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BEHIND THE MIST OF CORRUPTION:
A CASE FOR RECONSIDERING SMOG CHECKS

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Behind the Mist of Corruption: A Case for Reconsidering Smog Checks*

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> The constitution guarantees all people the right to live in a pollution-free environment. (...) The law may establish specific constraints on the exercise of certain rights or freedoms in order to protect it.
>
> (*Art. 19, No. 8*)
>
> *Constitución Política de la República de Chile (1980)*
> Translated from Spanish

Abstract

Private vehicle emissions are an important source of local air pollution and indirect influencers on the health and welfare of citizens around the world. In this paper, I evaluate two policies that impose limits on car use, in terms of efficiency and associated welfare gains under different setting characteristics. In particular, I compare driving regulations that classify cars by their emissions through smog checks with their vintage-specific counterpart. Specifically, I analyze the degree to which the finer classification of cars obtained from a rule that differentiates them according to their pollution rate is compromised in presence of corruption. I use a model of the car market and Chilean vehicle fleet data to quantify the extent of manipulation in smog check stations and analyze its effects on both the efficiency and effectiveness of this regulation. I conclude that there is no unique rule that labels one of the two policies as the dominant strategy for every context. That is to say, an emission-specific policy seems highly adequate in places either where corruption is unusual or where the car fleet is composed of vehicles with sufficiently heterogeneous emissions. In any other case, a vintage-specific regulation might be the convenient alternative.

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Any errors or omissions are my own responsibility.

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1. Introduction

Private vehicle emissions are an important source of local air pollution[1] and indirect influencers on the health and welfare of citizens around the world. Among the several health repercussions that derive from local air pollution are numerous respiratory problems of varying degrees of severity, where the most detrimental can lead to premature adult death and even increase infant mortality rates (World Health Organization (WHO), 2014). By the same token, one out of every nine deaths worldwide is the result of ambient air pollution-related conditions (WHO, 2016). In this sense, cars contribute to poor air quality through emissions of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC) and volatile organic compounds (VOC_s). According to WHO (2016), low and middle-income countries suffer disproportionately from transport-generated pollution, particularly in Asia, Africa and the Middle East. The above occurs mainly due to the use of old and inefficient vehicles, and the lack of public and active transport networks.[2]

Governments are no stranger to this issue and have implemented diverse policies seeking to improve local air quality through the control of the extensive (i.e., the type of car driven) and/or intensive (i.e., number of miles driven) margin associated to the vehicle fleet. Scrappage subsidies, annual registration/circulation fees, motor taxes, gasoline taxes and driving restrictions have been implemented worldwide in an attempt to reduce vehicles' pollutant emissions. Policies that impose uniform-limits to car use have been gaining popularity over time and, like any regulation instrument, have advantages and disadvantages. Despite their wide reach,[3] there are perverse incentives that arise as a consequence of them, leading consumers to buy additional high-polluting cars that increase the size of the car fleet and deteriorate its quality.[4]

There are two particular policies aimed to control private car pollution that are crucial for the purposes of this paper: vintage-specific restrictions and smog checks. Both have risen in order to correct the inefficiencies mentioned above. On the one hand, with vintage-specific restrictions limits to car use are no longer uniform but depend strictly on the age and year of production of each vehicle under this type of regulation. These policies have been implemented in Europe and China, characterizing some areas of the city as low-emission zones (LEZs) and banning high-polluting vehicles from entering those areas. The idea behind a vintage-specific restriction is to encourage drivers to switch to low-polluting cars instead of buying a second one when attempting to bypass the regulation. Cities as London, Paris, Rome, Beijing, as well as many in Germany, have implemented these policy instruments since 2008. On the other hand, conditioning the vehicle's annual registration on approving a pollutant emission test, the so-called automobile smog check, has gained recognition over time. This program defines an emission threshold for different gas tests and establishes that if exceeded, the vehicle is banned from circulation. One of the first places to implement such program was California (US) in 1984. Other states in the US have joined the initiative and currently

[1] As an illustration, motor vehicles collectively cause 75 percent of CO pollution in the U.S. (WHO, 2016). Likewise, in Chile's capital, Santiago, vehicles are responsible for 30% and 36% of $PM_{2.5}$ and O_3 concentrations, respectively (Rizzi and De La Maza, 2017).

[2] For instance, recent studies suggest that new cars can pollute up to 20 times less than cars that are 10 years or older (MMA, 2019). Additionally, according to the Environmental Literacy Council (2017), the use of public transport, especially subway, can decrease carbon dioxide emissions by 1.5 million tons each year in an average city in the US. Moreover, the report claims that since most subway systems are powered by electricity, they reduce emissions further below what would otherwise be emitted by cars.

[3] Among the cities around the world that have implemented such driving regulations include Athens (where they were introduced in 1982), Santiago (1986), Mexico City (1989), São Paulo (1996), Manila (1996), Bogotá (1998), Medellín (2005), Beijing (2008), Tianjin (2008), several German cities (2008), Quito (2010), Hangzhou (2011), Chengdu (2012), and Paris (2016).

[4] A good example for the latter statement comes from the Mexican experience with the *Hoy No Circula* (HNC) program implemented in 1989, and the corresponding evidence that analyzed its effects. See, for instance, Eskeland and Feyzioglu (1997); Onursal and Gautam (1997); Molina and Molina (2002); Davis (2008); Gallego et al. (2013).

require smog and/or emissions tests of their drivers (e.g., Illinois, Massachusetts and New Jersey). Some countries have also launched partial circulation bans that depend on emission tests with locality-specific standards, such as, among others, Austria, Canada, Chile, Mexico, Russia, and the United Kingdom.

Previous literature focuses on different policy instruments that aim to combat local air pollution caused by personal vehicle emissions, mainly to study their relative effectiveness. For instance, Barahona et al. (2019) (henceforth BGM (2019)) compare different driving regulation instruments and their efficiency in reducing vehicles' local pollutant emissions. Using both a model of the car market, and data from the Chilean vehicle fleet, circulation policies and smog check stations, they conclude that driving restrictions should be designed to work exclusively through the extensive margin, and never through the intensive one. They highlight vintage-specific driving restrictions among other policies that affect the extensive margin, for the former can move the fleet composition toward cleaner cars. Despite suggesting that smog checks could be potentially used to design efficient environmental instruments, they do not delve into the idea.

Notwithstanding, discussions and studies regarding smog checks in specific are not scarce. The effectiveness of this program is questioned by the economic literature, especially due to the possible presence of corruption that distorts cars' emission measurements. For instance, Oliva (2015) focuses on the presence of cheating on emission tests in Mexico City. Using a statistical test that detects unobservable behavior, she measures the extent to which the previously mentioned corruption undermines the policy efforts designed to reduce vehicle emissions. The author documents that the most common way to cheat is using donor cars, i.e., cars that substitute with clean emissions the ones from the high-polluting vehicles that are being tested. Her results indicate that 63 out of 80 centers in Mexico City cheat and use donor cars. In addition, she finds that around 9.6% of old-car owners pay bribes to deceive regulations. She concludes that important improvements could be achieved in terms of air quality if cheating was eliminated. On the other hand, Wenzel et al. (2004) study whether vehicles that initially fail and later pass emission tests, fail again a few years later. The initial idea behind this work, is that a persistent high failure rate might suggest that vehicles with malfunctioning emission controls are not receiving effective nor durable repairs. Nevertheless, the authors end up concluding that highly variable emissions, and not test fraud, are the cause of the large number of vehicles failing again soon after completing a previous smog check.

Moreover, Bennett et al. (2013) analyze how changes in the market conditions in which smog check stations compete affect how strict or permissive they are. The authors find that smog check firms facing more competition are more lenient (i.e., let cars with high emissions pass the test) for it can encourage stations to engage in corrupt or unethical activities. Moreover, they argue that new entrants are more lenient than incumbent stations. Similarly, Hubbard (1998) studies the extent to which market incentives lead inspectors to help vehicles pass their emission tests, and the role that the firm's competitive environment affects the above mentioned behavior. After examining California's vehicle smog checks, he concludes that given the *diagnosis-cure* nature of the auto repair market, moral hazard arises naturally and together with it, incentives to misrepresent cars' emissions to increase demand for the services they supply. In addition, Sanders and Sandler (2017) examine the direct link between smog check stations and local air pollution. They argue that the reduction in local air pollution levels is driven by high-quality stations and that low-quality stations have negligible impacts. In addition, their results suggest that emission inspections have become less effective at reducing local air pollution as more high-polluting vehicles from the 1970s and 1980s leave the road. In this manner, the social efficiency of such programs can be called into question when facing both heterogeneity in the smog check stations quality and improvements in the automobile technology.

In this paper, I study whether driving regulations that differentiate cars by their pollution rates through smog checks are preferable to the vintage-specific driving restrictions suggested by BGM (2019). In particular, I analyze whether there exist specific setting characteristics that appoint one or the other (or a combination of the two) as the policymaker's first choice. Specifically, I consider the level of manipulation in smog test results and the dispersion of emissions that characterize the vehicle fleet, as those features. A rule that differentiates cars according to their emissions may result in a finer classification than the one obtained from a vintage-specific regulation. This is true if the vehicle fleet is characterized by high-polluting new cars and/or well-maintained-low-polluting old cars (i.e., by a fleet with highly dispersed emissions). In such a scenario, conditional both on being labeled correctly and on low testing costs, an emission-specific driving regulation can be preferable to a vintage-specific one. Nonetheless, in the event of corruption and/or fraud during smog checks, driving regulations determined by this type of program may end up being suboptimal. High-polluting cars posing as clean by altering their emission test results can face significantly smaller restrictions than the ones that would really apply to them, jeopardizing the objective of the policy.

For this study, I take the model presented in BGM (2019) and compare vintage-specific driving restrictions with emission-specific ones. The main difference between my model and the one presented in the aforementioned work, is that I focus on a single-period setting, whereas the other authors on a two-period world. In it, cars can be divided into two types because they differ in their expected amount of pollutant emissions. In particular, one of those types has stochastic emissions, whereas the other has homogenous ones. Moreover, by combining this modification with the possibility to manipulate results, I am able to study the extent to which corruption is tolerable under a smog check policy and/or when a less refined program like the vintage(type)-specific one becomes optimal. In this setting, conditional on precise test results and sufficient emissions dispersion, is where smog checks present an advantage over regulations that depend only on an observable attribute of the car (i.e., vintage or type).

I focus on the Chilean case exclusively when tuning the model with data. I address this particular scenario, both because the model I base my work on is validated using these data and due to the fact that, to my knowledge, Chilean smog checks have not been studied by the economic literature before. Both reasons make it an interesting scenario to be analyzed.[5] The operation of these stations in Chile has not lacked controversies. Fake certificates, results manipulation, fraud, corruption and technology bypasses are words that are easily associated with these vehicle inspection stations. For instance, Peña (2018) and Díaz (2019) describe traffic accidents and truck rollovers in which subsequent investigations determined that the involved vehicles were circulating with expired inspections. Similarly, Quijada (2019) and CNNChile (2019) report several incidents of fake certificates seized at a time close to the renewal of the circulation fee. Both examples suggest that the smog check policy might not be suitable for the Chilean context.[6] Moreover, when considering that the regulation in this country is binary (i.e., if the inspection is approved the vehicle can circulate freely and must leave the market otherwise), its analysis becomes even more relevant. As mentioned above, high-polluting cars posing as clean by altering their emission test results could jeopardize the objective of an environmentally-oriented program.

[5] Furthermore, according to AirVisual (2018) (a global monitoring system of air quality), 9 out of the 10 most polluted cities in South America are located in Chile. The ones with the worst air quality are Padre las Casas, Osorno and Coyhaique, all three located in this country. In addition, its capital Santiago occupies the sixth place in the ranking. Thus, it appears that local air pollution is a serious issue in Chile, so studying a policy that presumably seeks to solve this problem seems relevant.

[6] Additionally, Ortiz (2016), Paulina (2019) and Candia and González (2016) expose several plants whose operators accepted bribes in exchange for an approved inspection. These payoffs ranged between USD 30 and USD 70. Some of the values in question were obtained using text analysis on Facebook posts.

This paper contributes to the literature by analyzing policies aimed to control private car pollution for the Chilean context in specific. Moreover, considering that the anomalous behavior of vehicle emissions may not only be a product of corruption or fraud but also due to the technological characteristics of the vehicles that are being checked, the present study helps assess the scope of corruption and its consequences on pollution control within this country. Additionally, modeling stochastic emissions allows this work to disentangle the behavioral and technological sources of inefficiencies in environmentally-oriented policies and suggest more efficient alternatives to combat local air pollution produced by vehicles.

The rest of this paper is organized as follows: Section 2 provides an overview of the smog check policies used as environmental tools around the world and analyzes the Chilean case in detail. Section 3 introduces motivating evidence and examines stylized facts that derive from the Chilean smog check setting, while Section 4 presents the theoretical framework of this work through a model of the car market. Next, Section 5 combines both preceding sections to calibrate the model and illustrate the main outcomes obtained from its resolution. Last, Section 6 discusses the two environmental policies compared and reviewed in this paper.

2. The Smog Check Setting

The most common means of enforcing emission standards on vehicles around the world are compulsory emission tests, also known as smog checks (Oliva, 2015). Nearly all smog check programs require vehicles to participate in yearly or biennial emission controls that compare their pollutant emission levels with locality-specific standards. In the event of surpassing at least one of the thresholds in question, the complete gas test is failed. These policies aim to reduce vehicle pollutant emissions in hopes of improving air quality, by ensuring that cars with excessive emissions are either eradicated from the market, or repaired to meet local standards.[7]

Yet, there are times in which versions of these emission tests arise not as environmental policies, but as road safety ones. They often demand easy-to-meet pollution standards as part of a set of visual and performance-related requirements that must be met to allow the vehicle to circulate. Accordingly, the objective of those policies is not to reduce air pollution *per se*, but to maintain the compliance of specific standards that ensure certain quality levels for the cars in circulation. That is to say, road safety policies require minimum standards in terms of gas emissions, to guarantee that, for example, the vehicle does not emit visible smoke through its exhaust pipe. The foregoing works as a minimum security measure to prevent the car from overheating and/or suffering serious mechanical failures that can lead to accidents.[8] It is important to make the distinction between exclusively environmental and road safety smog check policies, especially if the main concern is solving the problem of air pollution. One type of program might be more effective than the other for that objective, specifically if the standards required by road safety policies are not strict enough to mitigate the emission of pollutants caused by car use.

[7] Among the countries that require vehicles to go through an emission inspection as part of a *road worthiness* evaluation are Austria, Belgium, Bulgaria, Canada, Chile, Czech Republic, Finland, Germany, Hungary, Ireland, Israel, Mexico, Netherlands, Nigeria, Norway, Poland, Russia, Singapore, Slovakia, Sweden, Taiwan, the United States, and the United Kingdom.

[8] One question that arises in this context is why are inspection plants the preferred means to examine vehicles. Alternatively, the policymaker could place policemen on the streets to conduct the inspection. However, there are several reasons as to why this is an ineffective strategy. First, big and expensive machinery or even specific infrastructure is needed to inspect the car properly. Setting many inspection points on the streets might be infeasible or could significantly increase public spending. Second, inspecting the vehicle in its entirety takes more than 15 minutes, meaning that street checks could considerably delay travel and affect traffic. Third, changing the mandatory nature of inspections to something that can randomly happen to the vehicle means that not everyone gets tested. Last, and to that same extent, after identifying the points where inspections are conducted cars might selectively avoid them.

California was one of the first places to implement a smog check program in March of 1984, after the state recognized that vehicles were an important source of air pollution. The novelty of this law corresponded to an update and tightening of the preexisting emissions standards suggested by the United States Environmental Protection Agency (EPA) that had been regulating the vehicle fleet up to that moment. This adjustment meant both that vehicle manufactures had to meet California's goals for reducing the amount of pollution each vehicle emitted and also that drivers had to be held responsible for maintaining these standards during their car's lifetime (State of California Laws on Emissions, 2018). The smog check policy continues to be enforced in California to this day, with an exclusively environmental focus and a heterogeneous geographic application across the state. According to the State of California Laws on Emissions (2018), there are three different program areas within the state that vary in the emission test strictness, with an application dependent on the zip code of the car owner. The most stringent form of smog check is present in *enhanced areas*, i.e., areas where pollution is a severe issue. Next, in areas where pollution is a concern but not detrimental to health, the so-called *basic areas*, biennial smog check inspections are conducted. Last, in *change of ownership areas*, a smog check is only required when the vehicle is transferred to another person.[9] Overall, for the Californian case, smog checks are emission-specific tools that help reduce environmental pollution and whose strictness depends on the preexisting levels of pollution in each state area. Over the years, other states in the US have joined the environmental initiative and began to require smog and/or emissions tests from their drivers, with locality-specific standards. Examples of these include Illinois, Massachusetts, New Jersey, New York, Tennessee and Washington.

Along the same lines, Mexico launched in 1990 a smog check program with mandatory biannual gas tests for all vehicles. Under this legislation, vehicle owners are compelled to take their cars every 6 months to a registered smog check center, where both a visual inspection and an emission test are conducted. If the vehicle passes both examinations, a sticker with the vehicle's plate number is pasted on its windshield. In the event of failing at least one of the two, the owner can retake the test indefinitely within a two-month window upon paying the corresponding fee. For the case of this country, emission standards comply with the EPA 1 requirements (Oliva, 2015). All smog check stations are privately owned, but subject to government regulations. The local authority conducts unannounced inspections of the smog check stations to ensure that guidelines are being met, both for the visual inspections and the emission tests. It should be noted that the Mexican gas inspection is part of a broader examination of the vehicle, such that its final objective is not exclusively environmental as it is for the Californian case presented above.

The Chilean case of smog checks began in 1984 with the enactment of a decree-law by the Ministry of Transportation (MTT), that characterized vehicles' inspections and regulated smog check stations. This decree determines the responsibilities of the smog check stations and the requirements to approve the test, including a visual inspection and a pollutant emission check. The law compels vehicles to approve certain minimum standards as a prerequisite to renew their annual registration. In particular, for private cars, the revision has to take place once a year in a predetermined month dependent on the last digit of its license plate. The vehicle inspection process is fairly standardized across the country. Car owners visit a registered

[9] The state of California has special requirements for all circulating vehicles regardless of the area within the state in which they are driven and where they were bought. Withal, it may be very costly, and in some situations impossible, to modify cars bought out of state to meet the Californian emission prerequisites. Before circulation, each car must be certified and registered, during which its compliance with the demanded emission standard is also verified. After registration, an emission control label is pasted under the hood in the vehicle's engine compartment. If a driver is pulled over and an officer discovers that the vehicle's registration is incomplete, the driver can be charged USD 284 and up in fines, plus USD 1,000 and up in insurance hikes and penalties.

vehicle inspection station and pay a fee when arriving. Afterwards, its information is electronically entered by a center employee, recording its plate number, model, year, brand, weight and mileage.[10] Next, the car is visually examined, analysis that includes the inspection of lights, brakes, windshield wipers, among other things. After that, its engine is started and the center employee observes whether there is visible smoke coming out of the exhaust pipe. In the event that the above occurs, the revision is automatically failed. Else, the car is placed on a dynamometer as the final step in its gas inspection, an emission reader is attached to its tailpipe and its engine is started at various speeds to check different levels and types of emissions. No particular order is needed when conducting both the visual inspection and the emission test and the two must be passed to approve the inspection as a whole. In the event of failing the revision, the examination needs to be retaken. Retests have a different fee (usually lower than the one paid during the first attempt) and do not contemplate the full repetition of the inspection. Instead, they include the specific test in which the car failed, as well as the inspection of brakes and the gas emission analysis. The test can be retaken an unlimited number of times, the only condition dictated by the law is to have the inspection approved before either the circulation-fee or annual registration expires.

Additionally, the standards required by Chilean emission tests vary according to the weight of the car. The legislation defines 33 different weight values[11] (henceforth *inercias equivalentes*, as they are named in Spanish), each with particular emission standards for the HC, CO and NO tests:[12] the heavier the car, the harsher the standard. These thresholds have been updated multiple times since the first legislation, becoming more strict as time goes by. Nevertheless, they remain much more lenient than exclusively environmental policy standards such as the Californian and/or Mexican smog checks. Table 1 depicts the gas emission requirements for two of the most used car models in Chile. Both correspond to cars manufactured in 1998 and have the same associated *inercia equivalente* value. On the one hand, for the Californian case, both vehicles are considered unequal and are thus required different standards, which are more strict than the ones demanded in Chile. On the other hand, for the Mexican case, both vehicles are considered equal for they were manufactured the same year and are thus compelled the same standards, which are also more strict than the ones that apply in Chile, at least until before 2018.

Using the MTT Smog Check dataset, I am able to follow the Chilean smog check stations across time, having information regarding their characteristics and business model for each month from year 2013 to 2018. Additionally, the dataset depicts information regarding all private vehicle inspections conducted between 2008 and 2018. Each entry corresponds to one examination and details characteristics related to both the car and its revision process' results. Specifically, it includes NO, CO and HC gas test results, local pollutants with a crucial role in air quality. The dataset includes all vehicle smog checks conducted in Chile since 2008, consisting of more than 30 million observations in total.

[10] It is worth mentioning that the information entering process was performed manually by most centers up until recently. Yet, there are still a few plants in the 2nd, 5th and 15th region that continue to enter it manually up to this day. Naturally, the above makes data more prone to errors and corruption. It should be noted, however, that in this paper I use data from stations that upload their information to an online network, leaving aside those plants with older information processing systems.

[11] It should be noted that tests with weight-specific requirements are relatively new throughout Chile. They were initially implemented in 2006 in Santiago and were gradually expanded to other regions over time, such that part of the rest of the country remained using idle and 2500 rpm tests up until recently. For that reason, most of the data used in this paper regarding results for weight-specific standards correspond to inspections conducted in Chile's capital. The foregoing does not compromise the relevance of this paper, given that the most critical zone in terms of pollution is Santiago. Therefore, every following exercise that uses these weight-dependent measurements still suits the purposes of this work.

[12] These tests are equivalent to the ones implemented in California and are called ASM (Acceleration Simulation Mode). They evaluate HC, CO and NO emissions with two methods: constant speed tests run at 50 percent power and 15 miles per hour (i.e., ASM 5015) or 25 percent power and 25 miles per hour (i.e., ASM 2525).

