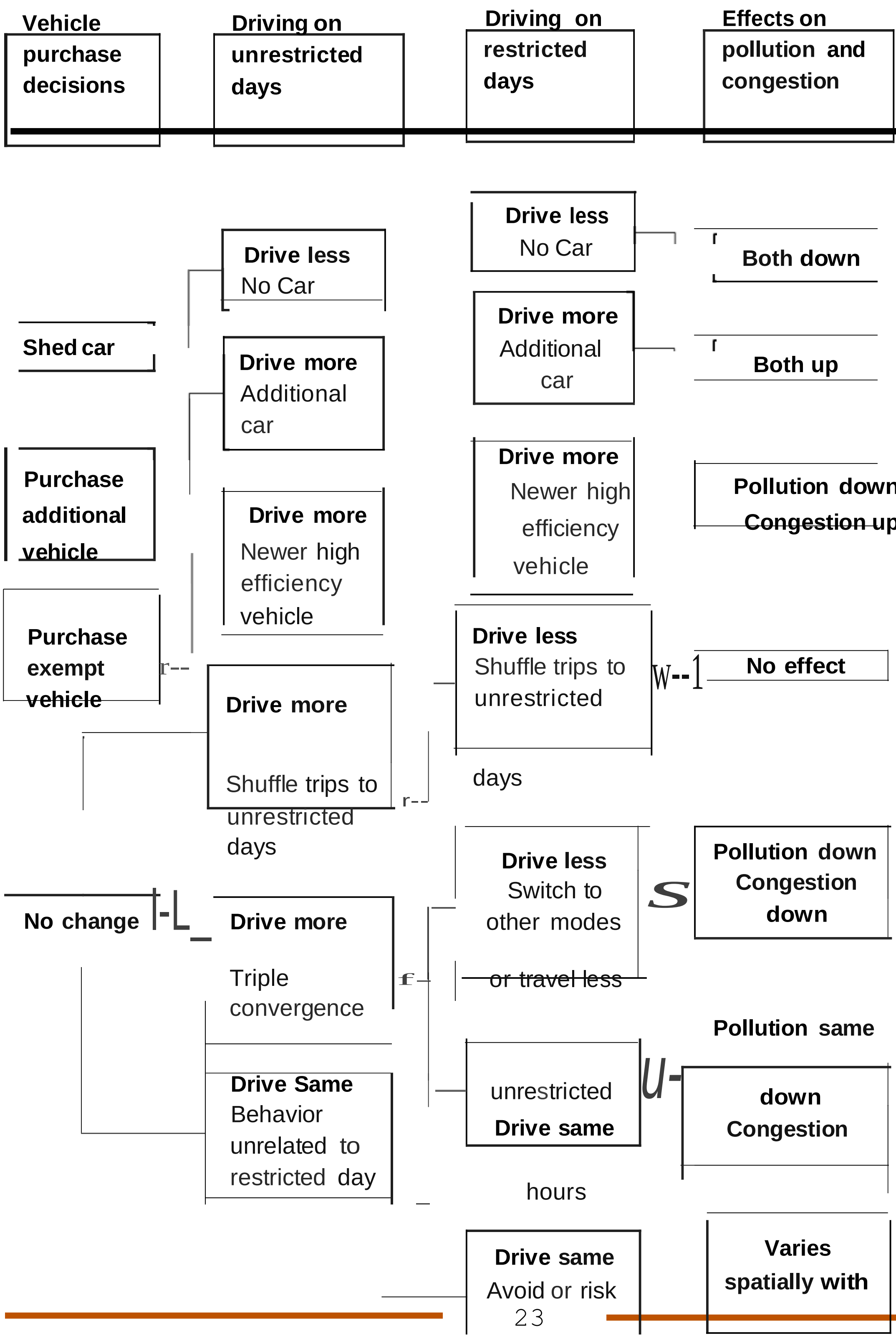
Other researchers find different relationships across different types of policies. For example, de Grange and Troncoso (2011) find that Santiago's long-term policy, which excludes cars with catalytic converters, had no impact on the use of private cars, but that short-term emergency bans that extended the policy to all vehicles reduced car use by 5.5% and increased Metro use by 3%. Z. Liu et al. (2018) find that a tightening of Langfang's restrictions increased overall travel speeds, while Davis (2017) finds that extending the restriction policy to weekends as well as weekdays did not reduce local pollutants in Mexico City. Several recent studies examine the effects of a two-week temporary odd-even restriction in Delhi by comparing several days of direct measurements of traffic and pollution during the restriction compared to measurements before and after the restriction (Chowdhury et al., 2017; Joshi et al., 2016; Mishra et al., 2019; Mohan et al., 2017). These studies produce mixed findings, but generally rely on only a few data points.

1.5.1. A note on research design and findings

We do not exclude any peer-reviewed papers that examine license-plate based restrictions based on research design. Although there is a range in research quality, we do not see a systematic difference in positive, negative, or null findings across studies with strong or weak designs. We do, however, generally find that studies from Beijing conclude that the policy reduced pollution and congestion, whereas studies from Mexico City do not. Studies from other geographies produce mixed results or do not have a large enough sample of papers to draw conclusions. In addition to differences in outcome measures and research design, variations in policy design, enforcement, and other local conditions likely influence the efficacy of license-plate-based driving restrictions.

1.6. Behavioral responses to license-plate-based driving restrictions

Figure 1.3 presents a diagrammatic summary of the interrelated ways that vehicle purchase decisions and travel behavior on restricted and unrestricted days are likely to influence the effects of license-plate-based driving restrictions on pollution and congestion. For example, households that have a single restricted car may respond to the policy by switching modes, driving during unrestricted hours, violating the policy, or shuffling trips to other days. Some households might respond by choosing not to purchase a car or, depending on local context, purchasing a low- polluting exempt vehicle. This section summarizes academic findings about how households respond to driving restrictions through vehicle purchases and travel behavior on restricted and unrestricted days. We emphasize how these decisions relate to overall pollution and congestion. We also identify and highlight gaps in the existing literature and opportunities for future research.



enforcement **enforcement**

Figure 1.3. License-plate-based restrictions' relationships to vehicle purchase decisions, travel behavior, congestion, and pollution

1.6.1. Vehicle purchases

In addition to reducing the number of days residents drive their cars, license-plate-based driving restrictions likely influence vehicle purchase decisions. We already discuss the purchase of additional cars to avoid the policy and find mixed evidence. Household members might also respond by choosing not to own a car or purchasing specific types of vehicles that are exempt from the driving restrictions.