Table 1: Example of Emission Standards

			ASM 5015 Test		
		Standard	Nitric Oxide (NO)	Carbon Monoxide (CO)	Hydrocarbons (HC)
Hyundai Accent 1998	California	Pass/Fail	499	0.58	68
		Gross Polluter	1,981	2.08	286
	Mexico	2003 - 2004	1,200	1.00	100
		Since 2019	700	0.70	100
	Chile	Until 2012	1,504	1.10	194
		2013 - 2017	1,429	1.05	184
		Since 2018	1,186	0.85	152
Suzuki Esteem 1998	California	Pass/Fail	487	0.57	66
		Gross Polluter	1,970	2.07	283
	Mexico	2003 - 2004	1,200	1.00	100
		Since 2019	700	0.70	100
	Chile	Until 2012	1,504	1.10	194
		2013 - 2017	1,429	1.05	184
		Since 2018	1,186	0.85	152

Notes: Table 1 presents the pollution thresholds for the ASM 5015 gas tests for both Hyundai Accent 1998 and Suzuki Esteem (Suzuki Baleno in Latin America) 1998 models. The ASM 5015 test is conducted in all three Californian, Mexican and Chilean smog checks. For the Californian case, pass/fail standards are used to determine if a vehicle passes the emission inspection, which occurs if the emission levels are equal or less than the given standard. Additionally, *Gross Polluter* standards are used to label a vehicle as such if the emission levels at the time of the initial inspection, before repairs, are greater than that standard. If classified as gross polluter, the vehicle must visit special certified smog inspection stations and undergo drastic repairs. For the Chilean and Mexican case, a vehicle passes the smog check if the emission levels are equal or less than the given standard. Limits are given in parts per million for NO and HC and in percentage of volume for CO. Values presented for Mexico period 2003-2004 correspond to the ones employed by Oliva (2015), that apply to the program Hoy No Circula.

Table 2 depicts the rejection rates by both car age and test (i.e., visual inspections and pollutant emission tests), for all first yearly revision attempts conducted in Chile between 2008 and 2018, distinguishing between the ones conducted in the Metropolitan Region (Chile's capital, also known as Santiago) and other regions. About 30% of vehicles fail the visual inspection in the Metropolitan Region and 4.2% the gas emission test. Contrarily, in the rest of the country, 21% fail the visual inspection and 10.8% the gas emission test. Broadly speaking, it seems that the main reason for failing the vehicle inspection is the non-compliance of visual standards. Yet, it looks like the former are harsher in Santiago than in other regions, whereas the opposite conclusion arises for gas inspections. This occurs even when comparing cars of the same age: there are relatively more rejections for visual reasons in Santiago and for gas related ones in the rest of the country. The above could suggest either significant differences in the required government standards for each geographical area, or particular manipulation mechanisms that affect rejection rates differently depending on the plant's location.

Additionally, an interesting conclusion can be suggested from the descriptive statistics in question: on average, the older the car, the more difficult it is for it to comply with gas emission standards. This is consistent with what is previously stated: it seems older cars are more polluting than newer ones. The above, either because newer models are cleaner due to a more efficient design, or because pollutant emissions increase as the car is used and, through this, its gas processing mechanisms are worn out.

The Chilean government tenders licenses for smog check stations every few years. Thus, analogous to the Mexican case, all smog check stations are privately owned, but subject to government regulation. In 2008, 68 licensed stations operated throughout Chile, with 18 of them located in Santiago. Only ten years later, the number of licensed stations across Chile rose to 124, with 32 of them located in Santiago. Nevertheless, unlike other countries, the price structure associated to the vehicle inspection varies among stations. The above, both intra and inter-region, suggesting that prices are not exclusively determined by government intervention. Table 3 presents data on the pricing structure for different stations located in two regions in Chile, as an example of the high variance of prices and their dispersion both within and between regions.

Table 2: Average Rejection Rate by Test and Geographical Area

		Age Group						
		1-5	6-10	11-15	16-20	21-25	26+	Total
	Visual Rejections	26.36%	30.88%	33.83%	30.40%	25.84%	27.45%	29.98%
Metropolitan Region	Gas Rejections	0.94%	2.18%	6.69%	8.57%	9.48%	12.81%	4.18%
	No. of Revisions	3,513,329	4,799,860	2,889,443	1,739,746	649,525	304,292	13,896,570
	Visual Rejections	14.47%	19.97%	22.01%	21.66%	23.21%	25.14%	20.55%
Rest of the Country	Gas Rejections	1.23%	3.95%	12.66%	19.61%	17.85%	18.27%	10.81%
	No. of Revisions	2,468,499	4,105,295	3,510,608	2,919,355	1,773,927	941,818	15,719,835

Notes: Table 2 presents descriptive statistics for rejection rates both by test and age of the car, considering all first yearly inspection attempts conducted in Chile between 2008 and 2018, inclusive. Results are presented disaggregated by age group and separating Chile's capital from the rest of the country. Visual rejections consider any type of deficiency related to the visual inspection stage (i.e., windows, lights, windshield wipers, brakes, among others), whereas gas related ones contemplate all kinds of faults related to the measurement of emissions both for the visible smoke test and the ASM, idle and 2500 rpm tests.

Table 3: Example of Vehicle Inspection Pricing Structure

Region	**County**	**Station Code**	**Year**	**Price**
5	Los Andes	AB–0528	2016	9,000
5	Los Andes	AB–0528	2017	9,150
5	Viña del Mar	B–0521	2016	17,000
5	Viña del Mar	B–0521	2017	17,300
5	Viña del Mar	B–0523	2016	18,700
5	Viña del Mar	B–0523	2017	18,700
13	Melipilla	B–1321	2016	17,510
13	Melipilla	B–1321	2017	17,510
13	Quilicura	B–1325	2016	13,300
13	Quilicura	B–1325	2017	14,000
13	Quilicura	B–1331	2016	8,600
13	Quilicura	B–1331	2017	8,900
13	Puente Alto	B–1312	2016	18,070
13	Puente Alto	B–1312	2017	18,370
13	Puente Alto	B–1333	2016	8,600
13	Puente Alto	B–1333	2017	8,900

Notes: Table 3 presents prices for private vehicle inspections for different Chilean counties, for years 2016 and 2017. All prices displayed were charged in April of each year, presented in Chilean pesos (CLP).

Some stations share the same fee structure, even when located in different counties and evolve similarly over time, as it occurs for two of the stations located in *Quilicura* and *Puente Alto* (i.e., B–1331 and B–1333, respectively). Other charge structures remain constant from one year to the next, as is the condition for one of the stations in *Viña del Mar* and the plant located in *Melipilla* (i.e., B–0523 and B–1321, respectively). Additionally, there is not only high variance in prices intra-region, as concluded when comparing *Los Andes* with *Viña del Mar*, but also intra-county as it occurs for *Quilicura* and *Puente Alto*.

3. Motivating Evidence

The objective of this section is to present some stylized facts regarding the Chilean smog check policy as motivating evidence. This is done in order to understand the context in which the previously mentioned program is implemented and to determine whether manipulation of test results exists; and if so, how it affects the project in question. Particularly, this section aims to quantify the effects of corruption on local air pollution, to assess how optimal a smog check program is in presence of fraud. Moreover, instead of using the complete vehicle fleet dataset, I work with two car models to account for external factors that could otherwise distort the analysis (e.g., technological progress, demand shocks, generalized technical failures).

3.1. *ASM Test Results and Manipulation*

I begin by presenting the distribution of ASM 5015 and 2525 test results for the two most used car models in Chile. As previously mentioned, these correspond to the Hyundai Accent and the Suzuki Esteem, both manufactured in 1998. It should be noted that the two share the same *inercia equivalente* value (which equals 1,247 kg) and are thus required the same emission standards according to the Chilean legislation. Consequently, test results are presented by measured gas (i.e., NO, CO and HC) and not disaggregated by model in this section of the paper. Moreover, it is worth mentioning that the right tail of every test result distribution is very long and light. As a consequence and for illustrative purposes, all figures in this section depict trimmed data to keep focus on their relevant section, i.e., the vicinity around the required emission threshold. Additionally, it is worth noting that as most emission sampling systems, the ASM method does not lack potential measurement error nor has an infallible accuracy. For that reason, there are precise instrument requirements that ensure certain quality levels for the detection method. According to MTT (2015), Chilean standards are subject to the requirements described in EPA (1996). In sum, the compelled instrument accuracy corresponds to 25 ppm NO, 0.02% CO and 4 ppm HC, both for the 2525 and 5015 analysis. On that account, if meeting instrument requirements was costly to the stations and the latter were subject to frequent government scrutiny, stations would comply right on the demanded precision and thus have machines as precise as enforced. Along these lines, henceforth I assume that every instrument used in the detection method meets the accuracy requirement strictly.

To illustrate the variability of results obtained by the two car models of interest, Figure 1 presents histograms of emission measurements for revisions conducted in year 2014.[13] Panel (a) of the figure displays

[13] I chose to work with test results obtained during year 2014 for several reasons. First, there could be important technological changes regarding finer emission measurements and/or car reparations between 2011 and 2018. Selecting a year that is a midpoint in the technological progress allows me to account for the latter. Second, when considering that both models in question are getting older (and probably more polluting) as time goes by, using a year at the beginning of the period could underrepresent the average emissions of the cars in question. In the same way, if some of them are exiting the market over the course of time, it is likely that those in worse conditions are the first ones to do so. Thus, choosing a year that is at the end of the period could be problematic as well.

NO 5015 test results and hints fair signs of bunching just below the emission threshold. The above suggests manipulation of pollutant level recordings, such that the original distribution of emissions is altered when approving cars that did not meet the standard and whose results were purposely placed just below it. Note that data accumulation below the threshold is much more prevalent in this test, albeit the rest of the panels also hint moderate signs of manipulation. Therefore, I presume that for this case bunching is not a statistical artifact but somewhat reliable evidence of corruption. Consequently, in what follows I focus on the NO 5015 test results that show the strongest signs of manipulation.

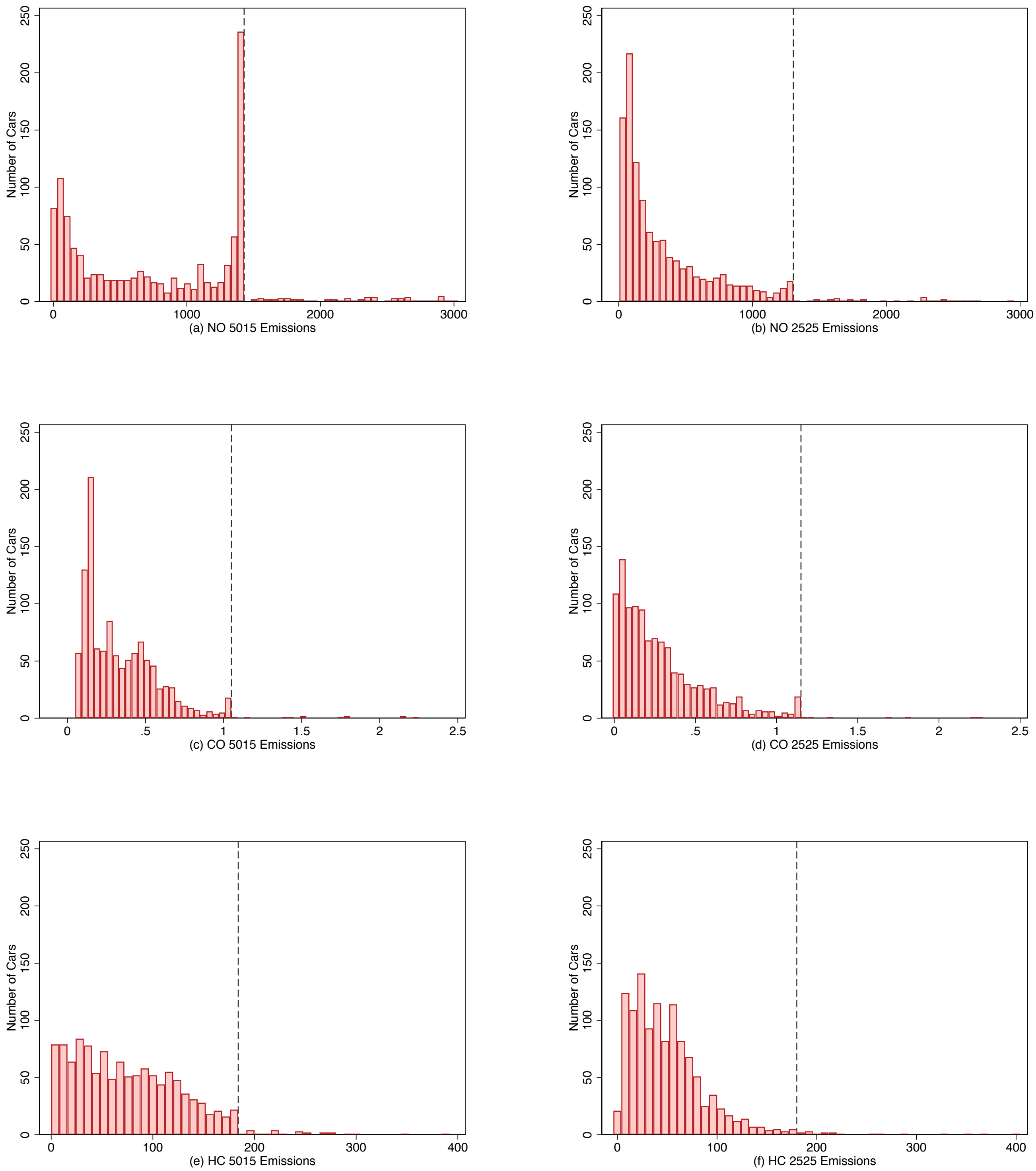
To elucidate whether this NO anomaly is also present in other years of the data, Figure 2 presents NO 5015 test results for all years in the database (i.e., 2011-2018). The figure in question allows me to ensure that the analysis in this section is not exclusively driven by the particular election of year 2014, as well as to verify that regardless of the chosen year there is an unusual accumulation of data in the NO 5015 test.[14] In line with the above, and despite slight changes both in the number of cars depicted in the different histograms and the general shape of the distribution, all 8 panels suggest manipulation of results through the presence of bunching at the left of the threshold.[15] Therefore, I continue to work with 2014 data not worrying that the election of this particular year is the main driver of my conclusions. Furthermore, in spite of having the emission standard strengthen with time, it seems that the bunching of data moves along with the latter, such that there is always an unusual accumulation just below the allowed limit of pollutant emissions. This result is quite interesting: it appears that the average of NO emissions decreases over time despite using the same vehicle sample (with slight changes in the number of cars as time goes by). The above contradicts the idea that cars should become more polluting as they age, as suggested in Section 2.

Table 4 depicts the average NO emission results for the sample of interest to illustrate the previous point. The former decreases over time for both failed and approved tests, contrary to the number of test-takers whose evolution does not seem to have a clear trend. Note that, in absence of corruption, two mechanisms should be displayed in the table: while the average of emissions should increase as the car ages, the number of test-takers should decrease along with their age if, as presumed, those who malfunction leave the market. Another aspect of the table should be taken into consideration, namely that it does not represent a balanced panel of data. This occurs since many vehicles are missing (or skipping) more than one inspection during the period of time in question. If I reduced the two-model sample aiming to balance the panel, I would end up with a few observations only, insufficient to perform a meaningful and illustrative analysis of emission recordings. However, Panel (a) in Figure 3 presents the NO 5015 emission behavior in $t + 1$ for cars that were located in the bin at the left of the threshold (henceforth *bunchers*) in t. This figure shows cars that had two consecutive inspections during the relevant period of time, tracking them individually by plate number. As a benchmark, Panels (b) and (c) present the emission behavior in $t + 1$ for cars that approved the NO 5015 test but were not located in the bin at the left of the threshold in t. The probability of being a buncher (and therefore, suspect of cheating) in $t + 1$ is greater when the car is a buncher in t. Likewise, the probability of registering lower emissions in $t + 1$ than in t, is also greater if the car is a buncher in t. Thus, it seems that the emission behavior of bunchers is different than the one of cars that approve the test with lower emissions, further strengthening the idea that there is fraud behind this phenomena.

[14] Moreover, this feature is still present when separating the analysis between old and new stations. The latter, present from 2015 onwards, share the same accumulation of data with the former, as shown in Figure A1.

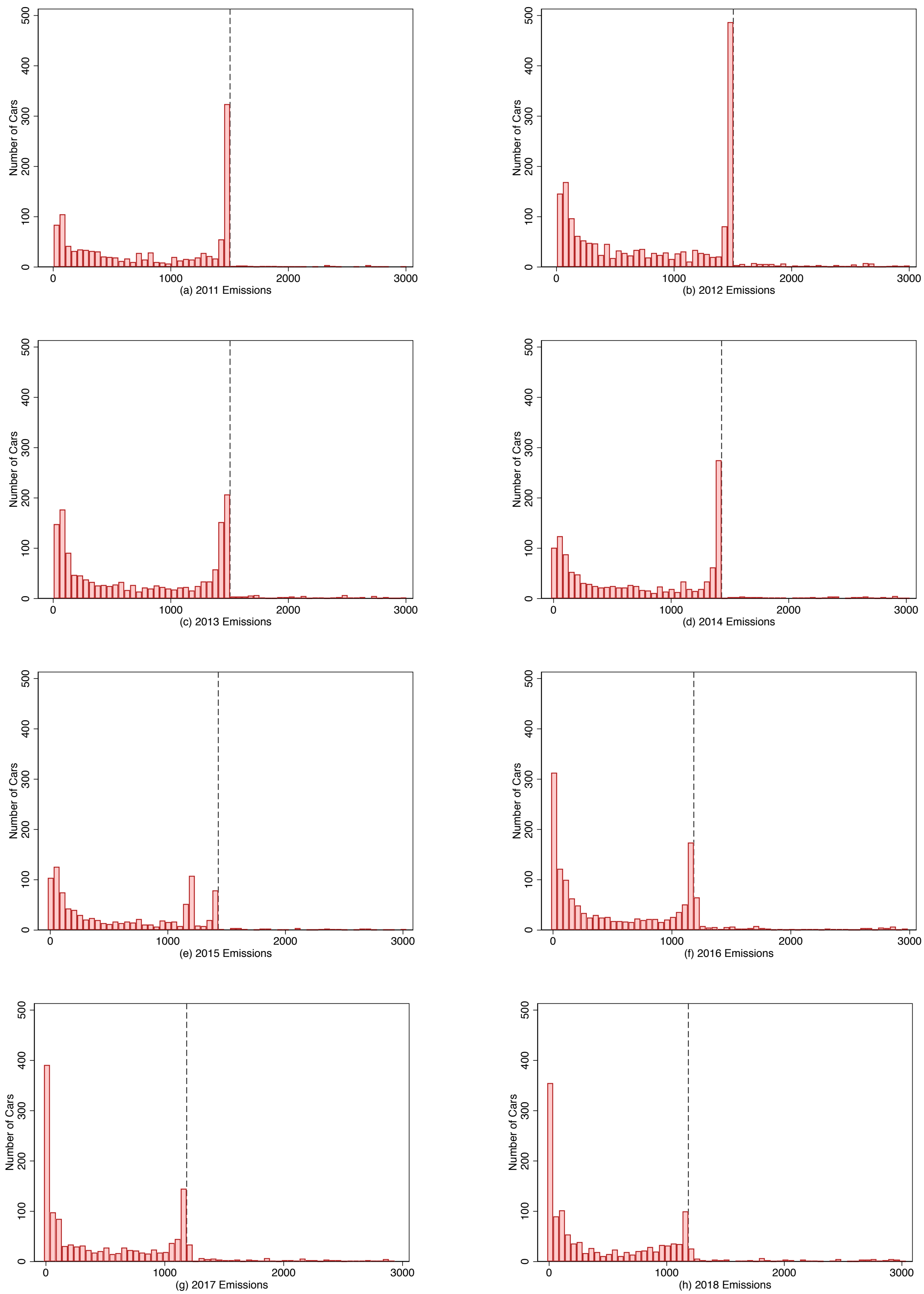
[15] Additionally, Figures A2 through A6 present CO and HC 5015, and NO, CO and HC 2525 test results for all years in the database. These are shown to strengthen the argument made above, namely that each different test result distribution is reasonably similar over time, as well as to illustrate that manipulation occurs mainly in the NO 5015 test results.

Figure 1: Histograms of Emissions for ASM 5015 and 2525 Test Results



Notes: Figure 1 presents registered gas measurements for all revisions conducted in Chile during year 2014 for models Hyundai Accent 1998 and Suzuki Esteem 1998. Required standards are indicated in each histogram with a vertical dashed line. The emission test is approved when emissions are equal or less than the corresponding standard, hence the bins that depict approved gas inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are given in parts per million (ppm) for NO and HC and in percentage of volume for CO.

Figure 2: Histograms of Emissions for NO 5015 Test Results



Notes: Figure 2 presents registered NO 5015 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in parts per million (ppm).

Table 4: Average NO Emissions per Year

Year	Emission Standard	Age	Pass: Avg. NO Emission	Pass: Share of Cars	Fail: Avg. NO Emission	Fail: Share of Cars	All Test Takers: Avg. NO Emission	All Test Takers: No. of Cars
2011	1,504	14	836.7	94.0%	3,351.5	6.0%	986.5	1,192
2012	1,504	15	798.5	91.7%	2,692.9	8.2%	953.9	1,902
2013	1,504	16	727.4	91.2%	2,909.8	8.8%	918.5	1,610
2014	1,429	17	707.2	92.1%	2,869.2	7.9%	877.8	1,343
2015	1,429	18	579.4	92.8%	2,528.5	7.1%	718.0	1,022
2016	1,186	19	474.9	90.2%	2,401.4	9.8%	664.8	1,474
2017	1,186	20	428.8	89.3%	2,344.9	10.7%	633.8	1,393
2018	1,186	21	406.9	89.5%	2,536.3	10.5%	630.9	1,321

Notes: Table 4 presents average NO emissions by year and test result for the two-model sample. The smog check is approved if the emission levels are equal or less than the given standard, and failed otherwise. Limits and average NO emissions are given in parts per million (ppm). Share of cars presents the ratio between the number of cars in the category in question and the total number of cars that took the test that year, as depicted in the last column.