If a substantial number of households choose not to purchase cars or shed them, this would likely reduce metropolitan congestion and pollution. Using a contingent evaluation approach Blackman et al. (2018) estimate that *Hoy No Circula* reduces cars' average annual value by about $130 per year. If cars are worth less, then residents are less likely to buy them. Based on this reduction in value, Eskeland and Feyzioglu (1997) estimate that about 8% of car-owning households would sell their cars in response to *Hoy No Circula*. Given its potential importance and car ownership rates in places like Mexico City and Beijing, there is surprisingly little research into the role that driving restrictions might play in reducing the probability of buying a car.

Vehicle exemption policies likely also play an important role. In Mexico City, for example, the policy changed to exempt cars with catalytic converters in 1996 and has since undergone several substantial changes. By 2017, most cars on the road in metropolitan Mexico City were exempt from general travel restrictions (INEGI, 2017). Comparing the age of the vehicle fleet across municipalities, Barahona et al. (2020) conclude that Santiago's vehicle exemptions reduced the share of older and high-polluting vehicles relative to other similarly wealthy municipalities. Chinese cities that exempt electric vehicles from driving restrictions have also seen a substantial increase in electric vehicle sales (Diao et al., 2016; T. Lu et al., 2020; Y. Rao, 2020; N. Wang et al., 2017). Given the importance of vehicle exemptions on purchases, there is a need for additional research into how exemptions shape travel behavior. For example, exemptions likely reduce average pollution per mile travelled, but also encourage additional travel in newer vehicles with lower operating costs. There may also be important spatial and socioeconomic impacts. Only relatively wealthy households are likely to view purchasing a new, low-emission vehicle as a possible response to driving restrictions.

1.6.2. Travel on restricted days

For households without exempt cars, there are multiple potential responses to car travel on restricted travel days. Perhaps the most studied response is switching modes. As with general findings about congestion and pollution, the evidence is mixed. In Mexico City, neither Davis (2008) nor Guerra and Millard-Ball (2017) find evidence of increased transit or taxi use. Others observe statistically significant increases in transit and taxi use in Delhi (Mohan et al., 2017) and Beijing (Gu et al., 2017; Yang et al., 2018). L. Zhang et al. (2019) find that transit use increased after policy implementation in some but not all six Chinese cities and attribute these differences to differences in policy implementation. Cheng et al. (2020) conclude that taxi use increased most in wealthier areas with worse transit in Xi'An. Other general findings include increased home values near transit (Y. Xu et al., 2015), a small increase in shared electric bike use (Campbell et al., 2016), an increase in bike share (de Buen Kalman, 2021), and an increase in bicycle use (Gu et al., 2017).

In addition to influencing mode choice, license-plate restrictions might encourage drivers to avoid taking trips, shuffle trips to unrestricted hours, or shuffle trips to unrestricted days. Avoiding taking trips is relatively understudied, but Gu et al. (2017) find no evidence of reduced trip-making in Beijing. Shuffling trips outside of restricted hours appears to occur in some cities but is likely a niche approach. In most cities with license-plate restrictions, only a small fraction of trips occurs outside of restricted hours. During Santiago's emergency restrictions, de Grange and Troncoso (2011) identify a statistically significant 3.5% increase in traffic during the hours prior to the ban. In Bogota, W. Zhang et al. (2017) observe an increase in NO2 in hours during both restricted and unrestricted hours, but a decrease in NO only during restricted hours. By contrast, Carrillo et al. (2016) conclude that Quito's decreased pollution is not offset by increases in pollution at unrestricted hours or unrestricted geographies. Similarly, neither Gu et al. (2017) nor Guerra and Millard-Ball (2017) find a statistically significant shift in driving outside of restricted hours using household travel data. Since most non-exempt cars are only used two-to-three weekdays per week, Guerra and Millard-Ball (2017) conclude that shuffling car trips from a restricted day to an unrestricted day is a particularly easy behavioral response to driving restrictions.

Finally, many households may respond to travel bans by cheating. Although some authors assume near universal policy compliance (Davis, 2008, 2017), most studies suggest that there is substantial non-compliance with driving restrictions (Guerra & Millard-Ball, 2017; Z. Liu et al., 2018, 2020; Mohan et al., 2017; L. Wang et al., 2014). For example, L. Wang et al. (2014) find that nearly half of regulated car owners violated the restriction rules in metropolitan Beijing and that violations are more likely to occur during peak hours, on social trips, and on trips outside of the city center. In an exception, Viard and Fu (2015) report high rates of compliance based on license-plate data from a centrally located parking garage in Beijing. Central locations, however, are where the policies are most likely to be enforced (Guerra & Millard-Ball, 2017; L. Wang et al., 2014).

1.6.3. Travel on unrestricted days

Most unrestricted travel behavior relates directly to restricted travel behavior. For example, if someone cheats or shuffles trips to times immediately before the travel ban, driving behavior on unrestricted days is likely unaffected. If travel is shifted to unrestricted days, by contrast, driving would tend to increase on those days. Shifts in travel behavior, however, could also have larger network effects. For example, if traffic decreases due to the policy, the resultant decrease in congestion would likely attract new drivers due to latent demand. Researchers have observed that increased driving tends to quickly fill and congest new highway investments and road expansions (Cervero & Hansen, 2002; Downs, 1992, 2004; Duranton & Turner, 2011).