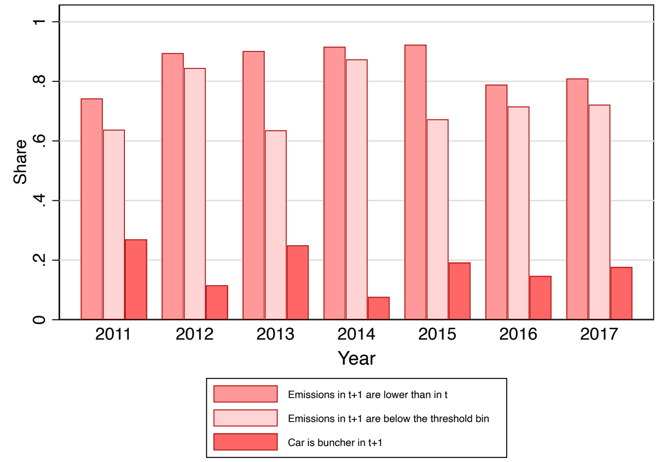
A few other exercises can be performed to characterize the nature behind the accumulation of data observed in the NO 5015 test results. Mainly, to strengthen the argument that bunching is not a statistical artifact but somewhat reliable evidence of manipulation. For instance, if it evidenced the presence of corruption in the inspection process, I would expect a buncher to pass all other gas and visual tests, i.e., to approve the complete examination. This conjecture makes sense: if the car owner pays a bribe to approve the inspection, all individual tests and not only the NO 5015 evaluation should be passed. With that in mind, I study the share of cars by category: distinguishing between those that are located in the bin at the left of the threshold and the rest, as well as those that approve the complete test and the ones that fail it. Not all NO 5015 bunchers approve the whole test, suggesting that there is a true distribution of unaltered emissions that is presumably smooth around the threshold. In other words, not all bunchers are indeed cheating. Table A1 presents the numerical values of this analysis. Nevertheless, as formerly presumed, approving the NO 5015 test with results just below the threshold decreases the probability of failing any other emission test as well as the whole inspection.[16] Table A2 depicts the OLS results of the different emission rejection indicators regressed on a dummy for bunchers.

Moreover and to the same extent, it seems that there are vehicles which, despite having failed the NO 5015 test, are approving the complete inspection. The above suggests that the final approval-rejection decision is more subjective and corruptible than what is stipulated by the regulation, further strengthening the idea that there is manipulation in these inspections. Figure A7 presents average rejection rates for every group of cars in each bin from Panel (d) of Figure 2 and for the different gas checks in the inspection.[17]

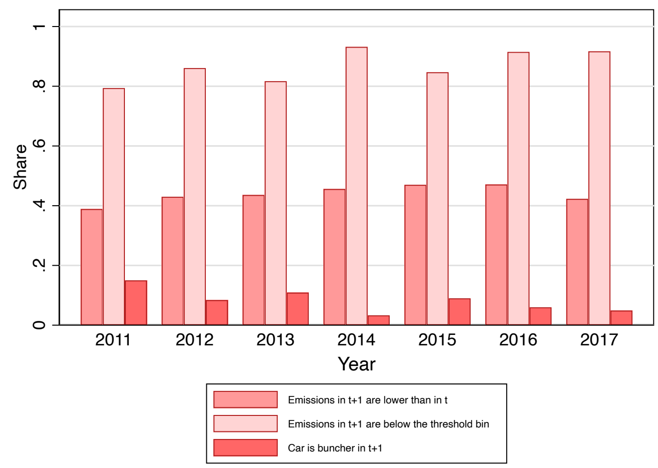
[16] Note that visual inspections cannot be included in this analysis, since the MTT database only contains the complete inspection outcome and result dummies for emission tests. Hence, visual inspection rejections are only obtained from discrepancies between complete inspection rejections and emission tests approvals.

[17] One possible alternative to this calculation is to estimate simple correlations using OLS, regressing rejection dummies on an indicator that takes the value 1 if the car is in the bin in question. These results are presented in Figure A8 and imply similar conclusions to the ones obtained from the previous figure.

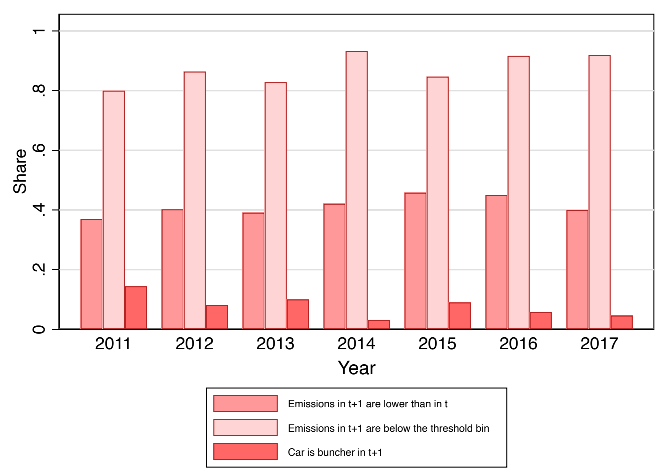
Figure 3: Persistency of Behavior by Car Type



(a) Bunchers



(b) All Non-Buncher Approvers



(c) Fair Non-Buncher Approvers

Notes: Figure 3 presents the emission behavior for different car groups, considering consecutive inspections only. Panel (a) depicts the share of cars that were bunchers in t and are in the category in question in $t+1$. Likewise, Panel (b) (Panel (c)) depicts the share of cars that passed the test in t but were not bunchers (that approved the test in t but were not in any of the three bins at the left of the threshold) and are in the category in question in $t+1$. The sum of the last two bars for every year represents the share of cars in the group in question, that approved the NO 5015 emission test in $t+1$.

3.2. *Stylized Facts and Emission Exercise*

Let the smog checks consist only of NO 5015 tests as an initial simplifying assumption. In addition, let the set of old cars in the economy be the one depicted in Panel (d) of Figure 2. From this, the number of old cars in the economy corresponds to 1,343, whose emissions are presented in the formerly mentioned figure. Every old car in the sample has the same *inercia equivalente* value (equal to 1,247 kg) and was fabricated the same year, thus is subject to the same NO 5015 emission standard (equal to 1,429 ppm NO). Table 5 presents NO emission recordings for inspections conducted in year 2014 by the above mentioned cars to illustrate the distribution of cars with NO emissions that were registered around the threshold.

Taken together, the unusual data distribution presented in Table 5 suggests the presence of manipulation in the NO 5015 test results. While there is an accumulation of data just below the threshold, their absence just above it suggests that results were altered to allow cars to approve the test.[18] Moreover, the McCrary Test associated to the discontinuity around 1,429 ppm NO has a density test value of -14.4. From this, the null hypothesis of no manipulation can be rejected (p-value = 0.000), reinforcing the idea that the latter exists in this setting.

Table 5: Emission Records in 2014: Two-Model Sample

	NO Emissions (ppm)	**Number of Cars**	**Share of Cars**	**Test Result**
Exact Emissions	1,427	27	1.9%	Pass
	1,428	33	2.5%	Pass
	1,429	25	2.0%	Pass
	1,430	0	0.0%	Fail
	1,431	0	0.0%	Fail
	1,432	0	0.0%	Fail
Emission Intervals	0 - **1,429**	1,237	92.1%	Pass
	1,430 - 16,000	106	7.9%	Fail
	1,379 - **1,429**	275	20.5%	Pass
	1,430 - 1,479	1	0.0%	Fail
	0 - 16,000	1,343	100%	-

Notes: Table 5 presents the number and share of cars with registered NO emissions around the threshold (highlighted in bold in the table). Altogether, 275 cars register emissions that are at most 50 ppm below the cutoff (i.e., between 1,379 and 1,429) and only 1 whose emissions are at most 50 ppm above it (i.e., between 1,429 and 1,479). Note that 50 ppm corresponds to twice the size of the required accuracy for NO tests. The maximum value recorded for NO emissions in this sample corresponds to 16,000 ppm. Share of cars presents the ratio between the number of cars in the category in question and the total number of cars in the vehicle fleet (i.e., 1,343).

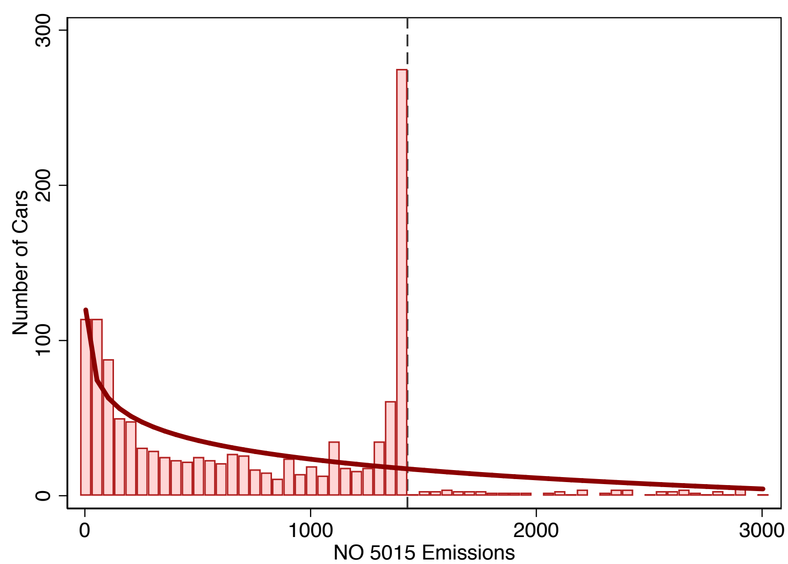
Henceforth, I assume that an old car is labeled as high-polluting (thus banned from circulation) if its emissions e are greater than the required standard $\bar{e}$ (i.e., if $e > \bar{e} = 1,429$ ppm NO), and as low-polluting otherwise. Then, with the supposition that smog check stations only test for NO 5015 and that the set of old cars behaves as the two previously-analyzed car models, the subsequent challenge is to determine how

[18] There is another important conclusion that can be derived from this table. One concern when studying the data, is that bunching might be a result of the database construction and not a consequence of fraud in the emission measurement process *per se*. For instance, if many cars that approved the inspection were imputed an emission equal to the threshold in case they ended up with an incomplete data entry post examination. However, since the emissions that characterize the cars in the bin at the left of the threshold are quite heterogeneous, I am able to rule out that option.

many of them are manipulating their results. Naturally, not every car whose emissions are just below the cutoff is indeed cheating since there is a true distribution of unaltered emissions that is presumably smooth around the threshold. Figure 4 adds a logarithmic prediction to the histogram in question, as an illustration of the possible true data distribution, to estimate the number of cheaters. Consistent with the probability density function of an exponential distribution, the prediction fit implies that the higher the emission level, the smaller the number of cars that register it. To that same extent, the logarithmic prediction suggests that less than 20 cars should register an emission at most 50 ppm NO below the threshold. Note that the same analysis can be conducted for the two following bins below the threshold, since the logarithmic prediction suggests frequencies far smaller than the ones displayed in each one of them.

Something interesting to keep in mind when analyzing the figure in question, is that cars closer to the threshold seem to cheat more than ones farther away. Simply put, the closer to the threshold from the right, the more cars seem to be missing below the prediction. However, this can also be a direct result of the fact that there are hardly any cars with emissions well above the threshold, so cheaters are scarcer the greater the distance to it. From the fit, I assume conservatively that 20 cars legitimately belong in the bin to the left of the threshold. Note that from the set of old vehicles and given the approval threshold in question, I would have, in absence of manipulation, 27% of vehicles classified as high-polluting and the rest as low-polluting. Nevertheless, in this scenario with manipulation, only 7.9% of cars end up labeled as high-polluting. The latter means that around 70% of high-polluting cars manipulate their results.

Figure 4: Frequency Plot and Logarithmic Trendline for NO Measurements



Notes: Figure 4 depicts a histogram of frequencies for NO 2014 measurements and its corresponding logarithmic prediction fit. Histogram bins are such that their width is twice the size of the required accuracy for NO 5015 tests (i.e., 50 ppm NO). The dashed line indicates the required standard (1,429 ppm NO), such that approved inspections are located to its left. The logarithmic prediction indicates that less than 20 cars should register an emission at most 50 ppm NO below the threshold.

An interesting exercise that follows from the results presented above, is to compare real and anticipated total emissions produced by old vehicles in circulation, given the hinted cheating results in NO 5015 tests. To do so, I assume that the true distribution of emissions follows the logarithmical shape presented in Figure 4. In addition, I consider that this distribution has a support between the emission standard and twice its value (i.e., 2,858 ppm NO). Furthermore, I presume initially that if the gas test is failed, the car is banned from circulation (i.e., repairing the car is not possible nor is there a possibility to retake the test). From the above, I am able to determine how larger are actual emissions from recorded ones (and from them, the total emissions anticipated by the policymaker), where the latter derive directly from the registered smog check results. To do so, I assign to the cheaters emission values that follow the functional form proposed as fit. From this, I am able to suggest that true emissions are 17.3% greater than expected.[19] Panel (a) of Table 6 depicts both real and anticipated emissions by car category as well as the percentage difference between them for the exercise in question.

In addition, the above mentioned exercise can be extended to illustrate the environmental impact of modifying the threshold to a more rigorous one. For instance, adjusting it to meet the HNC Mexican 2003-2004 standard depicted by Oliva (2015), which equals 1,200 ppm NO. To analyze the effects of such an arrangement, I continue to work with the two-model sample used above and assume that the true distribution of emissions is the one that follows the logarithmic fit presented in Figure 4. Under this new (and more strict) standard I would have, in absence of manipulation, 62.4% of cars classified as low-polluting and the remaining 37.6% as high-polluting. Naturally, the share of clean cars decreases as the standard becomes more demanding, since I am assuming that the true distribution of emissions remains unchanged. Additionally, for this second exercise, I assume that 70% of high-polluting cars alter their emissions.[20] Moreover, I assume that cheaters' emissions are actually distributed between the threshold and twice its size (i.e., 2,400 ppm NO), as suggested in the previous exercise. Likewise, I presume that manipulated emissions end up getting registered at most 50 ppm below the required standard. Conducting the same analysis as before, I conclude that true emissions are 25.8% greater than expected ones in this scenario. Panel (b) of Table 6 presents the exercise results. By the same token, Appendix A.1.2 repeats both previous exercises assuming a different source of manipulation in smog tests, finding similar results to the ones depicted above.

Altogether, emission standards might end up being suboptimal in presence of corruption if policymakers are using historical smog check results to establish them and/or if standards are set up to ensure an upper bound for pollution levels. This is especially the situation if anticipated emissions differ from real ones as substantially as suggested by both previous exercises. Additionally, following BGM (2019), an additional 1% of local vehicle-produced air pollution in the city of Santiago costs around USD 5 MM each year, and might even reach USD 10 MM under specific climatic conditions. Using this information, I am able to estimate the social cost of the NO 5015 test fraud, based on the results obtained from the two previous exercises. To do so, I assess both the representativeness and contribution of this two-model sample for the Chilean context, to extrapolate and generalize the formerly obtained results to the whole vehicle fleet in Santiago.

[19] Recall that smog checks measure vehicle emissions with their engine started at a particular speed and percentage power. Hence, the calculation of the aforementioned difference implicitly assumes that all vehicles are driven, on average, the same number of miles, and at the same speed and percentage power.

[20] As previously mentioned, it seems that manipulation is more common the closer the car is to meeting the standard. Moving the standard to a harsher value automatically increases the share of cheaters, since the true distribution of pollution suggests that the lower the emission the greater the number of cars that register it.

The two-model sample used for this analysis consists of 17-year-old car inspection results conducted during year 2014, where 30% of the whole 2014 sample comprises cars that are 17 years or older. Yet, from the sum of NO emissions registered during the year in question, these cars account for 43% of the total pollutant emissions. Thus, if I assume that cars that are 16 years or newer do not manipulate their emissions, true pollution levels were 7.4% (= 43% × 17.3%) greater than expected during year 2014 and would have been 11.1% (= 43% × 25.8%) greater than expected in a scenario with Mexican standards.[21] From this, the annual social cost associated to the previous exercises lies between USD 37 MM and USD 55.5 MM. Moreover, taking into account that there are approximately 5.6 MM inhabitants in Santiago, the annual per capita social cost of the NO 5015 test fraud lies between USD 6.6 and USD 9.9.[22] Table A3 presents reestimations of the costs in question, considering different non-linear fits for the 2014 NO 5015 emission results. The above, to ensure conclusions are not driven by the particular election of a logarithmic fit as the true distribution of data.

Note that the estimates presented in this section are lower bounds of both the true difference between anticipated and real emission levels and the social cost derived from such inefficiencies. First, if cheaters are not different from cars that failed the NO test, I could have attributed the average emissions of cars that failed the test (equal to 2,869 ppm NO in this context) to every cheating car. By the law of large numbers both averages should be equal. Instead, I allow cheaters to have emissions really close to the threshold and distribute the rest following the logarithmic fit towards its right tail. Second, since I am focusing exclusively on a particular gas test, I am implicitly leaving all other tests and their potential cheaters aside. Third, I assume that all NO 5015 altered emissions are located at most 50 ppm to the left of the threshold, when in fact they could be distributed between zero and the required standard. Last, I am not only assuming that the fraud is committed exclusively by cars that are 17 years or older, and that cheating occurs only in NO 5015 tests, but I am also estimating its subsequent harm with the lowest cost per additional percentage point of vehicle-produced pollution suggested by BGM (2019), corresponding to USD 5 MM each year.

In this way, it seems that the presence of corruption can make a smog check policy both inefficient and ineffective for the objectives of the central planner. Moreover, it can also implicate substantial costs for society in terms of the welfare decline that results from the damage caused by pollution. That being said, it seems reasonable to ask whether a smog checks program is always a dominated strategy for the central planner in the presence of corruption, or if there are tolerable levels of corruption under which this policy is still preferred and convenient given the available alternatives. This is true since the program in question manages to identify the different levels of pollution produced by vehicles at a very precise level, when results are not manipulated. I study this trade-off in the next two sections. First, through a theoretical model of the car market and second, with its calibration, to understand and quantify the trade-off between corruption and the finesse with which cars are classified as high or low-polluting.

[21] Compared with both initial exercises there is an additional implicit assumption in this calculation that uses the whole vehicle sample: the amount of miles driven, and the percentage power and speed at which this is done, are both independent of the age of the car and uniform across vintages.

[22] As a benchmark, consider the famous “Tissue Paper Case” that got exposed during 2017 in Chile. The two major paper producers colluded and charged a price premium for tissue paper. When their corruption was exposed and verified, part of their punishment consisted in paying around USD 10 to every Chilean over the age of 18, to compensate for the 10 years of corruption in the industry. See Fiscalía Nacional Económica (2017) for more details.

Table 6: Real and Anticipated Emissions Comparison: Exercise

	Total in Circulation	**Labeled: Low-Polluting** Non-Cheater	**Labeled: Low-Polluting** Cheater	**Labeled: High-Polluting**
		Panel (a) : Chilean-Standard Exercise		
Anticipated Emissions	874,784	513,049	361,735	304,138
Real Emissions	1,026,245	513,049	513,196	304,138
Difference	17.3%	0.0%	41.9%	0.0%
Share of Cars	92.1%	73.1%	19.0%	7.9%
		Panel (b) : Mexican-Standard Exercise		
Anticipated Emissions	738,273	322,739	415,534	372,207
Real Emissions	928,701	322,739	605,962	372,207
Difference	25.8%	0.0%	45.8%	0.0%
Share of Cars	88.8%	62.4%	26.4%	11.2%

Notes: Table 6 presents total pollutant levels by car category based on the two-model dataset for both exercises. To compute cheaters' true emissions, I assume their true emission distribution has a support between the emission standard and twice its value (i.e., 2,858 ppm NO for Panel (a) and 2,400 ppm NO for Panel (b)). Cars labeled as low-polluting are the ones allowed in circulation, whereas high-polluting vehicles are eliminated from the car fleet. Share of cars presents the ratio between the number of cars in the category in question and the total number of cars in the vehicle fleet (i.e., 1,343). Cars labeled as high-polluting are presented in one classification only, because every vehicle in this category legitimately belongs to it.

4. Theoretical Framework

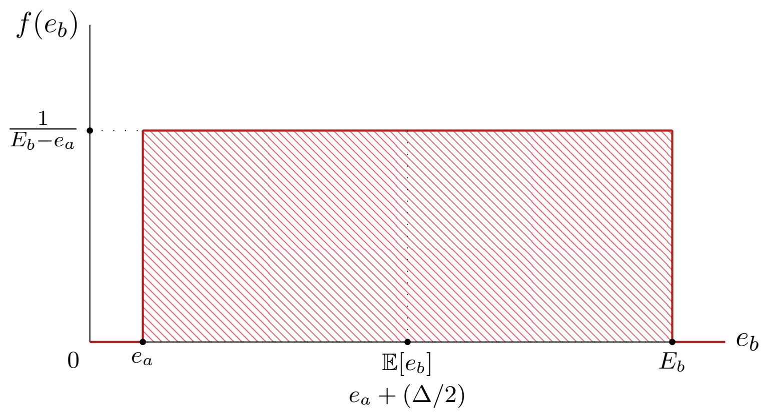
I take the model presented in BGM (2019) and alter it for the analysis in this paper. First, I work with a single-period world in which there are two types of cars equally valuable to consumers, that differ only in the amount of pollution they emit. In this regard, since consumers do not value pollution directly, there are no perceived quality differences between the two. Second, vehicle pollution is not always known by the central planner because it is stochastically determined for one of the car types. Nevertheless, she can become aware of these unknown emissions through the implementation of mandatory vehicle inspections in smog check stations as part of an environmental program that regulates vehicle circulation based on pollutant emissions. In such a scenario, the car dealer is certain about the pollution emitted by her car only after visiting the station in question, whereas the driver does not know this value from first source and only observes the resulting classification of the car she wants to acquire (e.g., whether she buys a *high* or *low* emission car based on a windshield sticker). In a world without both manipulation and measurement error, the result of the vehicle inspection indicates the true local pollutant emission values of the car. However, if there is corruption in the stations, the information observed both by the policymaker and the car driver might differ from the true pollution generated by the car, and inefficient driving restrictions might arise from the aforementioned imperfect information.