1.7. Conclusion

In this paper, we reviewed the academic origins, uses, and empirical findings about the second-car hypothesis. While the hypothesis has disseminated widely and offers a compelling and digestible narrative about why license-plate based restrictions do not work, this assertion rests on shaky empirical grounds. Across studies, we find weak evidence of the second-car hypothesis playing more than a minor role in the many behavioral responses to license-plate-based restrictions. Very few households own more than one car in cities with license-plate-based driving restrictions. Those with multiple cars tend to be wealthy and are likely to have owned and driven multiple cars regardless of the policy. As a result, adjusting a specific policy to address second-car purchases will likely not do much to change the policy's ability to reduce local congestion and pollution. There are many other simpler and less expensive ways to avoid or adjust to the policy than purchasing a second car.

We also find a substantially divided literature in terms of whether and where license-plate-based restrictions reduce pollution or congestion. Half of the studies reviewed find that the restrictions reduce pollution or congestion. A quarter find no effect or an inverse effect. A quarter present mixed results, such as short-term reductions with no long-term effect. While differences in findings likely relate to differences in research approach and outcome measurement, policy design and behavioral responses also play a role. Better understanding the behavioral responses to car bans is critical to understanding whether and why restriction policies work.

We conclude with three main takeaways for researchers and policymakers. First, researchers and policymakers should not expect to find anything close to a 20% reduction in pollution or congestion from banning a fifth of vehicles from the road. In the most studied cities, like Beijing and Mexico City, many vehicles are exempt from the policy. Behavioral responses, such as cheating or shuffling car trips to unrestricted hours and unrestricted days, will also reduce policy effectiveness. In addition, private cars only represent a share of the total traffic on the street and traffic only produces a share of total local pollution. These shares, moreover, vary by pollutant, city, and neighborhoods within cities.

Second, based on the complex and interrelated behavioral responses to license-plate-based driving restrictions, researchers and policymakers should focus evaluation on the correct ecological unit, the household. Most existing studies, which rely on aggregate pollution and congestion data, are poorly suited to understanding how driving restrictions work or fail to work. There is also a notable lack of qualitative research, such as interviews and focus groups, to provide insight into the multiple ways that residents respond to and potentially avoid driving restrictions. While additional study into the second-car hypothesis may be warranted, researchers should focus on other behavioral responses. Whether and to what extent households choose not to purchase a car is particularly understudied and potentially important. The overall effects of vehicle exemptions on pollution and congestion are also poorly understood.

Third and finally, license-plate-based restrictions have a wide variety of implementation and enforcement strategies. As such, findings from one context may translate poorly to another. Mexico City and Santiago's policies, for example, exempt newer vehicles with lower emissions and may influence air pollution by changing the composition of the vehicle fleet. Existing research designs, which generally focus on the immediate moments before and after policy-implementation, would not capture these effects. Similarly, Beijing's car lottery, enforcement policies, and recent exemptions for electric vehicles make it a substantially different context from Delhi and the Latin American cities where other studies into license-plate-based restrictions have been conducted. In order to better understand the limitations and potential benefits of driving restrictions, policymakers and researchers should focus on specific behavioral responses to specific policies.

Chapter 2. An evaluation of Mexico City's license-plate-based driving restrictions

2.1. Introduction

This chapter combines data from a large household travel survey (INEGI, 2017), interviews in moderate-income neighborhoods, and a focus group with moderate-income drivers to better understand different socioeconomic groups' behavioral responses to Mexico City's *Hoy No Circula* driving restrictions. When first implemented at the end of 1989, *Hoy No Circula* banned all private cars—excluding public transportation and state-owned vehicles—from circulating in Mexico City and surrounding municipalities of Mexico State for one weekday per week from 5am to 10pm. By 1997, the law provided exemptions for lower-polluting vehicles with catalytic converters. Two years later, exemptions extended to any vehicle under two years old with vehicles between 2 and 9 years old eligible for exemption after undergoing and passing an emissions test. Residents display stickers with hologram numbers associated with differing exemptions from the policy. At the time of our study, local authorities issued four hologram types with varying restrictions on weekdays, Saturdays, and during temporary pollution-emergency days. Survey respondents report these government-issued hologram numbers on the 2017 household travel survey.

Although the policy is relatively well studied (Davis, 2008, 2017; Eskeland & Feyzioglu, 1997; Guerra & Millard-Ball, 2017), little is known about how vehicle exemptions influence travel behavior, pollution, or congestion. There is also disagreement on policy compliance and how residents shift behavior on restricted and unrestricted days of travel. Eskeland and Feyzioglu (1997) and Davis (2008) assume that residents comply with the policy but purchase additional secondhand cars that increase the total amount of driving and pollution. Guerra and Millard-Ball (2017) find evidence of non-compliance and conclude that residents have substantial opportunities to avoid the policy through smaller and more affordable behavioral adjustments than purchasing a second car. Of note, households with older restricted vehicles tend to use them only a couple of days a week, leaving ample room to shuffle car trips away from restricted days. Moreover, only 3% of households own two or more non-exempt vehicles. Qualitative research into how lower-income residents respond to and perceive license-plate-based driving restrictions is particularly lacking.

The remainder of this chapter is organized as follows. First, we briefly summarize the literature on behavioral responses to license-plate-based driving restrictions. Next, we present an overview and justification for our mixed quantitative and qualitative research approaches and findings. Predicting hologram type on the road based on geographic and socioeconomic variables, we find that two-thirds of vehicles on the road have an exempt hologram type. These vehicles are more likely to be driven by wealthier residents during peak hours and in the most congested, central parts of the metropolitan area. Those driving non-exempt vehicles are statistically significantly more likely to be poorer, live in suburban areas, own one or fewer cars, and drive shorter trips in less restricted parts of the metropolitan area. To better understand the behavior of these residents of households with non-exempt vehicles, we also draw on community-level household surveys and a focus group in three inner suburban areas of metropolitan Mexico City. Car owners here generally have just one non-exempt car. Most of them rely on transit for daily trips, such as commuting to work, and tend to use their cars for family outings and irregular shopping trips. Of the subset of regular drivers, some report avoiding car bans by carpooling or switching their driving routines to non-restricted hours. Others drive during restricted hours but avoid highly policed arterials and downtown locations. Many report other avoidance practices, such as bribing a technician to pass an emissions test or swapping license plates, to avoid restrictions. Although aware of the implications of driving for air pollution and supportive of the policy's intentions to improve air quality and public health, focus group participants expressed frustration about a policy that primarily restricts poorer residents who drive the least but exempts wealthier motorists who drive the most.

Last, we conclude with a synthesis of the findings and a discussion of areas for future research. Based on our analysis, *Hoy No Circula* keeps a maximum of 8% of vehicles off the road on a given day. Given the high reported rates of policy violation, the actual share of vehicles kept off the road is likely much smaller. If vehicles contribute around 50% of local pollutants, the maximum possible reduction from *Hoy No Circula* is only 4%, a far cry from aspirations of reducing a fifth of local pollution.

2.2. Research approach

Figure 2.1 summarizes the three interconnected approaches we take to examining behavioral responses to *Hoy No Circula*. Our first approach relies on 31,167 car trips reported from the metropolitan Mexico City household travel survey (INEGI 2017) to predict whether the vehicle has an exempt or non-exempt hologram type as a function of driver characteristics, household location, and trip characteristics. This quantitative analysis provides a general overview of who drives, where, when, and what type of vehicle throughout the metropolitan area. The second approach draws on surveys and interviews of household members in two suburban communities that have close to average car ownership rates and income levels to examine the travel behavior of typical metropolitan residents. Most respondents do not own cars. Most car-owners, moreover, report driving infrequently and relying primarily on transit and walking instead. Finally, we conduct a focus group with regular suburban drivers about their responses to and perceptions of *Hoy No Circula*. Together these surveys, interviews, and focus group provide a nuanced perspective of how drivers without exempt vehicles avoid, adapt, and violate car bans as part of their daily routines. For narrative clarity, we elaborate on our quantitative and qualitative research methods and findings in separate sections.

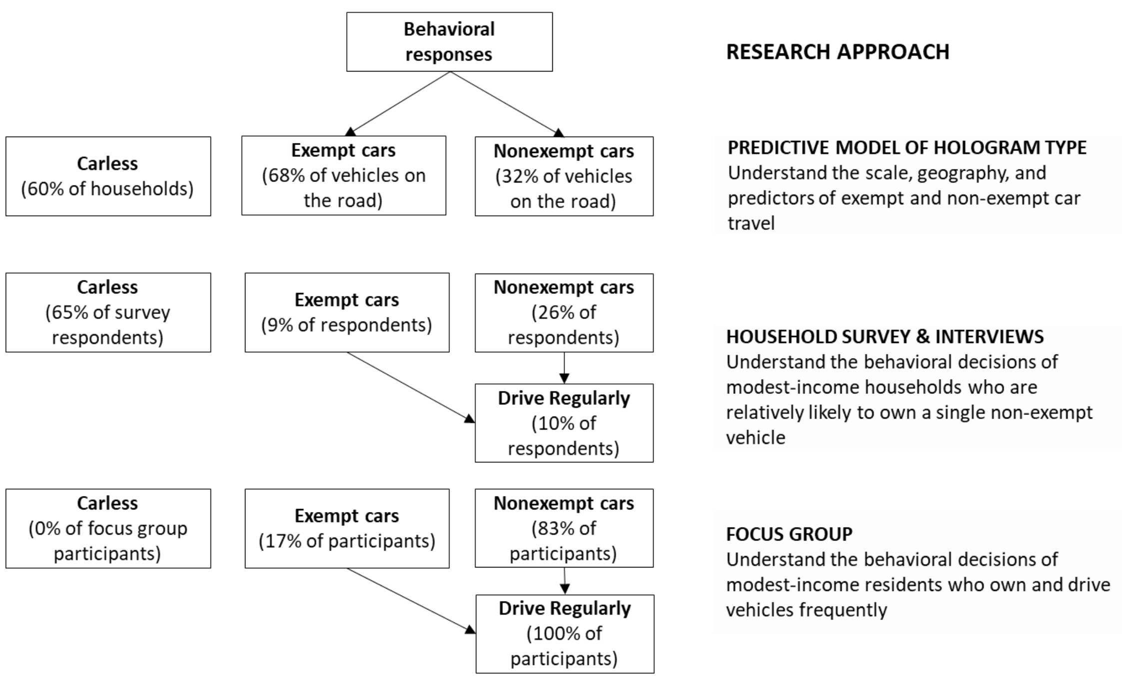


Figure 2.1 Overlapping research approaches to investigate responses to Hoy No Circula

2.3. Predicting vehicle hologram type

We use the 2017 household travel survey from the Mexico City metropolitan area to generate estimates of the total number of cars on the road by hologram type at different times of day. In addition to providing details on the travel behavior, socioeconomic, and demographic characteristics of metropolitan residents, respondents report vehicles' hologram type, which indicates whether the car can circulate freely, may be subject to a ban at a given time of day, or is restricted from driving at the time of travel. At the dates of the survey, hologram types "0" and "00" are exempt from all restrictions, whereas hologram types "1" and "2" are restricted from driving between 5am and 10pm on one weekday per week. Hologram "1" is further restricted from driving one Saturday per month from 5am to 10pm. Hologram "2" is restricted from driving on any Saturday from 5am to 10pm.

After removing a randomly determined 20% of households from the dataset for testing purposes, we develop predictive models of whether a car on the road at a given time on a weekday has either an exempt hologram ("0" or "00") or a non-exempt hologram ("1" or "2") type. To avoid double counting vehicles, we only use vehicle trips reported by the vehicle driver. We also estimate the same model for Saturday trips, as well as a model that predicts whether a vehicle is potentially restricted on Saturdays (hologram "1") or definitely restricted (hologram "2"). Our final reported multilevel logit models include random intercepts to account for unobserved variations in enforcement and behavior by municipality and clustered bootstrapped standard errors to account for correlations across trips by household members and individual residents. Finally, we extrapolate from our estimates using the sample data to generate estimates of the total number of vehicles circulating by hologram type by time of day, as well as by municipal origin-destination pairs.

2.3.1. Data summary

Table2.1 provides summary details on the variables used to predict hologram type, the theory behind including this predictor variable, and whether a variable was dropped due to statistical insignificance. These dropped variables include dummy variables for trip starting time, a dummy variable indicating whether a trip is taken just outside of restricted hours, municipal crime rates, municipal median income, and employment type. We also combined the levels of factor variables to reduce dimensionality when the levels were not statistically different with greater than 95% confidence. For example, we found that various levels of trip duration above and below the reported 25-minute threshold did not produce statistically different parameter estimate.