4.1. *Static Model Setting*

I start with a world in which there are two interacting agents that live for one period only: car producers and car drivers. The market consists of two types of vehicles that are both traded and driven: a and b.[23] There is a limited stock of type-a cars, $\bar{q}_a$, whereas type-b cars are supplied by perfectly competitive producers. The cost of manufacturing each car, denoted by $c \geq 0$, is homogeneous across the whole vehicle fleet. Contrarily, the annual car price varies across type, which I denote by p_t, where $t \in \{a, b\}$. Both car types share most features (e.g., consumer perceived quality, fuel efficiency and fuel cost, maintenance costs), except for the amount of pollution each one emits.[24] The present paper focuses mainly on local pollutants, such as CO, HC and NO, so that the pollution emitted by a car is a combination of those three contaminants. Type-a cars have homogeneous emissions, e_a, whereas type-b cars have an uncertain e_b emission level. Local pollutant emissions for these cars are uniformly distributed over the interval $[e_a, E_b]$ (i.e., $e_b \sim U(e_a, E_b)$). By defining $\Delta = E_b - e_a$, I have $\mathbb{E}[e_b] = e_a + \frac{\Delta}{2}$. Figure 5 depicts the distribution of emissions for type-b cars.

Furthermore, I assume that drivers live and use their cars in two distinct areas: "polluted" and "non-polluted". I denote the harm per mile h caused by a car of type t by $h_p e_t$ in the polluted area (e.g., Santiago) and $h_{np} e_t$ in the non-polluted area (e.g., rest of the country), assuming $h_p \gg h_{np} \approx 0$. Thus, the environmental damage a car causes does not only depend on how often the car is used, but also where it is driven. In this scenario, $h_{np} = 0$ implies that the social planner is only worried about negative driving externalities in the polluted area, for they do not exist in the non-polluted one. Thus, she should consider pollution-control policies in the former area only.

Figure 5: Emission of Local Pollutants for Type-b Cars



[23] A simple way to illustrate these two types of vehicles is to think about those that are new/less than 5 years old (i.e., type-a) and those that are old/over 5 years old (i.e., type-b); or those that are classified as light passenger vehicles (i.e., type-a) and those that are considered heavy (i.e., type-b).

[24] One way to understand this in a world where type-a cars are new and type-b are old, is to think that pollution depends on the age of the vehicle. Technological differences can explain the above, especially if new vehicles happen to filter their emissions more effectively. For instance, BGM (2019) mention the significant impact on pollution of vehicles with catalytic converts, feature that could also be used to distinguish type-a from type-b vehicles.

Additionally, there is a continuum of car drivers/households of mass 1 that vary in how they value driving. The consumer's type is denoted by θ and is distributed following a cumulative distribution function $F(\theta)$ over the interval $[0, \bar{\theta}]$. Moreover, drivers' valuation θ in area $k \in \{p, np\}$ is distributed according to the cumulative distribution $F_k(\theta)$ over the interval $[0, \bar{\theta}]$, from which I have $\mu F_p(\theta) + (1-\mu)F_{np}(\theta) = F(\theta)$ for all $\theta \in [0, \bar{\theta}]$ and μ is the fraction of households living in the polluted area.

A type-θ consumer who buys a type-t car for price p_t and runs it for x miles obtains the following utility:

$$u(\theta, t, x) = \frac{\alpha}{\alpha - 1}\, \theta\, x^{(\alpha-1)/\alpha} - \psi x - p_t. \tag{4.1.1}$$

The first term corresponds to the driver's gross benefit from car travel, which depends on her type θ, and exhibits decreasing returns (i.e., $\alpha > 1$). The second term captures monetary (e.g., parking, gasoline/diesel, maintenance) and non-monetary (e.g., time) costs of travel. I normalize to zero the outside utility of using public transport instead of buying a car, after assuming that utility is equal across households. Note that the consumer is not affected by pollution directly, hence if $p_a = p_b$, she is indifferent between buying a type-a or type-b vehicle. In the same way, note that the monetary and non-monetary costs of travel are independent from the car type. Each type-θ driver chooses whether to buy a car or not, and how much to drive it as to maximize (4.1.1). Thus, if a driver happens to buy a type-t car, utility maximization leads to the following number of miles driven:

$$x(\theta) = \left(\frac{\theta}{\psi}\right)^{\alpha}.$$

The driver anticipates these results, therefore choosing a type-t car, such that:

$$t(\theta) \in \arg\max_{t \in \{a,b\}} \left\{\kappa \theta^{\alpha} - p_t\right\}, \text{ where } \kappa = \left[(\alpha-1)\psi^{\alpha-1}\right]^{-1}. \tag{4.1.2}$$

4.2. *Equilibrium Benchmark: No Intervention*

To begin with, I characterize the market equilibrium in the absence of any policy intervention. Following BGM (2019), I assume that the car market is well integrated, such that households observe the same prices regardless of where they live.

Recall that the first term in (4.1.2) is independent from the car's type. Therefore, to solve it, she chooses the vehicle with the lowest price. In absence of any policy intervention, all cars are equal for the consumer and the limited supply of type-a does not affect her demand choices. Any price below c discourages car production because profits do not cover expenses. In this way, the equilibrium is that of perfect competition, such that $p_a = p_b = c$.

Another condition holds in this equilibrium: The lowest-valuation household to buy a car (identified as the type-θ^n household, where the superscript "n" indicates the setting of no intervention), obtains the same utility when buying a car and using public transport:

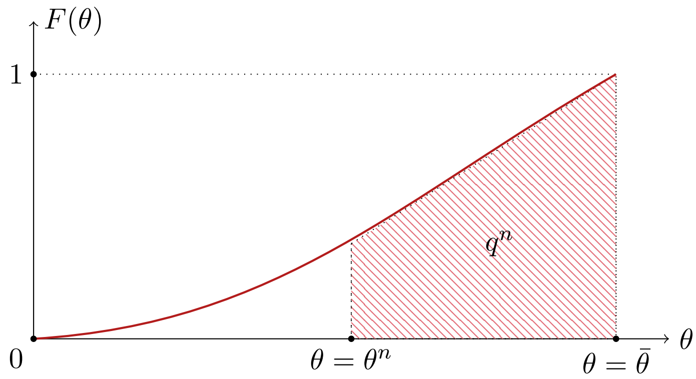
$$\kappa \left(\theta^n\right)^{\alpha} - p_t = 0.$$

In this regard, the last consumer to buy a car at price $p_a = p_b = c$, in a setting of no intervention is one of type:

$$\theta^n = \left(\frac{c}{\kappa}\right)^{1/\alpha} = \left[(\alpha-1)\psi^{\alpha-1}c\right]^{1/\alpha}.$$

Moreover, in equilibrium, the cutoff level θ^n must be consistent with the number of cars in the market $q^n = q_a^n + q_b^n$. Figure 6 presents the distribution of consumers in this setting of no intervention.

Figure 6: Consumers in a Setting of No Intervention



With this in mind and assuming that at price $p_a = p_b = c$ the market is equally divided between both types of cars, then:[25]

$$q_a^n = q_b^n = \frac{1}{2}\Big(F_p(\bar{\theta}) - F_p(\theta^n)\Big) = \frac{1}{2}q^n.$$

Thus, the no-intervention benchmark is characterized both by the mileage schedule $x^n(\theta) = \left[\frac{\theta}{\psi}\right]^{\alpha}$ and by the cutoff θ^n depicted above. Cars are bought by households with $\theta \geq \theta^n$, whereas households with $\theta \in [0, \theta^n)$ ride the public transport.

4.3. *Planner's Problem and Policy Interventions: Driving Restrictions*

In what follows, I study the policy proposed in BGM (2019) considering this setting where vehicle pollution is not always known by the central planner. Still, taking into account that the model in the present work is a single-period one where cars differ in type, a vintage restriction program is not directly applicable to this context without having first determined the feature that differentiates them. However, to make a parallel between their work and this one, a vintage restriction can be understood as one based on a single attribute of the vehicle. For this model I consider the type of the car (i.e., a or b) as said attribute. Hereinafter, I refer to single attribute restrictions – analogous to the ones proposed by BGM (2019) – as type-specific regulations. I later extend their analysis to incorporate another driving restriction, not based on the type of the car, but on the level of pollutants emissions that characterizes each one of them.

Following BGM (2019), the parameter $R_i \in [0, 1]$ defines the extent of the driving restriction, where i depicts the dimension that is relevant when determining whether a car gets a restriction or not (e.g., type/vintage: vr, smog check result of pollutant emissions: sc). A driving restriction reduces the number of car trips a driver would otherwise make uniformly over the period of time in which the regulation is applied. Formally, a driver θ who buys a type-t car that faces an effective restriction R_i, consequently drives the following number of miles:

$$x(\theta, R_i) = R_i \left(\frac{\theta}{\psi}\right)^{\alpha}. \tag{4.3.1}$$

[25] Note that in the following expression I am also assuming that $\bar{q}_a \geq \frac{1}{2}q^n$, i.e., the quota of type-a cars is large enough to cover half of the demand in the no intervention setting.

As this travel reduction falls indistinctively over trips of different values, her utility reduces to:

$$u(\theta, t, R_i) = R_i \kappa \theta^{\alpha} - p_t. \tag{4.3.2}$$

The proper way to define the last household to drive a car from a social standpoint, is to consider the social value created by the last driver, as well as all costs associated to the car. This, such that the private benefits of the last car in the market are exactly equal to its expected social cost, which occurs when:

$$\begin{aligned} R_i \kappa \theta^{\alpha} &= c + R_i h_p \mathbb{E}[e_t] \left(\frac{\theta}{\psi}\right)^{\alpha} \\ \Rightarrow R_i \kappa \theta^{\alpha} - R_i h_p \mathbb{E}[e_t] \left(\frac{\theta}{\psi}\right)^{\alpha} &= c. \end{aligned} \tag{4.3.3}$$

Note that in (4.3.3), the last socially optimal driver that is in the economy depends not only on the value of the restriction R_i and the manufacturing cost of said car c, but also on the expected pollution emitted by it.

Hereinafter, to simplify the analysis, I assume cars to be allocated efficiently. This is, less-polluting to be driven by consumers that value cars most and high-polluting by those that value them less.[26]

4.3.1. Type-Specific Driving Restrictions

Having the aforementioned context in mind, a type-specific driving restriction is denoted by $i = vr$, which says that a type-t car can only be used in the polluted area a fraction of the time. Naturally, considering that the planner is negatively affected by pollution, it is in her first-best interest to encourage higher type-θ households to ride type-a cars, for the former are the ones that drive the most and the latter are the ones that pollute less. Moreover, assuming that the optimal amount of circulating cars, q^{vr}, is such that $q^{vr} > \bar{q}_a$, the last household to buy a car purchases one of type-b.

Henceforth, I maximize the central planner's expected social welfare function ($E_{vr}[W]$) taking into account that what she is deciding is how to implement a driving regulation, $R_{vr} \in [0, 1]$, based on the car type exclusively (i.e., only taking into account whether the car is of type-a or of type-b).

In this context, the social planner determines the restriction upon type-a vehicles $R_a \leq 1$ and the one upon type-b vehicles $R_b \leq 1$ as to maximize:[27]

$$\begin{aligned} \mathbb{E}_{vr}[W] = \quad & - \quad c \left[F_p(\bar{\theta}) - F_p(\theta_b)\right] \\ & + \int_{\theta_a}^{\bar{\theta}} R_a \left[\kappa\theta^{\alpha} - h_p e_a \left(\frac{\theta}{\psi}\right)^{\alpha}\right] f_p(\theta) d\theta \\ & + \int_{\theta_b}^{\theta_a} R_b \left[\kappa\theta^{\alpha} - h_p \mathbb{E}[e_b] \left(\frac{\theta}{\psi}\right)^{\alpha}\right] f_p(\theta) d\theta. \end{aligned} \tag{4.3.4}$$

[26] I rely on efficient rationing to sort out drivers because all cars are equal for the consumers in a setting of no intervention. One could think that efficient rationing occurs even when cars are not sold "correctly" in the first place: lower type-θ drivers can resell their cars to higher type-θ drivers, thus allowing the market to allocate cars efficiently in equilibrium.

[27] There is a hidden assumption in the social planner's expected utility function. Initially, when taking the expected value of $h_p e_b x(\theta)$, one should use the joint distribution of e_b and θ. Notwithstanding, I assume both random variables to be independent, writing $\mathbb{E}[e_b]$ in the social planner's utility function. In terms of the model this assumption can be interpreted as follows: a type-θ consumer does not prefer one amount of emissions over the rest. This is consistent with the definition of the type-θ consumer's utility function: she only values the car in itself and the miles she gets to drive it. A second interpretation is that since the consumer does not know the emission level of type-b cars, her preferences do not depend on it.

Where (4.3.4) is obtained from expressions (4.3.1) and (4.3.2). First, θ_a is obtained from the rationing condition that arises from having a limited supply of type-a cars, thus:

$$
\begin{aligned}
&\bar{q}_a = F_p(\bar{\theta}) - F_p(\theta_a) \\
&\Rightarrow F_p(\theta_a) = 1 - \bar{q}_a \\
&\Rightarrow \theta_a^{vr} = F_p^{-1}\Big(1 - \bar{q}_a\Big).
\end{aligned}
$$

Second, θ_b is obtained from the social standpoint optimum that compares private benefits and social costs between buying a type-b vehicle and using the public transport:

$$
\begin{aligned}
&R_b \kappa \theta^{\alpha} - R_b h_p \mathbb{E}[e_b] \left(\frac{\theta}{\psi}\right)^{\alpha} = c \\
&\Rightarrow \theta_b^{\alpha} = \frac{c}{R_b\left(\kappa - \frac{h_p \mathbb{E}[e_b]}{\psi^{\alpha}}\right)} \\
&\Rightarrow \theta_b^{vr} = \left[\frac{c}{R_b\left(\kappa - \frac{h_p[e_a + \Delta/2]}{\psi^{\alpha}}\right)}\right]^{1/\alpha}.
\end{aligned}
\tag{4.3.5}
$$

Given that $\theta_b^{vr} > \theta^n$, the central planner needs to make sure that households $\theta < \theta_b^{vr}$ do not buy a car. This is equivalent to saying that the central planner determines a quota for type-b cars, controlling their number in the polluted area to:[28]

$$
F_p(\theta_a^{vr}) - F_p(\theta_b^{vr}) \geq 0.
$$

Additionally, p_a is obtained from the indifference condition between buying a type-a and a type-b vehicle, for the type-θ_a^{vr} consumer:

$$
\begin{aligned}
&R_a \kappa \theta_a^{\alpha} - p_a = R_b \kappa \theta_a^{\alpha} - p_b \\
&\Rightarrow p_a = \kappa \theta_a^{\alpha}\left(R_a - R_b\right) + p_b \ .
\end{aligned}
$$

In addition, given that there is perfect competition in the type-b car market, in spite of potential driving restrictions or production quotas, I have that $p_b = c$. Moreover, to ensure that type-a cars are being produced it must occur that $p_a \geq c$, hence $p_a \geq p_b$.

Appendix A.2.1 presents the mathematical resolution for the above mentioned central planner's optimization problem. From this, an optimally-designed driving restriction that is type-specific is defined by the duplet $\{R_b \leq 1, R_a = 1\}$, where R_b is the restriction faced by any household $\theta \in [\theta_b^{vr}, \theta_a^{vr})$ buying a type-b car, with θ_b^{vr} given by (4.3.5); and R_a is the restriction set upon any type-a car. This result is analogous to the vintage-specific driving restriction proposed by BGM (2019): type-a cars (or new ones in their paper) are the ones that have more freedom of circulation since they are the ones that pollute less, while type-b cars (or the older ones in their work) might face driving restrictions in presence of specific setting conditions.

[28] One way to understand the means by which the central planner determines the number of type-b cars in circulation, is to think she achieves this by fixing import quotas for the polluted area. However, considering that cars are locally-produced in this model, a more proper way to understand this assumption is to consider production quotas instead. Particularly, production limits that restrict the manufacture of vehicles at the local level (e.g., Singapore banned additional cars on its roads). By such means, perfectly competitive producers compete on prices trying to sell their type-b cars to drivers and p_b is set such that it reaches its manufacturing cost, even in presence of the above mentioned guidelines.

4.3.2. Pollution-Specific Driving Restrictions

In a setting where smog check stations are the policy intervention, the driving restriction is determined based on the amount of pollution emitted by each vehicle, which I denote with $i = sc$. This means that after measuring the emission level of the car with a smog test, an emission-level-sc car can only be used in the polluted area a fraction of the time.

To determine how much pollution each car emits, vehicles must visit a smog check station at the final step of their production process. Thus, car producers are in charge of it and must take their cars to the station before selling them to drivers. In this station, cars are inspected and their emission level is identified (i.e., car dealers learn the value of the emissions per mile e_t, $t \in \{a, b\}$, for their type-t car in question).

Once the gas emission level of the vehicle has been identified, the measurement is compared to a threshold $\bar{e}$ (previously determined by the central planner) and the extent of the driving restriction for the car is determined. If $e_t \leq \bar{e}$, $t \in \{a, b\}$, the car is characterized as *low-polluting* (classification indexed by the subscript "l") and if $e_t > \bar{e}$, $t \in \{a, b\}$, as *high-polluting* (classification indexed by the subscript "h"). I assume that once classified either as low or high-polluting, cars cannot be repaired to authentically reduce their emissions. One way to explain this is to assume that repairing costs are too high to be disbursed by car dealers, that these are of public knowledge and have no direct effect on prices. A possible extension to the model is to allow cars to be repaired in exchange for a payment r, such that $p_a - c - r > p_b - c$, namely $p_a - p_b > r$. Naturally, the inclusion of repairing costs has an effect on prices and therefore on the equilibrium of the problem.

Thus, the extent of the restriction $R_{sc} \in [0, 1]$, depends on the label that the car receives, (i.e., either $sc = l$ or $sc = h$). If tagged as l, the car faces a restriction of $R_l \leq 1$, whilst if labeled as h, the car faces a restriction of $R_h \leq 1$. For the purposes of the model, I assume that a car that has an emission level of e_a is immediately classified as low-polluting (i.e., the threshold is such that $e_a \leq \bar{e}$), namely that $P_r[e_a \leq \bar{e}] = 1$. It follows that every type-a car is labeled $sc = l$.

After the car has been taken to a smog check station, the producer of the car sells it to a driver who is aware of the restriction R_{sc} associated to that vehicle. Lastly, there is an associated fixed cost of operating a smog check station C_s (e.g., operational and administrative expenses, maintenance, etc.), that is relevant to the purposes of the central planner's decision.

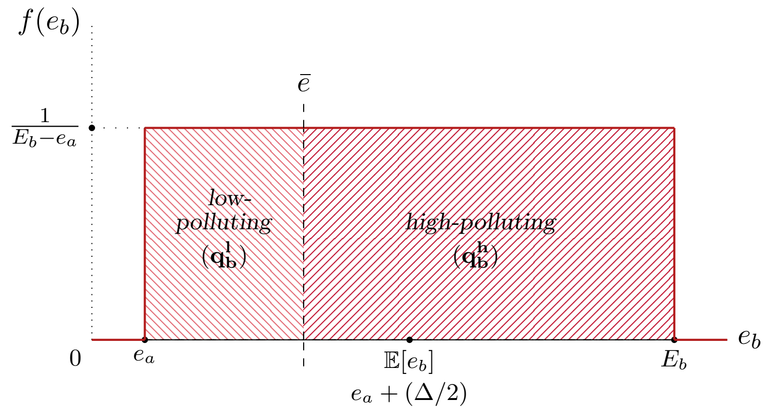
Perfect Information

I begin by analyzing the policy implications for a scenario in which it is not possible to manipulate the test conducted in the smog check station. Additionally, I presume that there is no measurement error in the gas examination process. Therefore, the emission measurement obtained from the revision corresponds to the actual emission of the car and each car is correctly classified as l or h. Recall that I assume cars to be allocated efficiently, that is, less-polluting to be sold to drivers that value cars most and high-polluting to those that value them less.

Again, assuming that the optimal amount of circulating cars, q^{sc}, is such that $q^{sc} > \bar{q}_a$, the last household to buy a car purchases one of type-b. Thus, the last car to be sold is one labeled as high-polluting and of type-b. To that same extent, given that there is perfect competition in the type-b car market, in spite of potential driving regulations or production quotas, I have that $p_h = c$.

Let q_b be the amount of type-b cars that are being sold in the polluted area, where $q_b = q_b^l + q_b^h$ and q_b^h (q_b^l) is the number of high (low)-polluting type-b cars in circulation. Naturally, the amount of low-polluting type-b cars, q_b^l, depends on the threshold $\bar{e}$ that classifies vehicles into two categories. Figure 7 depicts an example for the classification of these cars based on their emission level.

Figure 7: Classification of Type-b Cars based on their Emissions



In this context, the social planner determines the restriction upon low-polluting vehicles $R_l \leq 1$, the one upon high-polluting vehicles in circulation $R_h \leq 1$, and the threshold of emissions $\bar{e}$ to classify vehicles as l or h as to maximize:

$$
\begin{aligned}
\mathbb{E}_{sc}[W] = \quad & - \quad \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\
& + \quad \int_{\theta_a}^{\bar{\theta}} R_l \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^l] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^h] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta.
\end{aligned}
$$

Since $e_b \sim U(e_a, E_b)$, letting $\Delta = E_b - e_a$, I have:

$$
\mathbb{E}[e_b^l] = \int_{e_a}^{\bar{e}} \left(\frac{e_b}{\bar{e} - e_a}\right) de_b = \frac{e_a + \bar{e}}{2}.
$$

$$
\mathbb{E}[e_b^h] = \int_{\bar{e}}^{E_b} \left(\frac{e_b}{E_b - \bar{e}}\right) de_b = \frac{\bar{e} + E_b}{2} = \frac{e_a + \bar{e} + \Delta}{2}.
$$

First, θ_a is obtained from the rationing condition that arises from having a limited supply of type-a cars that is driven in its entirety:

$$
\begin{aligned}
& \bar{q}_a = F_p(\bar{\theta}) - F_p(\theta_a) \\
& \Rightarrow F_p(\theta_a) = 1 - \bar{q}_a \\
& \Rightarrow \theta_a^{sc} = F_p^{-1}\Big(1 - \bar{q}_a\Big).
\end{aligned}
$$

Next, θ_l is obtained from the indifference condition[29] between buying a low-polluting and high-polluting vehicle:[30]

$$\begin{aligned} R_l \kappa \theta^{\alpha} - p_l &= R_h \kappa \theta^{\alpha} - p_h \\ \Rightarrow \theta_l^{sc} &= \left[\frac{p_l - p_h}{\kappa \left(R_l - R_h \right)} \right]^{1/\alpha}. \end{aligned} \tag{4.3.6}$$

Third, θ_h is obtained from the social standpoint optimum that compares private benefits and social costs between buying a high-polluting vehicle and using the public transport:

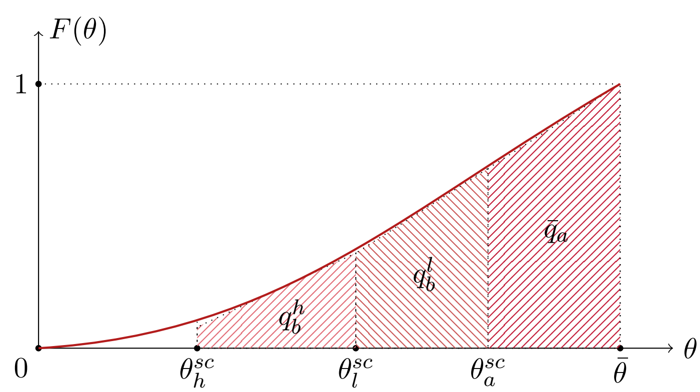
$$\begin{aligned} R_h \kappa \theta^{\alpha} - R_h h_p \mathbb{E}[e_b^h] \left(\frac{\theta}{\psi} \right)^{\alpha} &= c \\ \Rightarrow \theta_h^{\alpha} &= \frac{c}{R_h \left(\kappa - \frac{h_p \mathbb{E}[e_b^h]}{\psi^{\alpha}} \right)} \\ \Rightarrow \theta_h^{sc} &= \left[\frac{c}{R_h \left(\kappa - \frac{h_p[(e_a + \bar{e} + \Delta)/2]}{\psi^{\alpha}} \right)} \right]^{1/\alpha}. \end{aligned} \tag{4.3.7}$$

Note that $\theta_h^{sc} > \theta^n$, meaning that the central planner needs to ensure that households $\theta < \theta_h^{sc}$ do not buy a car. This is equivalent to saying that the central planner determines a quota for type-b cars, controlling their number in the polluted area to:

$$F_p(\theta_a^{sc}) - F_p(\theta_h^{sc}) \geq 0.$$

I denote this quota by $q_b = q_b^l + q_b^h$. Figure 8 depicts the consumer thresholds and corresponding car quantities for this smog check policy setting.