Table 2.1 Descriptive statistics of car trips taken in metropolitan Mexico City reported on the 2017 household travel survey

Level	Variable	Level/Summary	Share/info
Dependent variable	Hologram type	00	25.8%
		0	38.4%
		1	22.4%
		2	5.4%
		NA	7.9%
Driver level	Gender	Male	71.8%
	Age	mean	44.47
		std.	13.01
	Educational attainment	Less than secondary (and NA)	21.2%
		High School	23.5%
		Bachelor's or higher	55.3%
	Employed Status	Employed	83.3%
Household level	Household size	1	5.9%
		2	16.4%
		3	21.8%
		4+	55.9%
	Socioeconomic status	Lowest & second	32.4%
		Third & fourth	34.4%
		Highest	33.2%
	Number of cars in household	0	4.9%
		1	61.1%
		2	25.5%
		3+	8.5%
Trip level	Metropolitan geography involved in trip origin or destination	Federal District (not downtown)	34.0%
		Downtown	32.4%
		Restricted parts of suburbs	29.2%
		Unrestricted parts of suburbs	4.4%
	Destination	Home, School, Other	70.5%
		Office	14.3%
		Factory	2.8%

		Shop or commercial center	12.4%
	Trip duration	<=25min	33.5%
Municipal level	Distance to downtown (mile)	mean	11.23
		std.	6.37
	Home municipality	75 municipal levels	-

Several additional variables drop below statistical significance at the 95% confidence level after bootstrapping standard errors. We elect to keep these variables in the final reported models. The reported summary statistics for the predictor variables exclude all trips with unreported hologram types and that are not in the 80% household sample that we use to estimate the models. We include the full dataset for the summary of hologram types.

Driving trips in the Mexico City metropolitan area are disproportionately taken by employed men with relatively high educational attainment levels in households with relatively high socioeconomic status and a single car. The majority are driving a newer car with a "0" or "00" hologram, which indicates that a car can circulate freely during all hours of the day, except during emergency air quality days. A little over a quarter of circulating household vehicles have a hologram type "1" or "2" with another 8% of drivers not reporting the vehicle hologram type. Two-thirds of all trips originate or end within the Federal District of Mexico City and just over a third of car trips originate or end in the four most central municipalities, which we group together as downtown.

2.3.2. Predictors of hologram-type

Table 2.2 presents the results of three multilevel logistic regressions predicting circulating vehicles' hologram types by trip, as reported on the 2017 household travel survey, on a weekday or Saturday. Model 1 predicts whether a weekday driver has a hologram type that is restricted one weekday per week and one or all Saturdays per month relative to one that is unrestricted. Model 2 makes the same prediction for Saturday drivers, while Model 3 compares drivers with a hologram that is restricted on all Saturdays to those restricted one Saturday per month.

In general, wealthier employed drivers with high educational attainment in smaller households are statistically likelier to be driving exempt vehicles on weekdays and Saturdays. Although 80% of drivers on the road are men, women are relatively more likely to be driving exempt vehicles. Older drivers are also more likely to drive an unrestricted car. We tested a quadratic term to see if this trend diminished with age, but the result was not statistically significant. Finally, drivers from households with multiple cars are most likely to be driving exempt cars, suggesting that most car trips by members of households with multiple cars have nothing to do with individuals purchasing second cars to avoid *Hoy No Circula*. Even including controls for education and socioeconomic status, having just one car is statistically associated with having a non-exempt car.

Table 2.2 Binomial logit model predicting vehicle hologram type with multilevel random intercepts for home municipality

	Model 1	**Model 2**	**Model 3**
	Weekday	Saturday	Saturday
	Hologram types predicted		
Variables	1 & 2 vs 0 & 00	1&2 vs 0 & 00	2 vs 1
Gender: Male	0.340***	0.309***	0.066
	(0.033)	(0.046)	(0.109)
Age / 10	-0.249*	-0.650***	0.350
	(0.112)	(0.138)	(0.281)
Highest educational attainment			
High school	-0.417***	-0.425***	-0.366***
	(0.037)	(0.044)	(0.083)
Bachelor's or higher	-1.004***	-1.081***	-0.685***
	(0.037)	(0.045)	(0.095)
Employed	-0.072+	-0.229***	0.035
	(0.039)	(0.051)	(0.106)
Socioeconomic status			
Third or fourth	-0.296***	-0.270***	-0.173*
	(0.034)	(0.042)	(0.087)
Highest	-0.747***	-0.754***	-0.458***
	(0.043)	(0.053)	(0.138)
Household size			
Two	0.190**	0.200*	-0.265
	(0.071)	(0.086)	(0.182)
Three	0.260***	0.376***	-0.399*
	(0.069)	(0.083)	(0.171)
Four plus	0.413***	0.424***	-0.318*
	(0.065)	(0.079)	(0.160)
Number of cars in household			
One	0.187**	0.232***	0.327*
	(0.058)	(0.067)	(0.129)

Two	-0.222***	-0.329***	0.030
	(0.064)	(0.077)	(0.162)
Three plus	-0.541***	-0.455***	-0.073
	(0.083)	(0.103)	(0.258)
Trip destination			
Office	-0.169***	-0.112	-0.134
	(0.039)	(0.070)	(0.166)
Factory	0.233***	0.295**	-0.235
	(0.069)	(0.097)	(0.170)
Shop or commercial center	0.188***	0.107*	-0.014
	(0.045)	(0.044)	(0.084)
Trip duration: 25m or less	0.111***	-0.013	0.128+
	(0.031)	(0.036)	(0.072)
Trip distance (miles/10)	0.299***	0.260***	0.589***
	(0.062)	(0.064)	(0.124)
Metropolitan geography involved in trip origin or destination			
Downtown	-0.240***	-0.085	-0.129
	(0.041)	(0.052)	(0.127)
Restricted parts of suburbs	0.183***	0.216***	-0.122
	(0.047)	(0.058)	(0.114)
Unrestricted parts of suburbs	0.267**	0.643***	-0.053
	(0.101)	(0.116)	(0.193)
Constant	-0.766***	-0.479**	-1.961***
	(0.155)	(0.173)	(0.356)
Observations	31,167	19,900	6,408
Log Likelihood	-16,566.62	-10,853.74	-2,942.51
Akaike Inf. Crit.	33,179.25	21,753.48	5,931.03
Bayesian Inf. Crit.	33,371.23	21,935.15	6,086.63

Note: + p<0.1; *p<0.05; ** p<0.01; *** p<0.001; household-clustered bootstrapped standard errors in parentheses.