Figure 8: Car Quantities and Consumer Thresholds



[29] Note that the optimal number of miles driven associated to the consumer's optimization problem is the same for the two types of cars. Nonetheless, the prices of vehicles vary depending on their emissions due to the different driving regulations that apply to each one of them, allowing me to find a consumer that is indifferent between buying a high-polluting and low-polluting vehicle.

[30] Assuming $p_l > p_h$ in the expression for θ_l requires $R_l > R_h$, to guarantee that the term is both defined and positive. Note that assuming $p_l > p_h$ makes sense in the context of this model, for efficient rationing ensures that higher type-θ consumers buy low-polluting cars instead of high-polluting ones. Moreover, the central planner is concerned in controlling local pollutant emissions. Hence, allowing low-polluting cars to circulate more than high-polluting ones (i.e., $R_l > R_h$) is consistent with this goal. Contrarily, assuming $p_h > p_l$ is a contradiction given that I have $p_h = c$ due to perfect competition, and $p_l \geq c$ given that any price below c implies zero low-polluting cars are produced. However, it is also possible to assume that $p_l = p_h = c$, hence $R_l = R_h$. From the above, there are two possibilities: either $p_l > p_h$ and $R_l > R_h$, or $p_l = p_h = c$ and $R_l = R_h$.

Additionally, as depicted in Figure 8, $q_b = q_b^l + q_b^h = F(\theta_a^{sc}) - F(\theta_h^{sc})$, from which it is possible to obtain the following:

$$
\begin{aligned}
q_b^l &= q_b \times P_r[e_b \leq \bar{e}] \\
\Rightarrow q_b^l &= q_b \left(\frac{\bar{e} - e_a}{\Delta} \right) \\
\Rightarrow q_b^l &= \Big(F(\theta_a^{sc}) - F(\theta_h^{sc}) \Big) \left(\frac{\bar{e} - e_a}{\Delta} \right).
\end{aligned}
$$

From the above, I obtain another expression for the threshold θ_l^{sc}, which depends both on the emission standard $\bar{e}$ and the amount of type-b cars in circulation in the economy:

$$
\begin{aligned}
& F(\theta_l^{sc}) = 1 - (\bar{q}_a + q_b^l) \\
& \Rightarrow \theta_l^{sc} = F_p^{-1} \left(1 - \bar{q}_a - q_b^l \right) \\
& \Rightarrow \theta_l^{sc} = F_p^{-1} \left(1 - \bar{q}_a - \Big[F(\theta_a^{sc}) - F(\theta_h^{sc}) \Big] \left[\frac{\bar{e} - e_a}{\Delta} \right] \right) \\
& \Rightarrow \theta_l^{sc} = F_p^{-1} \left(F(\theta_a^{sc}) - \Big[F(\theta_a^{sc}) - F(\theta_h^{sc}) \Big] \left[\frac{\bar{e} - e_a}{\Delta} \right] \right).
\end{aligned}
$$

Appendix A.2.2 presents the mathematical resolution for the corresponding central planner's optimization problem. In this manner, an optimally-designed driving restriction that is pollutant-emission-specific is defined by the triplet $\{R_h \leq 1, R_l = 1, \bar{e}^{sc} \in [e_a, E_b]\}$, where R_h is the restriction faced by any household $\theta \in [\theta_h^{sc}, \theta_l^{sc})$ buying a high-polluting type-b car, with θ_h^{sc} given by (4.3.7); R_l is the restriction set upon any low-polluting car faced by any household $\theta \in [\theta_l^{sc}, \bar{\theta})$, with θ_l^{sc} given by (4.3.6); and $\bar{e}^{sc}$ is the optimally chosen threshold that determines whether a car is classified as low or high-polluting.

Finally, it is not difficult to see that the problem the central planner faces in the smog check station problem is the unrestricted version of the problem she faces in the type-restriction setting (at least in a scenario with perfect information). If it was optimal to set $\bar{e}^{sc} = e_a$, then both policies would yield the same result in terms of consumer thresholds, car prices and driving regulations for both type-a and type-b cars.[31] Consequently, leaving the operational costs aside, it is clear that $\mathbb{E}_{vr}[W] \leq \mathbb{E}_{sc}[W]$. However, to the extent that C_s is sufficiently large and the social planner can choose not to pay C_s by switching to a vintage restriction, then it follows that $\mathbb{E}_{vr}[W] > \mathbb{E}_{sc}[W]$.

Imperfect Information: Manipulation

It is interesting to analyze what happens when the information received by the central planner regarding the car's emissions differs from its true emission values (for instance, due to the existence of manipulation/fraud or measurement error in the evaluation of emissions). Let $\lambda \in (0, 1)$ denote the fraction of cars with high emissions that pose as low-polluting cars.[32] I assume that this fraction of cars presents fake emissions that are uniformly distributed over the interval $[e_a, \bar{e}]$.

[31] Note that in this event the threshold θ_l disappears, for every type-b car is classified as high-polluting. Moreover, the emission threshold $\bar{e}$ is such that it allows to classify cars based on their type, namely $q_a = q^l$ and $q_b = q^h$.

[32] Ultimately, one could consider an extreme scenario in which $\lambda = 1$, where the social planner does not trust the emission measurements, for all high-polluting cars pose as low-polluting. This scenario is equivalent to the one where a type-specific restriction, as the one presented in Section 4.3.1, is the optimal policy. The above, for smog check stations are not useful in adding information regarding the vehicles gas emissions and imply an operational cost of C_s to the social planner.

The mathematical resolution is equivalent both in a problem that considers measurement errors due to machine failures and in one where these occur as a result of manipulation or fraud. Nevertheless, observe that considering that all high-polluting cars, independent of the closeness to the threshold, commit fraud makes corruption in this setting more similar to a behavioral response than to a technological glitch. A comprehensive study of the mechanisms a social planner may impose to prevent mislabeling needs to incorporate the decision of cheating to the model. Consequently, one possible extension to the model is to allow λ to be determined endogenously by the agents actions. However, since the objective of this paper is to study the effects of fraudulent behavior, I consider λ exogenous for simplifying purposes.

In such context, the optimization problem of the social planner must be partially modified. In particular, her social welfare function changes to:

$$\begin{aligned}
\mathbb{E}_{scm}[W] = \quad & - \quad \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\
& + \quad \int_{\theta_a}^{\bar{\theta}} R_l \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_l] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right) \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta.
\end{aligned}$$

Where $\mathbb{E}[e_l]$ denotes the expected emission value for a car that is labeled as low-polluting (i.e., $sc = l$) taking into account that a fraction λ of high-polluting cars is mislabeled as low-polluting.

Appendix A.2.2 presents the mathematical resolution for the corresponding central planner's optimization problem. From this, in the event of manipulation, an optimally-designed driving restriction that is pollutant-emission-specific is defined by the triplet $\{R_h \leq 1, R_l = 1, \bar{e}^{scm} \in [e_a, E_b]\}$, where R_h is the restriction faced by any household $\theta \in [\theta_h^{scm}, \theta_l^{scm})$ buying a high-polluting type-b car, with θ_h^{scm} given by (4.3.7); R_l is the restriction set upon any low-polluting car faced by any household $\theta \in [\theta_l^{scm}, \bar{\theta})$, with θ_l^{scm} given by (4.3.6); and $\bar{e}^{scm}$ is the optimally chosen threshold that determines whether a car is classified as low or high-polluting.

Moreover, note that if either $\Delta = 0$ or $\lambda = 0$, then the scenario of imperfect information is equivalent to the problem without manipulation. Both conditions make sense from an economic perspective. On the one hand if $\Delta = 0$, all cars have an emission level of e_a, which means that even if the central planner determines $\bar{e} = e_a$, all cars get classified as low-polluting. Thus, corruption ceases to make sense in such context and the central planner faces the same problem she would face in its absence. On the other hand, if $\lambda = 0$, no high-polluting cars get mislabeled as low-polluting, such that there is no fraud and both scenarios (with and without manipulation) are equivalent.

4.3.3. Combining Policies: Vintage Driving Restrictions with Smog Check Stations

In what follows I modify the problem studied in Section 4.3.2, adopting both type-specific restrictions and smog check stations (combination indexed by the subscript vs, as in vintage-smog-check regulation). The above, by allowing the central planner to define three different driving restrictions upon circulating vehicles: R_a for type-a cars, R_l for low-polluting type-b cars and R_h for high-polluting type-b cars. In such a scenario, the central planner solves:

$$\begin{aligned}\max_{\bar{e},R_a,R_l,R_h} \mathbb{E}_{vs}[W] = \; & - \quad \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\ & + \int_{\theta_a}^{\bar{\theta}} R_a \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ & + \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^l] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ & + \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^h] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta.\end{aligned}$$

Consumer thresholds are the same as the ones used in the previous sections: θ_a is obtained from the limited supply of type-a cars, θ_l from the indifference condition between buying a low-polluting and high-polluting type-b car and θ_h from matching the private benefits and social costs from driving a high-polluting type-b car.

Appendix A.2.3 presents the mathematical resolution for the corresponding central planner's optimization problem. The analysis for this scenario is analogous to the one presented in Section 4.3.2. The only possibility that cannot be discarded is $R_a = 1$, $R_l = 1$ and $R_h \leq 1$, where the optimal pollution standard $\bar{e}^{vs}$ is such that $\bar{e}^{vs} = \bar{e}^{sc}$.[33]

Thus far, I have presented the theoretical framework of the car market, to begin to determine which of the two policies is optimal for the central planner, both in a world with perfect and imperfect information. In the next section, I calibrate the parameters of the model, to study how the central planner's welfare evolves when using the different policies studied in this section. This is done in order to determine if there are certain tolerable levels of corruption under which a smog check policy is still preferable to a type-specific one or if the latter always dominates the former in the event of manipulation.

5. Tuning the Model

The previous section illustrates with a single-period model the role that some parameters play in the central planner's problem. The two analyzed policies could not be compared in the aforementioned section, given that the planner's optimization problem has no analytical solution. Nevertheless, in what follows I suggest values for some of the model's parameters, seeking to calibrate and understand it through a numerical solution. By the same token, this section aims to determine the possible comparative advantages of each policy and the particular context characteristics that make one or the other preferable.

Specifically, I estimate the central planner's welfare function when using each program in presence of different characteristics of the economy, namely, the corruption level (λ) and the emissions dispersion (Δ).

[33] Despite not directly presenting the resolution of this problem in the presence of manipulation, the result is analogous to the one obtained in Section 4.3.2, namely $\bar{e}^{vsm} = \bar{e}^{scm}$. On that account, requiring the driving restriction faced by type-a cars to equal the one faced by low-polluting type-b ones seems not to be costly to the central planner in this model.

This is done in order to illustrate if and how the optimal policy changes depending on the problem setting. Initially, the query could have been not only to choose between vintage-specific driving restrictions (or type-specific as ascribed in the model) and smog check policies, but to assess whether a combination of both is ultimately the best alternative. However, Section 4.3.3 determines that both an emission-specific restriction and one that combines the former with vintage regulations, yield the same optimally-designed program given the construction of the model. Thus, for this particular analysis, the only relevant comparison is between a vintage-specific restriction and a smog check policy.

5.1. *Car characteristics, households' preferences, and pollution parameters*

Considering that the present paper aims to compare driving regulations that differentiate cars by their pollution rates through smog checks and the vintage-specific driving restrictions suggested by BGM (2019) using Chilean data to calibrate the model just like the authors do in their paper, most of the parameter values used in this section correspond to the ones utilized in the previously mentioned work.

To begin with, I fix the vehicle production cost c to USD $16,000$, which the authors obtain from the weighted average price of new vehicles in Chile.[34] Additionally, I fix four other model parameters. In particular, I define the value for the driver's returns from car travel (α), the monetary and non-monetary costs of travel (ψ), the marginal harm per mile in the polluted area (h_p), and the driving restriction set upon high-polluting cars (R_h), following the authors' estimations as presented in Table 7.

Table 7: Parameter Values

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
α	2.063	ψ	0.286	R_h	0.968	h_p	0.117

Notes: Table 7 depicts a fragment of Table 3 presented in BGM (2019). Parameters α, ψ and R_h are estimated using an iterated GMM method. Standard errors are omitted for simplicity. Note that R_h is presented as R in the original diagram; I impute this value to the driving restriction set upon high-polluting vehicles, insofar as to achieve the greatest comparability between both papers. The value of h_p is obtained from $h_p = \epsilon_p/e_a$, where ϵ_p is a new car (type-a) external cost and e_a its emission rate. I use the author's estimation $\epsilon_p = 0.0244$ and assume $e_a = 0.209$.

Moreover, I assume that the consumer's type, θ, distributes uniformly over the interval $[0, \bar{\theta}]$. In addition, given that 5 years or newer cars comprise around 20% of the sample and that new cars in the BGM (2019) model can be analogous to type-a cars in my model, I fix $\bar{q}_a = 0.2$. Since θ is assumed to distribute uniformly, the above is equivalent to saying that $\theta_a = 0.8 \times \bar{\theta}$. Note that the subsequent analysis does not change if other values for $\bar{q}_a$ are used, as long as they allow for the presence of both types of cars. Otherwise, either an oversupply of type-a cars or a complete ban of type-b vehicles makes the corresponding result trivial.

Withal, the two context characteristics that are relevant in this section are the corruption level (λ) and the emissions dispersion (Δ). Consequently, I consider all pairs (λ, Δ) that can be formed using a grid $(0, 1)$ for λ and $(0, 10 \times e_a)$ for Δ. Since in the model $\Delta = E_b - e_a$, the above is equivalent to E_b being assigned values between e_a and $11 \times e_a$. The linear relation between E_b and Δ makes the analysis equivalent if I allow one or the other to change, such that the economic interpretation and behavior of results remain unaltered.

[34] Particularly, the authors compute the manufacturing cost c using a car-price database of the Chilean market. This dataset consists of newspaper ads with car offers for new and used cars published in "El Mercurio" - Chile's main newspaper - during 1988-2000.

Furthermore, as I show in the previous section, consumers that value driving the most are exempt from the regulation when either of the two policies is implemented. In the model, the latter means that $R_a = 1$ and $R_l = 1$. Likewise, given the parameters in Table 7, it follows from the planner's optimization problem that $R_b = 1$ for the type-specific driving restriction scenario as shown in the final remark in Appendix A.2.1. Thus, the only restriction left to be determined is R_h, to which I impute the value presented in the table in question, to simplify the optimization process presented in this section.

Last, I index C_s to c weighted by different magnitudes that range between 10 and 400. Considering $c =$ USD $16,000$, the above means I presume C_s to be located between USD 0.16 MM and USD 6.4 MM. In particular, if I assume 1.5 MM vehicles get inspected each year, the yearly cost of operating a smog check station ranges between USD 0.1 and USD 4.3 per car examination.

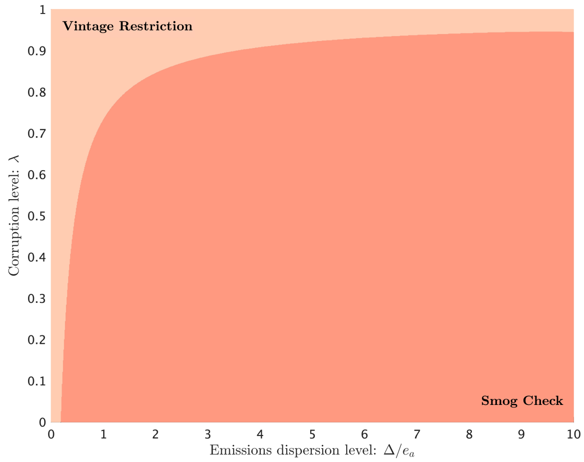
5.2. *Policy simulations*

In what follows, I solve the planner's optimization problem taking into account all the previously mentioned parameters and assumptions. To begin with, I compute the social planner's welfare when implementing a type-specific policy for each (Δ, λ) combination. Additionally, I estimate the social planner's welfare after she chooses the optimal emission standard $\bar{e}$ for each (Δ, λ) pair, in a smog check scenario.

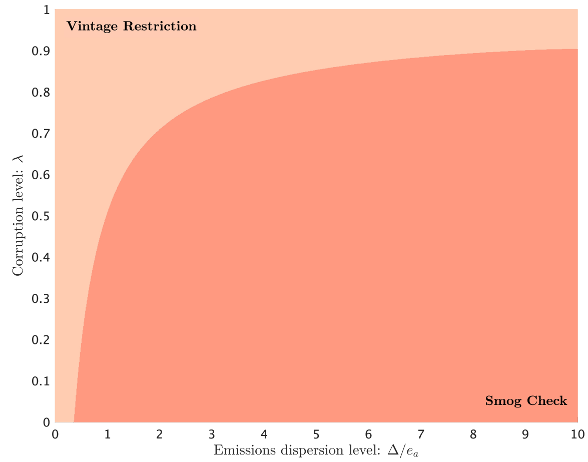
From this, I determine which of the two policies yields a greater welfare for each corruption-dispersion combination as presented in Figure 9. In relation to the corruption level (λ), the higher the share of cars that manipulate their test results, the less preferred a smog check policy is. The above, given that a larger percentage of high-polluting vehicles pose as low-polluting, get exempt from the regulation, and end up being driven (and polluting) more than optimal. Contrarily, regarding the relative emissions dispersion (Δ/e_a), a smog check program is preferred when emissions are more scattered.

Given that emissions for type-b cars distribute uniformly over the interval $[e_a, E_b]$, increasing Δ has two effects on the distribution. On the one hand, $\mathbb{E}[e_b] = e_a + \frac{\Delta}{2}$, thus augmenting Δ increases the sample's mean. On the other hand, $Var[e_b] = \frac{\Delta^2}{12}$, meaning that an increase in Δ also enlarges its variance. In this way, the effect of a change in Δ can be split into two: a mean and a dispersion effect, each entailing a different consequence. Therefore, there are at least two mechanisms in the model that explain why the above occurs. First, the higher the dispersion, the larger the emission level of the most polluting cars (E_b). Classifying cars depending on how much they pollute becomes more useful for the social planner in such a scenario, given that cars labeled as high-polluting are subject to a more strict driving restriction. Hence, being able to identify them through gas tests to assign them a more strict restriction can be helpful for the objectives of the planner. On the contrary, if emissions are sufficiently homogenous, disbursing money to differentiate cars by their pollution rates through smog checks is futile. Second, a smog check policy intensifies the efficient rationing of consumers by including pollution levels to their consumption choices. In this scenario, type-a and low-polluting type-b cars are bought by agents that value driving the most. Hence, the distribution of miles driven by emission level gets skewed to the left compared to a vintage restriction scenario. To such a degree, a smog check program ensures that higher θ drivers buy cars whose emissions are, on average, smaller than the ones acquired by lower θ drivers. The latter is particularly useful in a scenario were emissions are highly dispersed since involuntarily pairing high θ agents with high polluting cars is significantly damaging in the alternative scenario where a type-specific program is used.