In terms of trip characteristics, trips to offices are much likelier to be made in exempt vehicles, while shopping trips and trips to factories are relatively more likely to be in non-exempt vehicles. Longer distance trips are more likely to be in older, potentially restricted cars, but short-duration trips of 25 minutes or less are also associated with non-exempt holograms. This may relate to the ease of avoiding the restriction for short neighborhood trips but also the longer distance trips taken in the less-regulated suburbs and outside of the metropolitan area. Looking at the origins and destinations of trips, those that start or end in the most central and most policed parts of the city are most likely to be taken in exempt vehicles. Trips that occur entirely in the municipalities that fall outside of the policy restriction area are most likely to be taken in vehicles without exempt hologram types.

Model 3 provides some additional insight into differences between the trips made in the oldest, most polluting vehicles with a “2” hologram and newer, but still regulated vehicles with a “1” hologram. These trips are even more likely to be taken by less educated, poorer drivers with just one household vehicle and smaller household sizes. The only statistically different trip-related parameter estimate at the 95% confidence level relates to longer distance trips, suggesting that the 5% of Saturday trips that violate the policy have a fair amount in common with the 23% of trips that are only restricted one Saturday per month. At the very least, these trips are more like each other than trips taken by vehicles with exempt hologram types.

2.3.3 Cars on the road by hologram type

Based on Models 1 and 2 in Table 2.2, we predict and extrapolate the total number of household vehicles on the road in metropolitan Mexico City during a 24-hour weekday and Saturday by hologram type (Figure 2.2). At all times of day, there are more exempt vehicles on the road than non-exempt vehicles. These exempt vehicles are more concentrated during the morning and afternoon peaks. They are also more spatially concentrated in the downtown and the wealthier western half of the metropolis. Non-exempt vehicle travel is more concentrated in the suburbs, periphery, and the poorer northeastern parts of the metropolis. Exempt vehicles represent 69% of all private household vehicles on the road during restricted weekday hours, 65% during unrestricted weekday hours, 68% during restricted Saturday hours, and 63% during unrestricted Saturday hours.

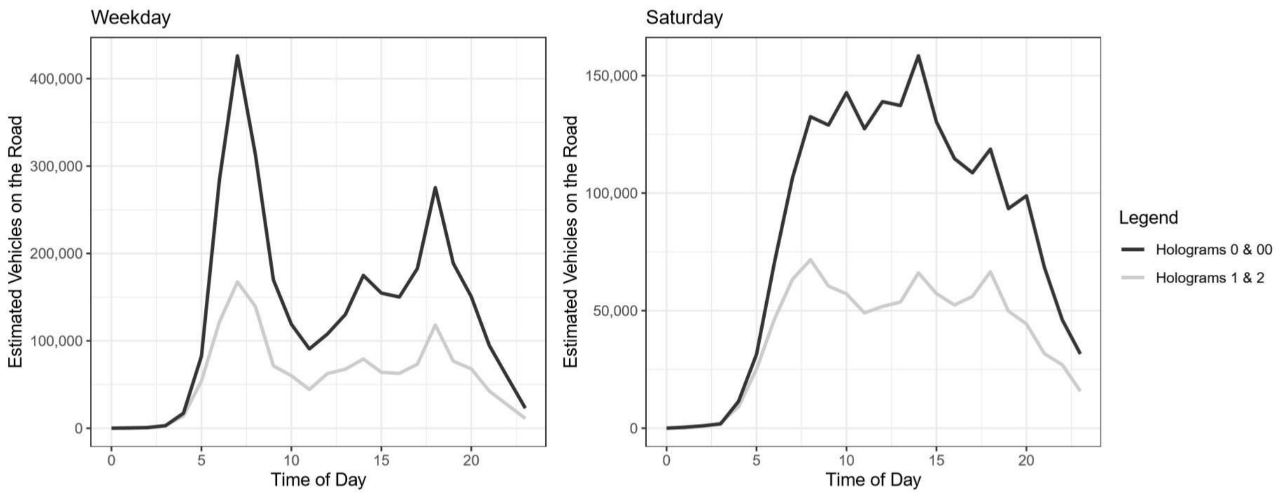


Figure 2.2 Household vehicle fleet on the road by hologram type and time of day in metropolitan Mexico City

In addition to the measures of fit presented in Table 2.2, we conducted several additional tests of predictive accuracy. Applying the models to the 20% of households set aside for testing purposes, our weekday model has an overall accuracy of 75% (64.3% true negatives, 17.9% false negatives, 6.7% false positives, and 12.5% true positives) and the Saturday model has an overall accuracy of 75% (63.0% true negatives, 17.6% false negatives, 7.7% false positives, and 13.1% true positives). We also aggregated the predicted and actual hologram types of car trips to the home municipality of the 20% of unsampled households. Comparing the predicted values to the actual values, we find correlations of over 0.99 for the total number of holograms by type and around 0.74 for the share of holograms by type. Comparing holograms by the origin and destination of trips, as opposed to household location, reduces the correlations for hologram share to around 0.64.

Taken together these findings paint a vivid picture of socioeconomic and geographic conditions of car travel and its relationship to *Hoy No Circula* in metropolitan Mexico City. Relatively wealthy drivers, who are exempt from the policy, make most metropolitan car trips and tend to concentrate trips during peak hours in the most central and congested parts of the city. Relatively poor drivers are much more likely to be subject to the policy and live and drive in suburban parts of the metropolitan area.