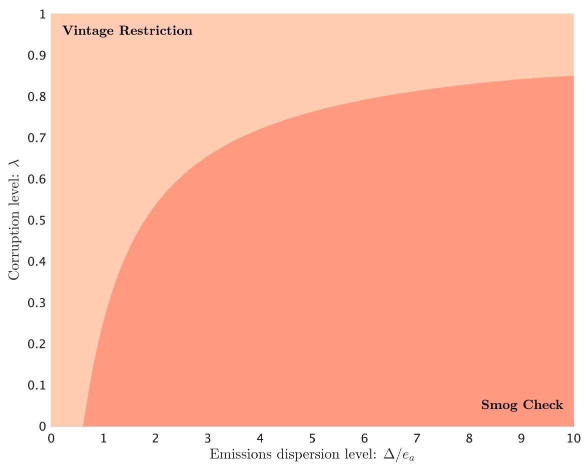
Figure 9: Optimal Policy Areas: Vintage Restrictions vs. Smog Check Stations



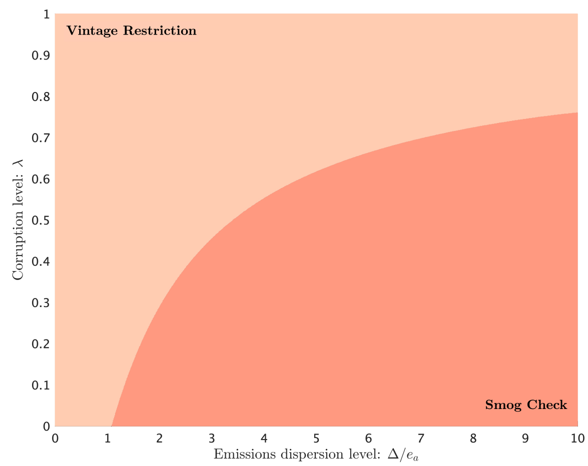
(a) $C_s = 10c$



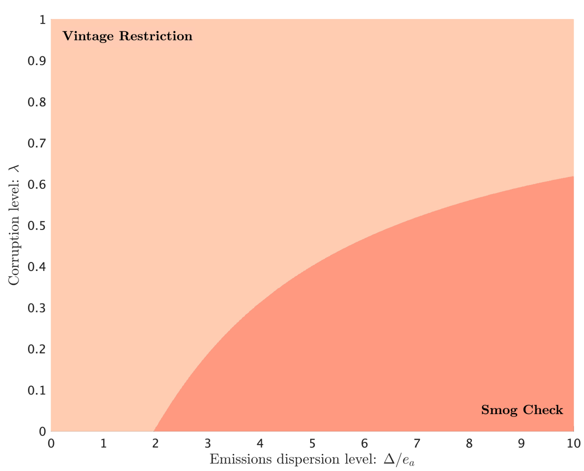
(b) $C_s = 25c$



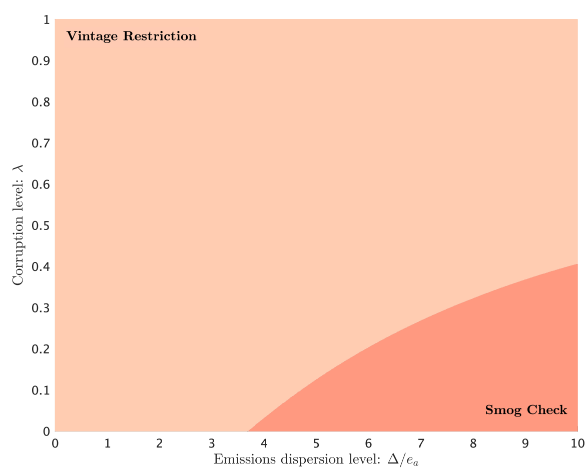
(c) $C_s = 50c$



(d) $C_s = 100c$



(e) $C_s = 200c$



(f) $C_s = 400c$

Last, note that Panels (a) through (f) of the aforementioned figure illustrate that the greater the value of C_s, the smaller the area in which a smog check policy is preferred. Recall that according to the model, if $\lambda = 0$, the problem the central planner faces in the smog check station setting is the unrestricted version of the problem she faces in the type-restriction one. However, even when $\lambda = 0$, a positive level of emission variability is necessary to ensure that the smog check policy is both cost-effective and the chosen one. The above is consistent with the fact that highly homogeneous emissions do not justify the money expenditure that allows the planner to accurately identify vehicle pollution levels. Thus, in a world where $\lambda = \Delta/e_a = 0$ a smog check program is never the preferred one and even when adding $C_s = 0$ to the latter scenario, the planner is at most indifferent between both programs.

5.3. *Calibration: Chilean Context*

After simulating the model and studying its main outcomes, it is worth determining where Chile locates in Figure 9. It should be kept in mind that the mentioned figure is obtained from the simulation of a model that allows the central planner to choose her optimal policy while seeking to combat air pollution. Nevertheless, as I mention earlier, it seems that the Chilean vehicle inspection program is more of a road safety program than an environmental one. For this reason, placing Chile within one of the panels from the previous figure is only suggestive of where it could end up if its policy changed to a more stringent one.

In order to calibrate the model for the Chilean case, I need all three values of λ, Δ and C_s for its particular context. First, recall that the value for λ is suggested in Section 3 and is obtained from an unusual data bunching in the NO 5015 test results for year 2014, from which I conclude that $\lambda = 0.7$.[35] Next, I estimate the value of Δ/e_a, using the mean and standard deviation of the 2014 inspection results for the six most conducted gas tests in Chile.[36] To stay consistent with Section 3, I focus on cars that share the same *inercia equivalente* value (equal to 1,247 kg), to account for external factors that could otherwise distort the analysis. However, contrary to what I do in the above mentioned section, I drop the two-model sample in question, and consider all car models with an *inercia equivalente* of 1,247 kg, to work with a database of cars of diverse ages. Note that if I assume that the two models used above do not differ, on average, from the complete vehicle fleet, it makes sense to use the value of λ for this scenario despite having obtained it from a smaller sample.

Table 8 proposes two different estimation methods for Δ/e_a. Since the right tail of every test result distribution is very long and light, I avoid calculating the dispersion as the difference between the average result of type-a cars and the highest value registered for type-b ones. Instead, I estimate Δ/e_a by comparing the average result of type-a cars with the 75th or 90th percentile of type-b vehicles' test results.

Moreover, I propose using the age of each vehicle in order to differentiate each type. In this way, type-a cars are the ones under the age of A and type-b the remaining. For the purposes of this paper, I take $A = 5$ and $A = 10$. The former as to stay consistent with the previous discussion. The second value is based on several policies around the world that claim cars over 10 years (or other similar age) are diametrically different from newer ones. The above, mainly due to a significant increase in the emission of gases and the deterioration of tires, brakes and lights, once the car turns 10.[37]

[35] In Appendix A.3, I repeat the present analysis using $\lambda = 0.5$, as proposed by Barahona et al. (2019).

[36] Thus far, the whole analysis in this paper is conducted using data from inspections carried out during year 2014. To maintain consistency, I choose to work with data from 2014 in this section as well.

[37] Among the places that use this 10-year-rule as the relevant feature to determine the circulating regulation and/or tax assigned to each vehicle are Madrid, London and all provinces in Catalonia.

From the first classification, presented in Panel (a) of Table 8, it follows that the average Δ_{75}/e_a corresponds to 3.6, whereas the one for Δ_{90}/e_a to 7.6. Similarly, the average Δ/e_a obtained when considering all 12 values from the last two columns from Panel (a) is 5.6. This value serves as a midpoint in the dispersion estimates, in case the chosen percentiles are not adequate. To that same extent, for the second categorization, presented in Panel (b) of Table 8, the average Δ_{75}/e_a corresponds to 3.5, whereas the one for Δ_{90}/e_a to 5.8. Likewise, the average Δ/e_a is 4.7.

Table 8: Mean and Standard Deviation of Gas Test Results

Test	**Type-a**		**Type-b**				Δ_{75}/e_a	Δ_{90}/e_a
	Mean (e_a)	Std. Dev.	Mean	Std. Dev.	Pctl. 75	Pctl. 90		
			Panel (a) : Type-a: age ≤ 5 & Type-b: age > 5					
NO 2525	84.7	158.1	266.4	360.3	350.0	773.0	3.1	8.1
NO 5015	113.7	234.8	472.5	594.5	763.0	1415.0	5.7	11.4
CO 2525	0.08	0.15	0.21	0.25	0.28	0.53	2.5	5.6
CO 5015	0.06	0.13	0.21	0.24	0.32	0.55	4.3	8.2
HC 2525	12.4	14.0	34.2	35.5	46.0	82.0	2.7	5.6
HC 5015	16.8	18.6	49.6	48.4	74.0	126.0	3.4	6.5
			Panel (b) : Type-a: age ≤ 10 & Type-b: age > 10					
NO 2525	123.1	217.2	366.9	411.0	526.0	986.0	3.3	7.0
NO 5015	184.6	337.0	680.5	666.3	1233.0	1427.0	5.7	6.7
CO 2525	0.11	0.18	0.27	0.28	0.38	0.67	2.5	5.1
CO 5015	0.10	0.16	0.29	0.26	0.44	0.65	3.4	5.5
HC 2525	16.8	19.7	47.1	40.4	65.0	105.0	2.9	5.3
HC 5015	24.3	28.8	67.5	53.2	104.0	151.0	3.3	5.2

Notes: Table 8 presents means, standard deviations and two relevant percentile values for emission test results registered during 2014 for all cars with an *inercia equivalente* value equal to 1,247 kg. $\Delta^t_{75} = \frac{P^t_{75,b} - e^t_a}{e^t_a}$, where $P^t_{75,b}$ is the 75th percentile for type-b cars in test t and e^t_a the average result of type-a cars in test t. The calculation is analogous for Δ^t_{90} but using the 90th percentile of the type-b car test t results instead. Limits are given in parts per million for NO and HC and in percentage of volume for CO.

Similarly, to suggest a value for C_s, I assume perfect competition among vehicle inspection stations. In a world free of market frictions, prices are set such that the net profit of each is zero. With that in mind, I estimate the revenue by plant for year 2014, considering the number of inspections and the yearly average price charged by each station in question. I calculate the latter for the Metropolitan Region only, since it is the one identified as the polluted area in my model. Along these lines, the data show an average revenue per plant of CLP 1,457 MM for the year 2014.[38] Bearing in mind that the average value during 2014 for USD in CLP was around 600 and that $c = \text{USD } 16,000$, the mean income per station corresponds to $152c$. From this, and under the assumption of perfect competition, it follows that $C_s = 152c$, which implies a cost per car inspected of USD 1.6.[39] Additionally, another approach that could be taken to estimate C_s in a more conservative way, is to calculate the average revenue of new entrants. This seems reasonable, since

[38] See Table A5 for details.

[39] It is possible that the firms that have been operating for a long time developed mechanisms that diminished their costs and allowed them to earn profits. Therefore, the value I obtain for C_s might be an upper bound of the true operational cost.

these are the ones which are most likely earning exactly what they spend, especially during their first year of operation. Unfortunately, the Chilean market for vehicle inspections did not have entrants up until late 2015 - early 2016, thus the analysis cannot be conducted for 2014. Notwithstanding, in spite of compromising the consistency with all other tests in this paper, it is relevant and interesting to be examined. The data show an average revenue per entrant of CLP 670 MM during year 2016.[40] Bearing in mind that the average value during 2016 for USD in CLP was around 660 and that $c =$ USD $16,000$, the mean income per station corresponds to $63c$. From this, under the assumption of perfect competition, I have $C_s = 63c$, which implies a cost per inspection of USD 0.7. Note that both proposed values of C_s are most likely lower bounds of the true parameter, since I am leaving all costs associated to cheating aside when estimating the two amounts.

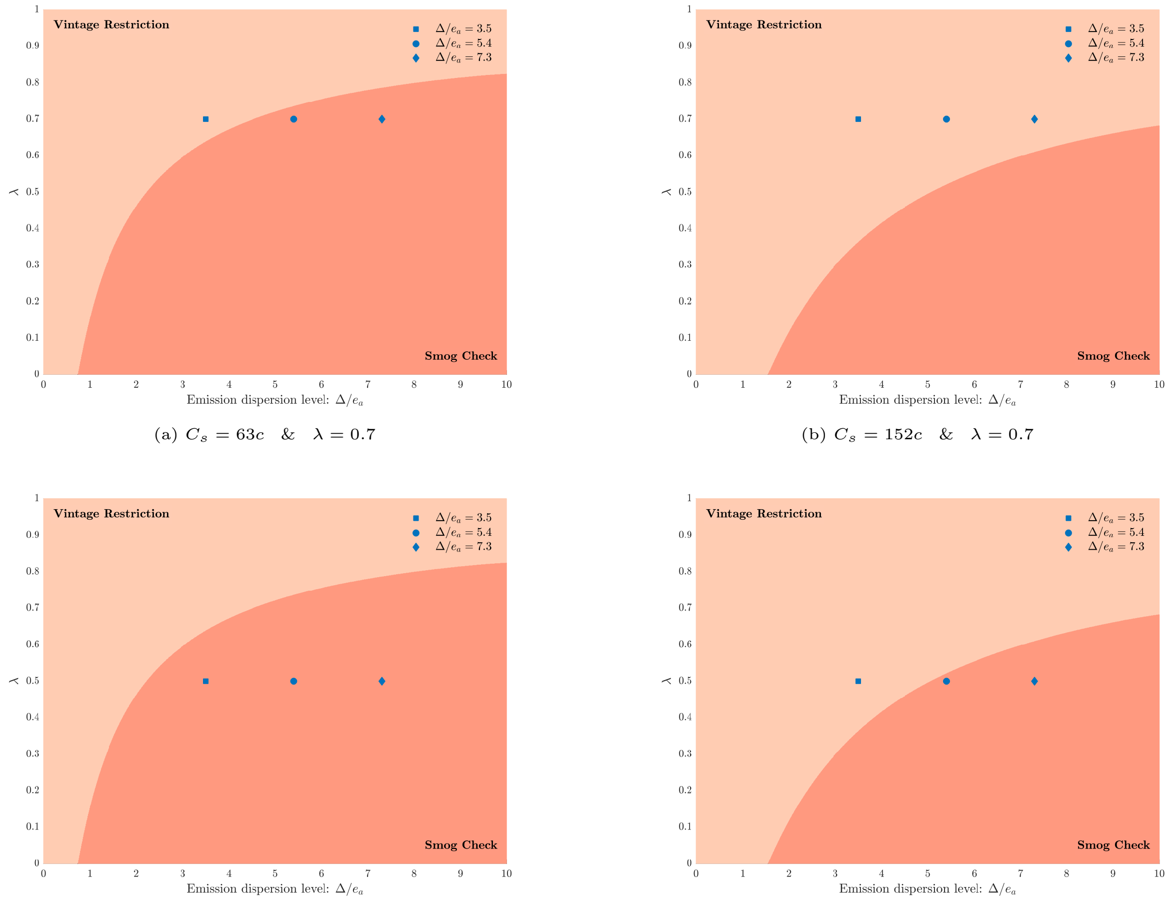
All things considered, I am able to suggest different values for λ, Δ/e_a and C_s, which allow me to illustrate the Chilean case under different parameter combinations. Figure 10 presents the location of Chile for each $(\lambda, \Delta/e_a, C_s)$ triple. From the figure, it seems that for the country in question it is optimal to implement a vintage-specific policy. Only for some specific combinations of variables, the program of smog checks seems to be optimal but very close to the indifference between the two programs. As formerly suggested, for lower operating cost values (C_s), it is more likely that an emission-specific policy is preferred. The above is depicted in Panel (a): two of the three scenarios are in the smog check station optimal area. Then, as this cost increases it becomes less likely that such a program suits the planner. The two-out-of-three ratio is replaced by a zero-out-of-three one when the operational cost is higher, as depicted in Panel (b). Panels (c) and (d) show similar results to those mentioned above but assuming $\lambda = 0.5$.

Furthermore, Table 9 displays the optimal standard $\bar{e}^{scm}$ for each $(\lambda, \Delta/e_a, C_s)$ triple, for each of the six most conducted gas tests in Chile. Naturally, the standard increases in size the larger the dispersion of emissions. Recall that in the model, $\bar{e}^{scm}$ determines the share of low and high-polluting cars in the economy. Hence, *ceteris paribus*, if the emissions dispersion increases, the threshold must also increase to keep the number of cars of each pollution level unchanged. Moreover, when comparing these to the ones depicted in Table 1, a few conclusions arise. First, every standard obtained from the simulation is more strict than the current Chilean one except for HC in Panel (b) of Table 9. Thus, actual levels are probably far from optimal. Second, not only are simulated values more strict than real ones, but the former are also similar to US and Mexican standards. The above suggests that, as proposed before, the Chilean smog check policy is not an environmental program, as it is for the case of California and Mexico.[41] However, a fair comparison between the three policies is possible when assuming similar $(\lambda, \Delta/e_a)$ pairs among them. To my belief, the most natural comparison is between Chile and Mexico. Along these lines, according to Oliva (2015), 9.6% of old-car owners circumvent the regulation in Mexico City every year. Additionally, Panel (a) of Table (2) in her paper shows that 17 years or older cars comprise around 16.4% of the vehicle fleet. From this, assuming all cheaters belong to the former age group, $\lambda = 0.59 \left(= \frac{9.6\%}{16.4\%}\right)$ for the Mexican case. Likewise, from Panel (b) of the same table I can estimate $\Delta/e_a = 3.0$. This is a lower bound of the true dispersion, mainly because the mean depicted in the author's table does not correspond to the one of cleaner cars (i.e., type-a) but the one for the whole sample. Thus, it seems that both scenarios are somewhat comparable and that the standards determined by the Mexican law are environmentally-oriented. However, as mentioned in Section 3, lowering thresholds might increase corruption, entangling significant social costs as a result. Thus, adjusting emission thresholds does not solve all the problems that this program seems to have.

[40] See Table A6 for details.

[41] Table A7 presents the same analysis assuming $\lambda = 0.5$, from which similar conclusions can be obtained.

Figure 10: Plausible Chilean Locations



(a) $C_s = 63c$ & $\lambda = 0.7$

(b) $C_s = 152c$ & $\lambda = 0.7$

(c) $C_s = 63c$ & $\lambda = 0.5$

(d) $C_s = 152c$ & $\lambda = 0.5$

Table 9: Optimal Emission Standard

Δ/e_a	$\bar{e}^{scm}/e_a$	**Optimal Emission Standard per Gas Test**					
		NO 2525 (1,072)	NO 5015 (1,186)	CO 2525 (0.82)	CO 5015 (0.85)	HC 2525 (147)	HC 5015 (152)
Panel (a) : Type-a: age ≤ 5 & Type-b: age > 5							
3.6	5.230	443.0	594.7	0.42	0.31	64.9	87.7
5.6	5.707	483.4	648.9	0.46	0.34	70.8	95.9
7.6	6.260	530.2	711.8	0.50	0.38	77.6	105.2
Panel (b) : Type-a: age ≤ 10 & Type-b: age > 10							
3.5	5.209	641.2	961.6	0.57	0.52	87.5	126.6
4.7	5.490	675.8	1,013.5	0.60	0.55	92.2	133.4
5.8	5.756	708.6	1,062.6	0.63	0.58	96.7	139.9

Notes: Table 9 presents the optimal emission standards obtained from combining both the model simulation and the data presented in the second column of Table 8. Each panel is calculated multiplying the value from the $\bar{e}^{scm}/e_a$ column and the data from its homonym panel in the second column of Table 8. Optimal standards are presented for the six different dispersion values suggested in this section, but assuming a single value for corruption $\lambda = 0.7$. Limits are given in parts per million for NO and HC and in percentage of volume for CO. The current Chilean standard (for year 2019) in parentheses below the name of each test.

6. Concluding Remarks

Private vehicle emissions are an important source of local air pollution and indirect influencers on the health and welfare of citizens around the world. Governments are no stranger to this issue and have implemented diverse policies seeking to improve local air quality through the control of the extensive (i.e., the type of car driven) and/or intensive (i.e., number of miles driven) margin associated to the vehicle fleet. Previous literature focuses on diverse driving regulation instruments that aim to combat the formerly mentioned problem. They conclude that these should be designed to work exclusively through the extensive margin, and never through the intensive one. Among the former are both driving regulations that differentiate cars by their pollution rates through smog checks and vintage-specific restrictions. In this paper, I compare and review the two policies under different characteristics of the economy. Particularly, under different levels of manipulation in gas test results and under diverse degrees of vehicle emissions dispersion.

After developing a model of the car market, I am able to identify and quantify a trade-off between the two context variables, specifically in their role as key determinants of each program's optimality. That is to say, the higher the level of corruption, the less desirable a smog check policy is, relative to a vintage-specific one. Contrarily, the higher the dispersion of emissions, the more effective an emission-specific policy is to assign vehicles an optimal restriction. From this, I conclude that there seem to be tolerable levels of corruption under which a smog check program is still preferred, conditional on vehicles having sufficient emissions' dispersion. Furthermore, there is a third variable that is relevant in deciding between both policies, namely the operational cost of the stations. Naturally, higher values of the latter make this type of policy less attractive.

Moreover, I analyze the Chilean case for smog checks and study whether, given its particular setting characteristics, its current policy is indeed the best fitting one. After calibrating the model for the formerly mentioned context, a few conclusions are obtained. First, the emission standards determined for the Chilean program are by no means ones that intend to combat air pollution. This, because enforced standards are much more lenient than the ones obtained from the resolution of a model that aims for an effective environmental program. The above reinforces one of my previously stated conjectures: Chilean smog checks are part of a road safety policy that lacks specific environmental goals. Second, given the features that characterize the Chilean vehicle fleet and its smog check program, a more suitable program is one that regulates cars based on their vintage. The latter, mainly due to the considerable levels of corruption that seem to characterize its market, as well as due to the substantial costs of operating each station.

To sum up, there is no unique rule that labels one of the two policies as the dominant strategy for every context. After all, for a program to be effective it must be chosen and adjusted for the particular setting in which it is being implemented. In places where corruption is unusual, either because test results are difficult to be altered or because law enforcement discourages manipulation, an emission-specific policy seems highly adequate. Likewise, if the car fleet that characterizes the zone in question is sufficiently heterogeneous, this type of program can be suitable as well.

That being said, it seems that smog check stations are a dominated strategy for the Chilean context. Besides recommending harsher standards to transform this policy into a more environmentally-oriented one, I suggest to strengthen both law enforcement and government regulation toward stations to increase the social welfare derived from such program. Whether the public spending related to such changes is cost-effective or if Chilean policymakers should eventually change the current program to a vintage-specific one, is a question that remains to be answered.

References

AirVisual (2018). 2018 World Air Quality Report.

Barahona, N., F. Gallego, J. P. Montero, and J. D. Salas (2019). Competing for fake certificates: The case of smog checks. Working Paper.

Barahona, N., F. Gallego, and J. P. Montero (BGM) (2019). Vintage-specific driving restrictions. Forthcoming in the Review of Economic Studies.

Bennett, V. M., L. Pierce, J. A. Snyder, and M. Toffel (2013). Customer-driven misconduct: How competition corrupts business practices. *Management Science 59*(8), 1725–1742.

Candia, V. and R. González (2016). Plantas de Revision Tecnica: Las triquiñuelas que se niegan a morir. LaSegunda.com [Online; posted 08-October-2013].

CNNChile (2019). Los tres errores que delataron las revisiones técnicas falsas en san javier. CNNChile.com [Online; posted 20-August-2019].

Davis, L. W. (2008). The effect of driving restrictions on air quality in Mexico City. *Journal of Political Economy 116*(1), 38–81.

Díaz, C. (2019). Fiscalización de buses interurbanos revela 16 máquinas con permisos de circulación falsos. Emol.com [Online; posted 10-August-2018].

Environmental Protection Agency (EPA) (1996). Acceleration simulation mode test procedures, emission standards, quality control requirements and equipment specifications. *United States EPA-AA-RPSD-IM*(92-2).

Eskeland, G. S. and T. Feyzioglu (1997). Rationing can backfire: The "day without a car" in Mexico City. *The World Bank Economic Review 11*(3), 383–408.

Fiscalía Nacional Económica (2017). TDLC condena a CMPC y SCA por colusión en el mercado del papel tissue. FNE.cl [Online; posted 10-December-2017].

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

Hubbard, T. (1998). An empirical examination of moral hazard in the vehicle inspection market. *RAND Journal of Economics 29*(2), 406–426.

Ministerio del Medio Ambiente (MMA) (2019). *Quinto Reporte del Estado del Medio Ambiente*. Gobierno de Chile.

Ministerio de Transportes y Telecomuncaciones (MTT) (2015). Revisiones técnicas tipo b: Manual de procedimientos e interpretación de resultados. *Chile 11*(2).

Molina, L. and M. Molina (Eds.) (2002). *Air quality in the Mexico megacity: An integrated assessment*. Kluwer Academic Publishers, Dordrecht.

Oliva, P. (2015). Environmental regulations and corruption: Automobile emissions in Mexico City. *Journal of Political Economy 123*(3), 686–724.

Onursal, B. and S. Gautam (1997). Vehicular air pollution: Experiences from seven Latin American urban centers. *World Bank Technical Paper No. 373, Washington, DC*.

Ortiz, M. (2016). Usuario denuncia en Concepción que planta de revisión técnica le cobró para aprobar trámite. BioBioChile.cl [Online; posted 08-October-2016].

Paulina, R. (2019). Plantas de Revisión Técnica: Fiscalía inicia investigación tras denuncia penal en contra del Seremi de Transportes. RadioPaulina.cl [Online; posted 04-September-2019].

Peña, J. (2018). Volcamiento en la dormida: Fiscalía afirma que bus tenía revisión técnica vencida e investiga presunta falla de frenos. Emol.com [Online; posted 19-October-2018].

Quijada, N. (2019). Carabineros incauta cerca de mil certificados de revisión técnica falsos en época de renovación de permisos de circulación. Emol.com [Online; posted 10-March-2019].

Rizzi, L. I. and C. De La Maza (2017). The external costs of private versus public road transport in the metropolitan area of santiago, chile. *Transportation Research Part A: Policy and Practice 98*, 123–140.

Sanders, N. J. and R. Sandler (2017, October). Technology and the effectiveness of regulatory programs over time: Vehicle emissions and smog checks with a changing fleet. Working Paper 23966, National Bureau of Economic Research.

State of California Laws on Emissions (2018). Smog check law. theSmogStop.com [Online; posted May-2018].

The Environmental Literacy Council (ELA) (2017). *Public Transportation*. The Environmental Literacy Council.

Wenzel, T. P., B. C. Singer, R. R. Slott, and D. H. Stedman (2004). Short-term emissions deterioration in the California and Phoenix I/M Programs. *Transportation Research Part D 9*(2), 107–124.

World Health Organization (WHO) (2014). *Burden of disease from Ambient Air Pollution for 2012*. WHO Library.

World Health Organization (WHO) (2016). *Ambient Air Pollution: A global assessment of exposure and burden of disease*. WHO Library.

Appendix

A.1. *Additional Material for Section 3*

A.1.1. Figures and Tables

Table A1: Share of Cars by Test Result and *NO* 5015 Bunching

		Test-Taker		
		Non Buncher	Buncher	Total
Complete Test	Pass	0.590	0.095	0.685
	Fail	0.277	0.039	0.315
	Total	0.867	0.133	1.000

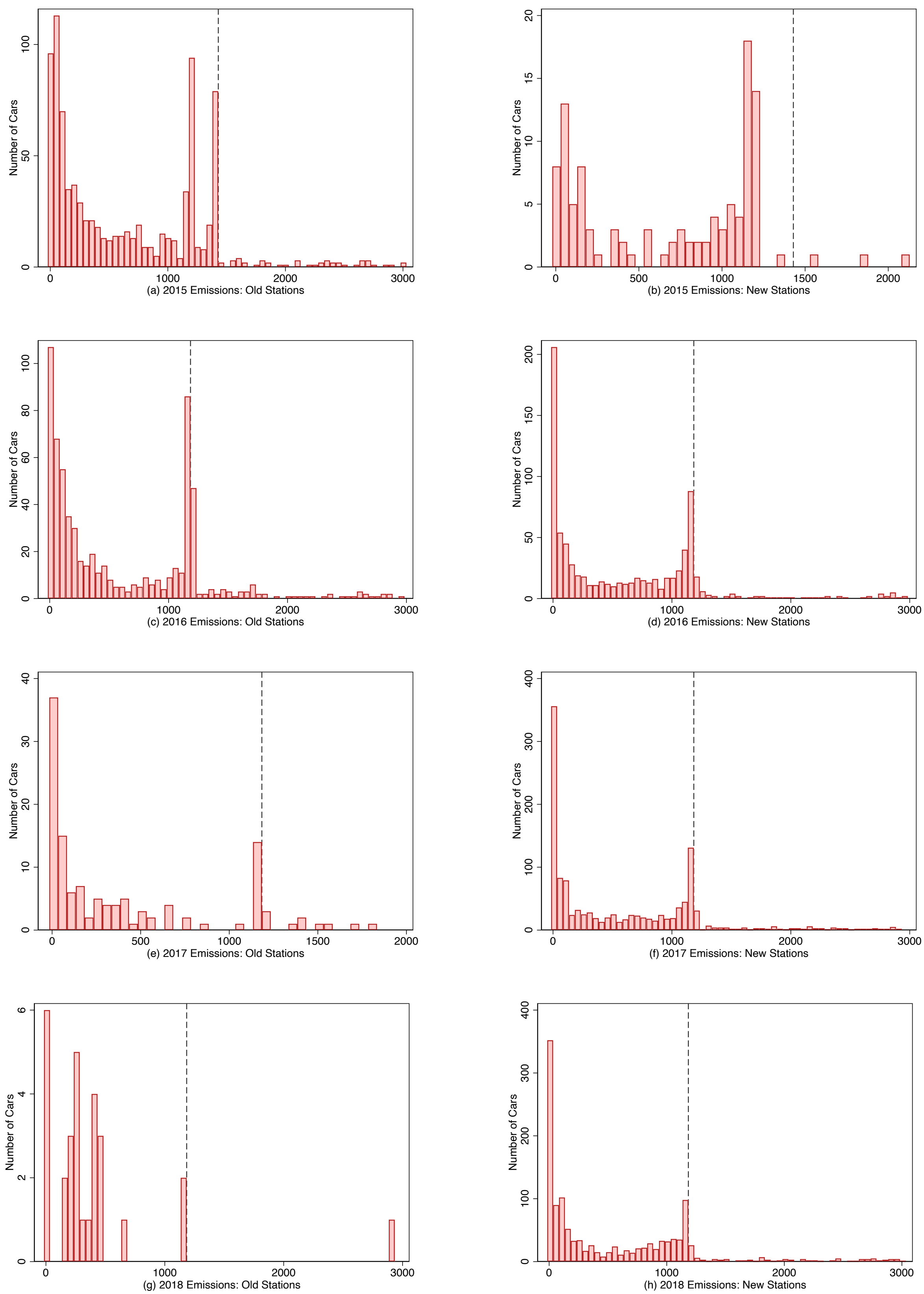
Notes: Table A1 presents the share of cars by category for all revisions conducted in Chile between 2008 and 2018 by models Hyundai Accent 1998 and Suzuki Esteem 1998. Buncher indicator includes all test-takers whose *NO* 5015 emission recordings are at most 50 ppm below the active cutoff each year. Note that 50 ppm corresponds to twice the size of the required accuracy for *NO* examinations. The complete test includes both visual and gas inspections. To pass it, all stages need to be approved individually.

Table A2: Linear Regression Estimation Results

Failed Test	**Mean: Non Buncher**	**Coefficient**	**Standard Error**
NO 5015	0.084	-0.080^{***}	0.003
NO 2525	0.051	-0.044^{***}	0.003
CO 5015	0.020	-0.020^{***}	0.001
CO 2525	0.019	-0.017^{***}	0.002
HC 5015	0.024	-0.024^{***}	0.001
HC 2525	0.015	-0.014^{***}	0.001
Gas	0.128	-0.118^{***}	0.004
Complete	0.319	-0.028^{**}	0.012

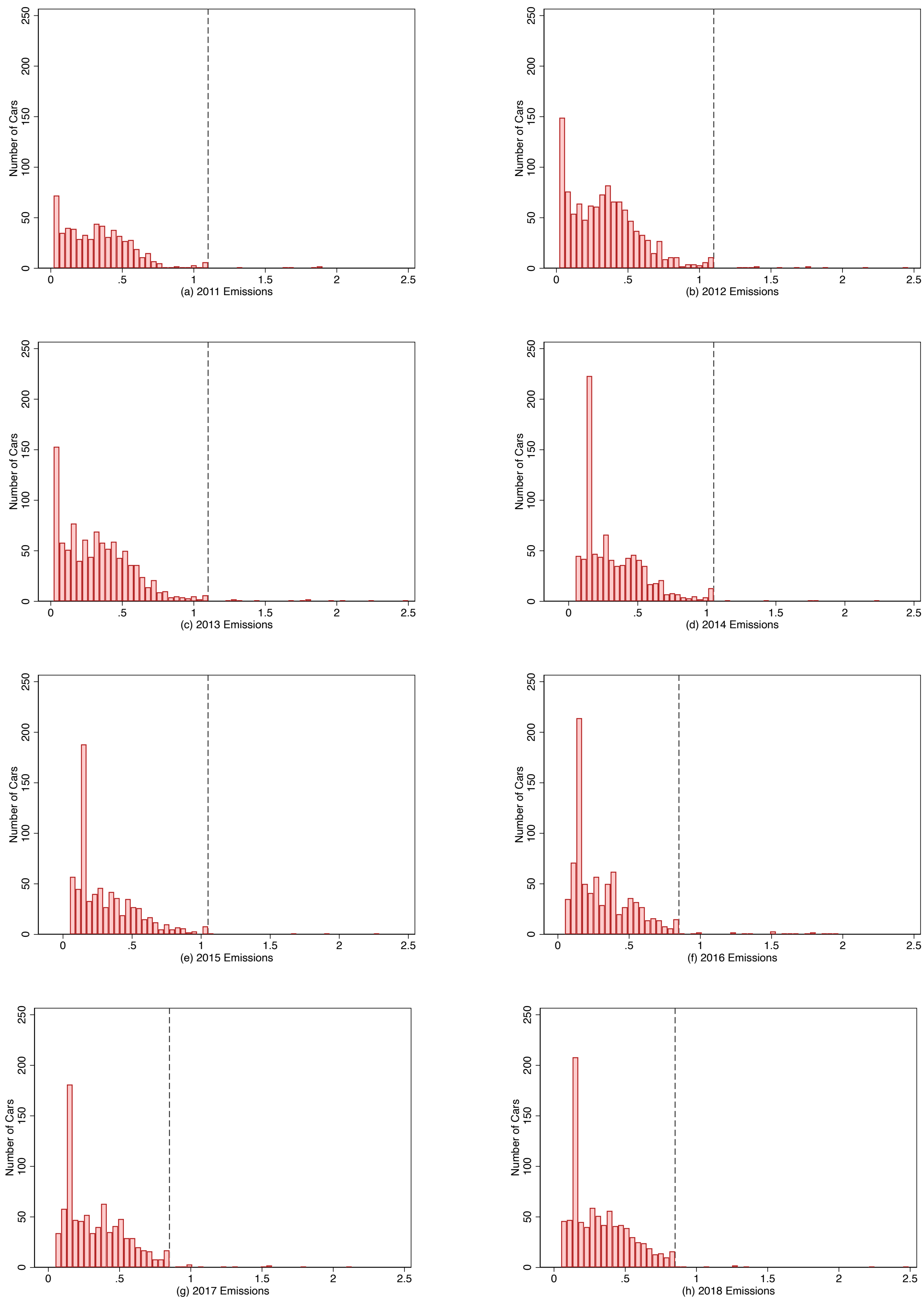
Notes: Table A2 presents OLS regression results of failed tests dummies on an indicator that takes the value 1 if the car is at most 50 *NO* ppm below the active cutoff. Depicted standard errors are robust to heteroscedasticity. The table includes all revisions conducted between 2008 and 2018 by models Hyundai Accent 1998 and Suzuki Esteem 1998.
$^{*}p < 0.10$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$

Figure A1: *NO* 5015 Emissions: Old vs. New Stations



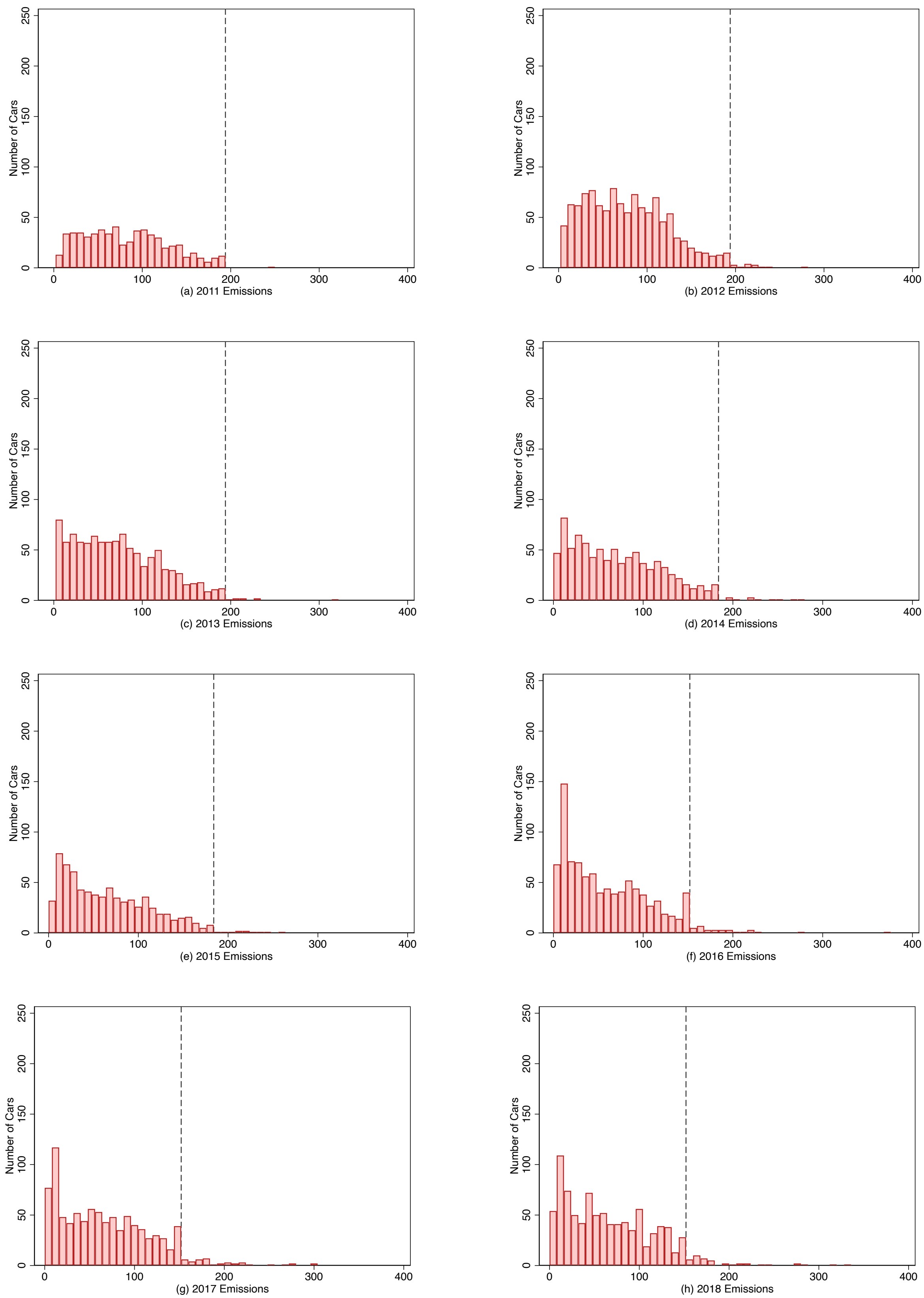
Notes: Figure A1 presents registered *NO* 5015 test results for all revisions conducted in Chile between the years 2015 and 2018 for the two car models of interest, distinguishing between old and new stations. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy. Measurements are presented in parts per million (ppm).

Figure A2: Histograms of Emissions for CO 5015 Test Results



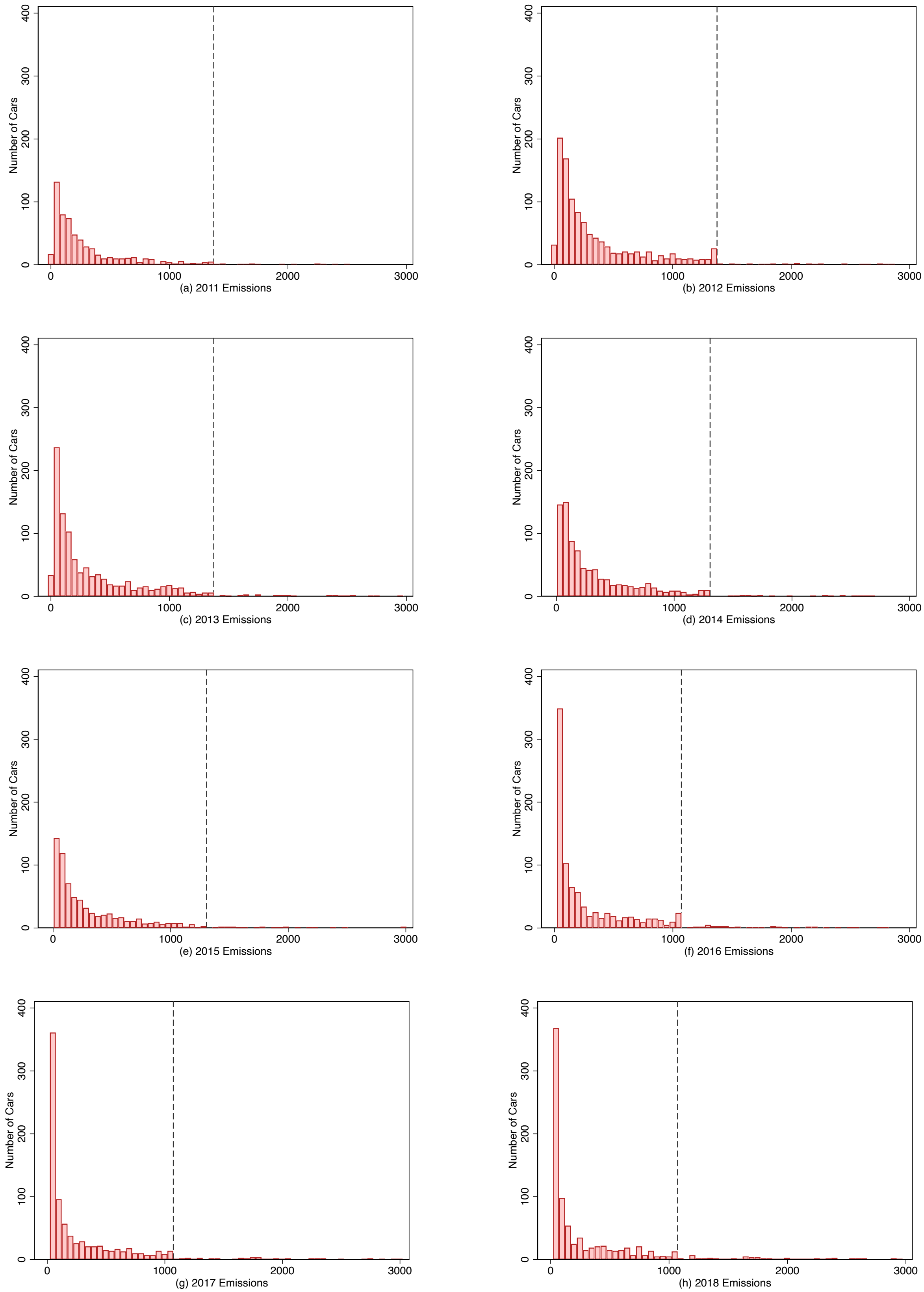
Notes: Figure A2 presents registered CO 5015 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in percentage of volume.

Figure A3: Histograms of Emissions for HC 5015 Test Results



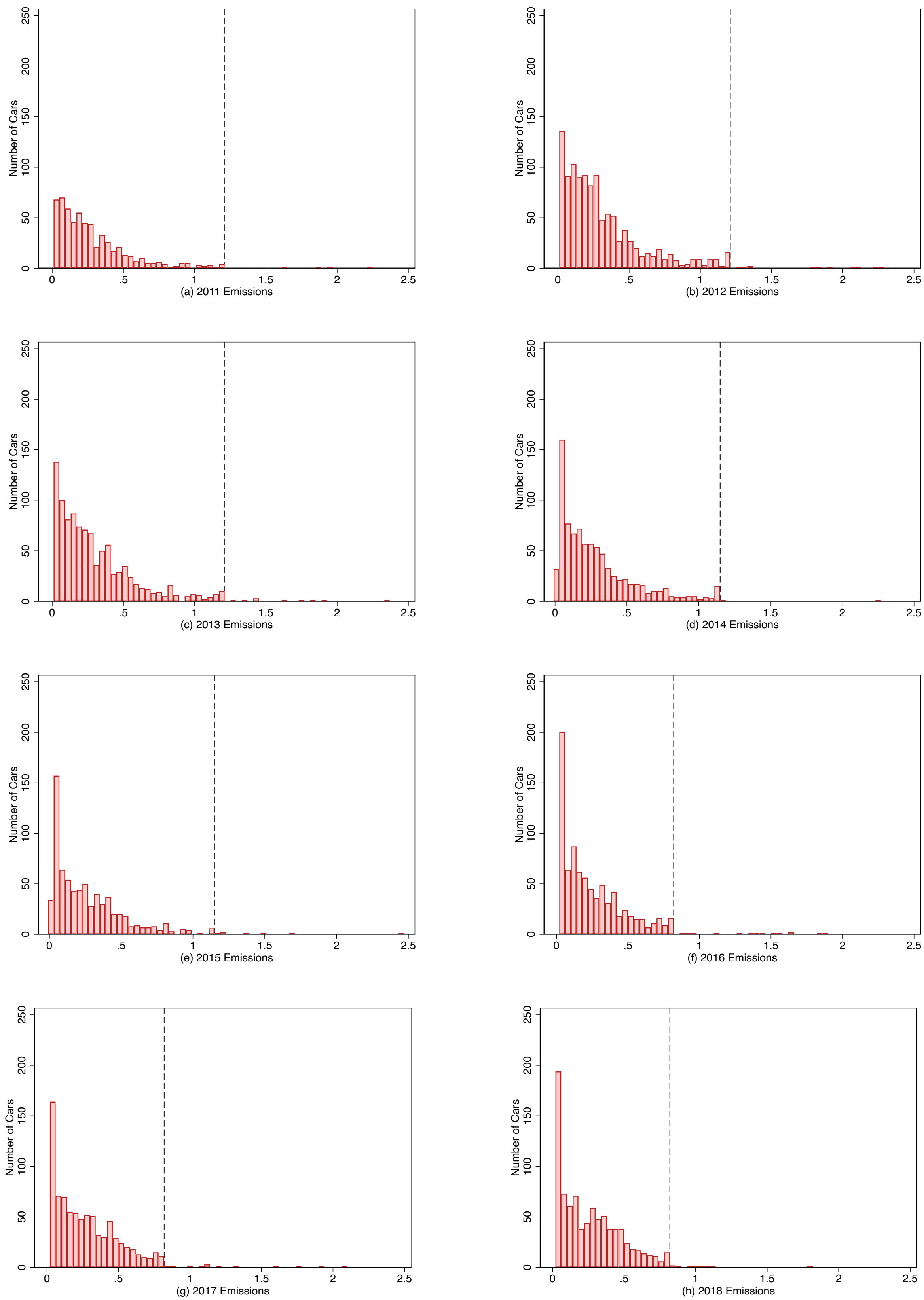
Notes: Figure A3 presents registered HC 5015 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in parts per million (ppm).