2.4. Surveys, interviews, and focus group

To better understand the behavior of these suburban drivers, we draw on household-level surveys of 301 commuters and in-depth interviews with 25 drivers. These surveys provide a community-level understanding of travel behavior and underscore differences across two archetypal middle-income neighborhoods: Isidro Fabela, an inner suburban neighborhood with relatively good transit access in Mexico City, and Los Alamos, a peripheral community in the State of Mexico. Here, our findings emphasize the behavior of households that generally either do not have a car or own a single non-exempt car. We supplement survey findings with a focus group of twelve regular drivers in the peripheral municipality of Tultitlán, State of Mexico, conducted on August 4th, 2019. These focus group respondents generally own a single car. Unlike most owners of a single non- exempt vehicle, however, they use their car as the primary form of transportation. We organized the 120-minute-discussion around how car bans influence participants' travel behavior. Participants elaborated on the numerous legal and illegal strategies that they and others employ to access work and other daily activities on restricted travel days. Focus group also discussed perceptions of fairness and overall policy effectiveness.

Table 2.3 compares survey and focus group neighborhoods' car-ownership rates, distance from downtown, and share of workers in the informal sector with metropolitan Mexico City. Isidro Fabela and Tultitlán have typical car-ownership rates, while car ownership is lower in Los Alamos. Informal employment is particularly high in Isidro Fabela, which has easier access to central commercial parts of the metropolitan area.

Table 2.3. Selected neighborhood characteristics for qualitative study locations

Characteristics	Isidro Fabela, Tlalpan, Mexico City	Los Alamos, Chalco, State of Mexico	Tultitlan, State of Mexico	Metropolitan Mexico City
Car Ownership	38%	25%	42%	40%
Informal workers	68%	52%	58%	57%
Distance to Mexico City's city center	18 km	44 km	43 km	NA

1. *Source: Authors with information from INEGI (2010)*

2.4.1. Moderate-income car-ownership and use

The household surveys provide insight into the behavior of typical moderate-income residents in inner-suburban and peripheral neighborhoods. Most survey respondents in Isidro Fabela, Los Alamos, and Tultitlán do not own a car. As one respondent put it, “Buying a new car is particularly expensive for low-income families. We must invest many (or most) of our family resources to buy a modest car and properly maintain it, so it passes the emission testing.” Of the 35% that own a car, 74% have a restricted hologram type—generally a hologram type “1.” Most car owners, however, indicated that *Hoy No Circula* did not have much effect on their driving routines since they did not drive regularly. As one interviewee stated, “I barely use my old vehicle (Volkswagen). Driving is expensive for me, and I avoid driving as much as possible.” Most survey respondents reported walking for daily shopping and school trips. The most reported use of a personal car was to visit other family members, often on the weekend. Only a quarter of car owners (10% of total respondents) use their vehicle frequently and commute to work with it.

2.4.2 Regular drivers

This 10% of interviewees and the focus group participants provide insight into the behavior of regular drivers living in three typical moderate-income suburban municipalities. While these drivers may not be representative of most moderate-income car owners, they drive their cars substantially more. As one resident of Los Alamos, “My car improves my quality of life as I drive to get everywhere.” Of the focus group drivers, 17% own an exempt vehicle. The remaining 83% have a car that is restricted at least one weekday per week and one or more Saturdays per week. *Hoy No Circula* affects these participants substantially more than most metropolitan residents, who either have an exempt vehicle or no vehicle. Interviewees and focus group participants reported a wide range of behavioral responses to the restriction policy. These included intended responses (e.g., switching to transit), unintended responses (e.g., shuffling trips outside of restricted hours), and illegal behaviors (e.g., driving despite restrictions and bribing police). While *Hoy No Circula* makes driving more difficult, participants reported preferring driving to transit due to speed, convenience, and safety. Many also mentioned cost, which is frequently lower than transit when traveling short distances with multiple family members or coworkers.

In terms of intended program responses, several regular drivers described shifting modes and carpooling on days when their vehicle is banned from circulating. For example, one regular commuter noted that, "Although I cannot entirely agree with car bans, I comply because I cannot afford expensive environmental sanctions. I have adjusted my commute routine to follow car bans. I drive to my factory job except on Wednesdays during restrictions when I switch to public transportation." Other participants carpool to drop kids to school during restricted days of the week.

Regular drivers also employ unintended behavioral responses that adhere to the policy restrictions but are unlikely to lead to reduced pollution. Notably, drivers shuffle car trips to unrestricted days or times of day. At times, this is relatively simple. For example, one participant noted that: “Car bans do not affect me on Saturdays because I do not need to drive to my factory job. I wait until Sunday to do my family's food shopping or other activities with my family.” Others, however, pay a steep time cost to avoid enforcement, particularly if they need to drive to centrally located parts of Mexico City. Small business owners appear to bear the brunt of these costs. One interviewee, for example, already carpools with his boss to their car repair shop in Mexico City. On restricted days, they leave at 3:30 am and do not begin the long drive home to Tultitlán until after 10pm. Similarly, a local musician reported driving his restricted truck at 3 am to arrive at his job in Mexico City before 5 am and waiting after 10pm to return home. Another unintended response is to purchase a second car. One small business owner bought a second car for 20 thousand Mexican pesos (around 1,000 USD) and alternates driving the two cars to run his business. It is an expensive approach to avoid the restriction but relates directly to his business’ ability to generate income.

Finally, nearly every interviewee and focus group participant discussed cheating at length. The most common approach is to avoid the highly policed arterials of Mexico City and stick to smaller local roads in the State of Mexico. As one interviewee from Los Alamos stated, “I use my car to drive everywhere because I mostly travel locally within Chalco. When my vehicle is restricted, I use inner streets that have less police monitoring. I would not go to Mexico City; there are many transit police officers there.” If caught, moreover, bribes to local police are substantially less expensive and time-consuming than the environmental sanction. “In the unlikely event that a transit police officer catches us driving during restricted hours, we may ask a pardon by explaining that we only drive locally. In some instances, we may negotiate a bribe with police officers." Residents also discussed paying bribes to repair technicians to pass emissions tests, obtaining exemptions through trade unions, and even swapping license plates on the same car.

2.4.3. Equity implications

Issues of unfairness permeated discussions about *Hoy No Circula* with regular drivers. Many also questioned whether the policy was effective and expressed concerns about persistent peak pollution episodes and rising traffic congestion. One participant lamented that "*Hoy No Circula* is an ineffective policy to reduce air pollution because it exempts many cars. Wealthy drivers pay their permits to pollute and drive a lot ." Another complained that the policy did little to affect the wealthy households most responsible for congestion: "Even if all cars became fuel-efficient, hybrid or electric, roads will still be overcrowded and occupied by wealthy motorists that drive a lot to conduct almost any activity." Another responded, "Look at the highways, most vehicles have zero or double zero stickers. Upper-income residents are not affected by car bans because they own multiple cars. Look at high-income families, the parents and the kids have their respective vehicles. The vehicle fleet has grown excessively in the past two decades because families own multiple cars." Views on fairness also affected residents' reported willingness to cheat the policy: "Low-income workers drive to work and make a living for their families. Policymakers need to understand that modest workers drive for necessity. We know that old cars pollute more, but we cannot afford to replace our vehicles constantly." The connection between fairness and cheating was frequently tied to a right and need to work: "My ten-year-old car does not trigger congestion if I drive within my municipality. Our contribution to congestion and pollution is not as significant as the harm they produce on our everyday commutes. We need to find ways to avoid car bans to work and make a living."

2.5. Synthesis of findings and conclusion

In this paper, we draw on quantitative and qualitative analyses to explore how metropolitan residents respond to Mexico City's license-plate-based travel restrictions through vehicles purchases and travel behavior on restricted and unrestricted days. Our findings point to three primary responses that make it unlikely for *Hoy No Circula* to produce anything close to the 20%

reduction in pollution or congestion that policymakers have hoped to achieve. The most common behavioral response is for wealthier households to purchase an exempt vehicle. Of the 40% of households with one or more cars, nearly 60% report having one or more exempt vehicles. These households tend to be wealthier, have more cars, and drive them much more than households with non-exempt vehicles. During restricted weekday hours, seven in ten private vehicles on the road are exempt. These vehicles, moreover, are more likely to be driven in the most congested parts of the city at the most congested times of day. While vehicle exemptions for newer cars almost certainly increase total driving and congestion, it is unclear whether the modernization of the vehicle fleet has produced a net reduction in local pollution. This depends on whether the reduced emissions per kilometer of travel offsets the increased travel and any network effects related to congestion. Future research could shed light on the mitigation potential of vehicle upgrading and increased car driving to mitigate air pollution and greenhouse gas emissions.

The second primary behavioral response applies largely to the 15% of households that have a single non-exempt vehicle. Just 53% of these one-car households reported making a driving trip on the metropolitan household travel survey. While it is not possible to determine which of these are regular or irregular drivers, most households with a single restricted car use it infrequently. Similarly, suburban survey respondents and interviewees reported generally leaving their cars at home, especially on long trips to Mexico City. Suburban driving in non-exempt vehicles is particularly popular for family recreational and shopping trips, where carpooling already plays an important role in keeping transportation costs down irrespective of *Hoy No Circula*.

The third primary approach that we find is a suite of behavioral responses employed by the small share of drivers who own and regularly use a non-exempt vehicle. In a full-compliance scenario with no irregular drivers or unintended policy responses, we estimate that *Hoy No Circula* keeps a maximum of 8% of vehicles off the road on a given weekday (a quarter of the 31% of non-exempt cars.) The true share is likely substantially lower. Many car trips in non-exempt vehicles are taken by irregular drivers who can shuffle trips easily without reducing how much they drive each week. Moreover, shifting car trips to unrestricted times, buying additional cars, and cheating would all reduce *Hoy No Circula*'s effectiveness. Driving on local roads in areas with limited police presence appears to be a particularly popular approach. When caught, focus group participants report being able to talk their way out of the fine or pay a bribe to avoid sanctions. In total, only a small fraction of metropolitan drivers appears to adjust their behavior through the desired mechanisms of reducing their driving. As one focus group participant put it, "Wealthier families pay their permits to pollute the air. Most cars circulate daily without any restrictions, while owners of old vehicles find ways to drive their cars."

Hoy No Circula could potentially also reduce pollution and congestion by discouraging car ownership in the first place. Most households in the metropolitan area do not have a car. While the share that chooses not to own a car because of *Hoy No Circula* is likely small, our research design does not provide insight into this behavioral mechanism. Finally, we do not see much evidence that second-car purchases are a common response to *Hoy No Circula*. Only 3% of metropolitan households own multiple non-exempt vehicles.

In addition to demonstrating multiple behavioral responses that limit the policy's ability to keep cars off the road, our analysis provides additional insight into *Hoy No Circula's* spatial and equity impacts. Uneven enforcement has likely resulted in a concentration of exempt vehicles in the central parts of the metropolis. Higher polluting vehicles may also have been pushed toward the side streets of lower-income peripheral neighborhoods. In terms of equity, interviewees and focus group participants made questioned the efficacy and fairness of a program that exempts the wealthier households that drive the most. While the policy does little to harm the poorest commuters, who are least likely to drive, regular drivers with a single restricted vehicle disproportionately bear the burden of *Hoy No Circula,* especially if they live on the periphery and use their car to commute to central, more highly policed parts of the metropolitan area.

While most participants expressed support for environmental policies to improve air quality and public health, regular drivers respond to the policy through a variety of intended, unintended, and illegal ways. Cheating appears to be particularly commonplace on trips outside of central parts of the city. As expressed by participants, many drivers illegally use restricted cars because they need to work and make a living for their families. They perceive that the approach of *Hoy No Circula* that incentivizes replacing relatively old cars with fuel-efficient vehicles is particularly unfair since most households can barely afford the costs of driving a modest vehicle. Unlike congestion charging, fuel taxes, or registration fees, this approach also fails to generate revenues that can help to compensate lower-income households or invest in alternative transportation modes. Instead, the largest financial beneficiaries of the policy may well be the producers and sellers of new cars.

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