Figure A4: Histograms of Emissions for *NO* 2525 Test Results



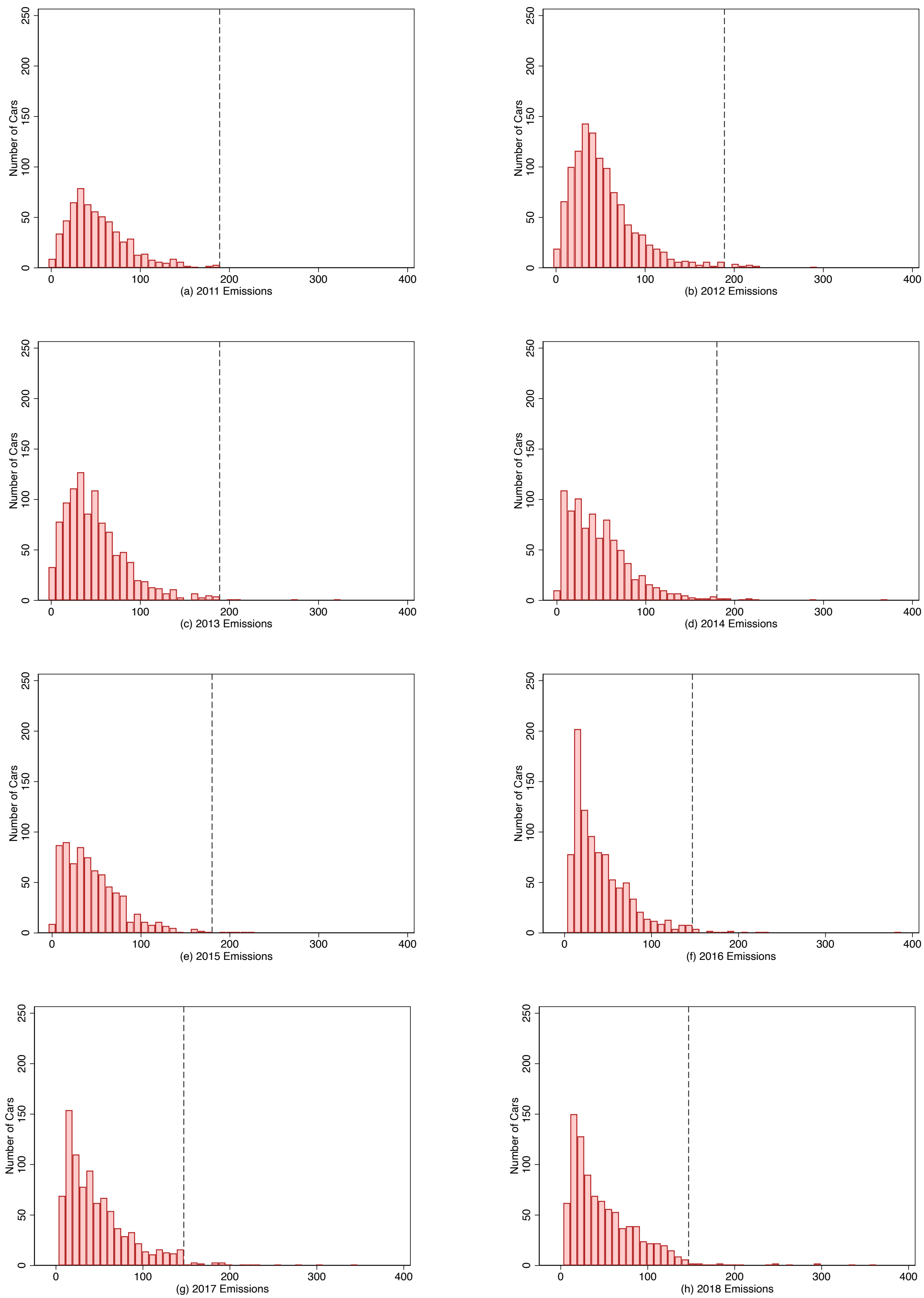
Notes: Figure A4 presents registered *NO* 2525 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in parts per million (ppm).

Figure A5: Histograms of Emissions for *CO* 2525 Test Results



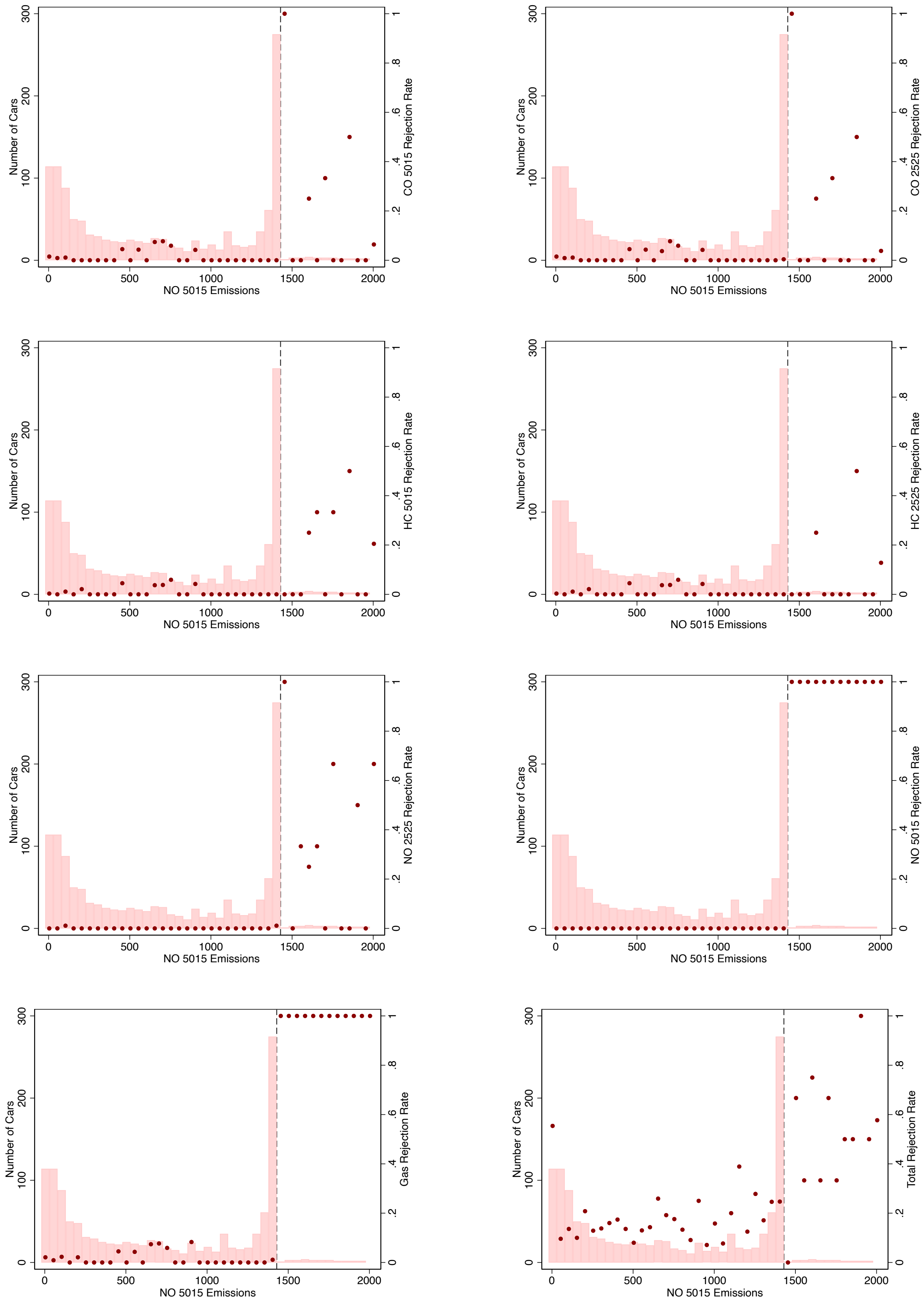
Notes: Figure A5 presents registered *CO* 2525 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in percentage of volume.

Figure A6: Histograms of Emissions for HC 2525 Test Results



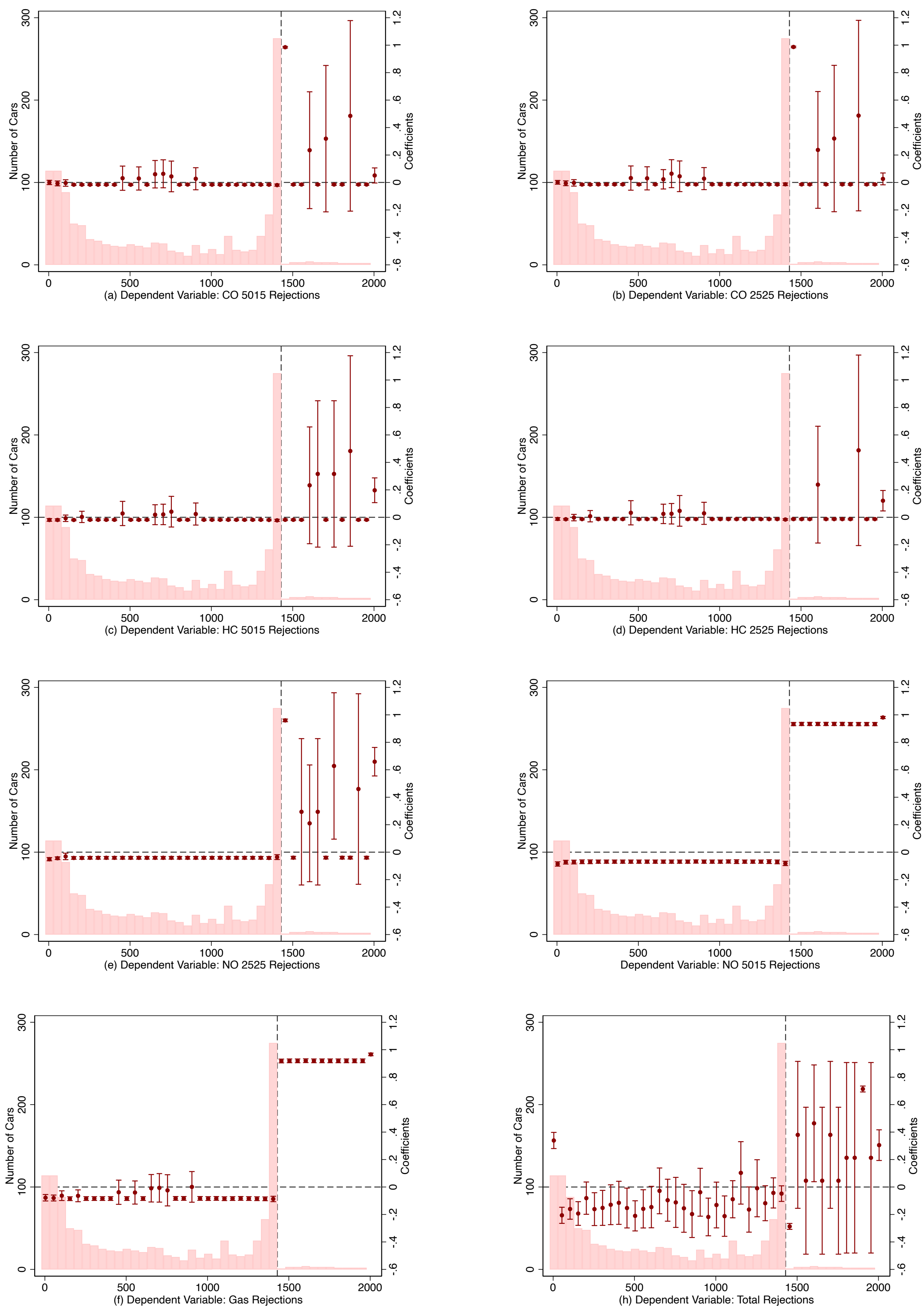
Notes: Figure A6 presents registered HC 2525 test results for all revisions conducted in Chile between the years 2011 and 2018 for the two car models of interest. Emission standards are indicated with a vertical dashed line in each histogram. The test is approved with emissions that are equal or less than the corresponding standard, hence the bins that represent the approved inspections are to the left of the dashed line. Bins are such that their width is twice the size of the required accuracy, to account for possible measurement errors in the detection method. Measurements are presented in parts per million (ppm).

Figure A7: Average Rejection Rates per Car Group following *NO* 5015 Test Results



Notes: Figure A7 presents average rejection rates for the different emission tests conducted by the two models of interest during 2014. Averages are estimated for every car group located in each bin of the histogram in Figure 4. The number of cars is presented in bars and indexed to the left ordinate axis, whereas rejection averages are depicted as dots and labeled in the right ordinate axis. *NO* 5015 measurements are presented in parts per million (ppm).

Figure A8: Regression Results per Car Group following *NO* 5015 Test Results



Notes: Figure A8 presents OLS regression results (coefficients and confidence intervals) for the different emission tests conducted by the two models of interest during 2014. Regressions are estimated for every car group located in each bin of the histogram in Figure 4, regressing rejection dummies on an indicator that takes the value 1 if the car is in the bin in question. The number of cars is depicted in bars and indexed to the left ordinate axis, whereas coefficients and confidence intervals are depicted as dots and capped lines, labeled in the right ordinate axis. *NO* 5015 measurements are presented in parts per million (ppm).

Table A3: Pollution Difference and Social Cost under Different Fits

Fit	$\mathbf{R^2}$	**Pollution Difference**		**Social Cost**	
		Chilean Standard	Mexican Standard	Total	Per capita
Logarithmic	0.29	7.4%	11.1%	37.0 – 55.5	6.6 – 9.9
Quadratic	0.23	5.8%	9.8%	29.0 – 49.0	5.2 – 8.8
Cubic	0.24	6.8%	10.1%	34.0 – 50.5	6.1 – 9.0
Quartic	0.25	7.8%	11.5%	39.0 – 57.5	7.0 – 10.3
Exponential	0.24	9.2%	12.9%	46.0 – 64.5	8.2 – 11.5
Donut (1 bin)	0.79	6.7%	10.5%	33.5 – 52.5	6.0 – 9.4
Donut (3 bins)	0.85	6.5%	10.4%	32.5 – 52.0	5.8 – 9.3

Notes: Table A3 presents results obtained from repeating both exercises in Section 3.2 using different fits for the data in Figure 4. The table displays pollution differences (comparing anticipated and real emission levels) and their subsequent lower – upper bounds of both total social cost in USD MM and per capita social cost in USD. *Donut* (n bins) fits correspond to results using a logarithmic prediction obtained after eliminating n bins on each side of the emission threshold. The coefficient of determination (R^2) for the exponential fit is an adjusted one, whereas R^2 for *donut* fits are estimated after dropping the n bins in question.

A.1.2. Exercise with Alternative Measure of Corruption

Acknowledging that the exercise in Section 3 is computed using suggestive corruption evidence based on *NO* 5015 gas test results, I repeat the analysis using another source of manipulation suggested by Barahona et al. (2019). The authors study the Chilean market of smog check stations, particularly how prices and plant quality evolve when new firms enter it. Specifically, they measure quality comparing the initial emission test failure rate of certain vehicles at a determined station, with the failure rate for similar vehicles in nearby centers. Thus far, their main results suggest that when facing competition, incumbents tend to relax their certification standards (i.e. adjust quality), but do not alter their offered prices. This lenient behavior entails that around 4% of the total inspected cars are approving the gas test when in fact should fail it. Moreover, these cars have, on average, emissions around 1.5 times higher than their required threshold. In other words, it seems that high-polluting cars are the ones fraudulently approving these emission tests.

As mentioned in Section 3, 30% of the whole 2014 sample comprises cars that are 17 years or older. Moreover, given the emission standards for 2014, and in absence of manipulation, 27% of said old vehicles get classified as high-polluting and the remaining as low-polluting. Henceforth, following the section in question, I assume manipulation is done by high-polluting old cars (i.e., 17 years or older) exclusively. In such manner, from the proposed results presented in Barahona et al. (2019), it follows that 50% $\left(= \frac{4\%}{30\% \times 27\%}\right)$ of high-polluting cars alter their emissions.

Hereinafter, I repeat the exercise presented in Table 6 using the formerly mentioned results and assuming manipulation occurs in the *NO* 5015 tests exclusively. To maintain consistency, I continue to work with the sample used in the original exercise along with its corresponding logarithmic fit. To begin with, since 7.9% of cars get labeled as high-polluting as depicted in Figure 4, then to ensure that 50% of originally high-polluting cars are altering their results, I need 7.9% of cars manipulating their results and be falsely located to the left of the threshold. With this I repeat the analysis of the section in question, both the one with 2014 Chilean standards and the theoretical exercise with Mexican requirements.

In sum, under the corresponding emissions standards, true emissions are 7.3% greater than expected in a setting with the levels of corruption studied in this section. Panel (a) of Table A4 depicts both real and anticipated emissions by car category as well as the percentage difference between them. On the other hand, in a scenario with Mexican standards, true emissions are 11% greater than expected. Panel (b) of Table A4 presents these results.

Moreover, if I assume that cars that are 16 years or newer do not manipulate their emissions, true pollution levels were 3.1% (= 43% × 7.3%) greater than expected during year 2014 and would have been 4.7% (= 43% × 11%) greater than expected in a scenario with Mexican standards. From this, the annual social cost associated to the previous exercises lies between USD 15.5 MM and USD 23.5 MM. Moreover, its annual per capita social cost ranges between USD 2.8 and USD 4.2.

Although the per capita social cost decreases significantly with lower manipulation percentages, as can be appraised when comparing Table 6 with Table A4, these are still relevant in magnitude, thus need to be taken into account. Both exercises are illustrative and suggest that when in presence of manipulation in the results of Chilean smog checks, significant social costs arise both with lenient and more stringent standards.

Table A4: Real and Anticipated Emissions Comparison: Additional Exercise

	Total in Circulation	**Labeled: Low-Polluting**		**Labeled: High-Polluting**
		Non-Cheater	Cheater	
	Panel (a) : Chilean-Standard Exercise			
Anticipated Emissions	874,784	722,696	152,088	304,138
Real Emissions	938,509	722,696	215,813	304,138
Difference	7.3%	0.0%	41.9%	0.0%
Share of Cars	92.1%	84.2%	7.9%	7.9%
	Panel (b) : Mexican-Standard Exercise			
Anticipated Emissions	738,273	561,700	176,573	372,207
Real Emissions	819,234	561,700	257,534	372,207
Difference	11.0%	0.0%	45.9%	0.0%
Share of Cars	88.8%	77.6%	11.2%	11.2%

Notes: Table A4 presents total pollutant levels by car category, using the two-model dataset for both exercises and based on the manipulation values suggested by Barahona et al. (2019). To compute cheaters' true emissions, I assume the true emission distribution has a support between the emission standard and twice its value (i.e., 2,858 ppm NO for Panel (a) and 2,400 ppm NO for Panel (b)). Cars labeled as low-polluting are the ones allowed in circulation, whereas high-polluting vehicles are eliminated from the car fleet. Share of cars presents the ratio between the number of cars in the category in question and the total number of cars in the vehicle fleet (i.e., 1,343). Cars labeled as high-polluting are presented in one classification only, because every vehicle in this category legitimately belongs in it.

A.2. *Additional Material for Section 4*

A.2.1. Mathematical Resolution for Section 4.3.1

As mentioned in Section 4.3.1, the social planner determines the restriction upon type-a vehicles $R_a \leq 1$ and the one upon type-b vehicles $R_b \leq 1$, as to maximize (A.2.1):

$$\begin{aligned} \mathbb{E}_{vr}[W] = & - c\left[F_p(\bar{\theta}) - F_p(\theta_b)\right] \\ & + \int_{\theta_a}^{\bar{\theta}} R_a \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\ & + \int_{\theta_b}^{\theta_a} R_b \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta. \end{aligned} \tag{A.2.1}$$

Where θ_a and θ_b are obtained as presented in the aforementioned Section 4.3.1 together with the rest of all relevant variables mentioned above.

From this, differentiating (A.2.1) with respect to R_a and R_b, the following first order conditions are obtained:

$$[R_a] : 0 \leq \int_{\theta_a^{vr}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta. \tag{A.2.2}$$

$$\begin{aligned} [R_b] : 0 \leq & \int_{\theta_b^{vr}}^{\theta_a^{vr}} \left[\kappa\theta^\alpha - h_p \left[e_a + \tfrac{\Delta}{2}\right] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\ & + \left[c - R_b \left\{\kappa(\theta_b^{vr})^\alpha - h_p \left[e_a + \tfrac{\Delta}{2}\right] \left(\frac{\theta_b^{vr}}{\psi}\right)^\alpha\right\}\right] f_p(\theta_b^{vr}) \frac{\partial \theta_b^{vr}}{\partial R_b}. \end{aligned}$$

When considering (4.3.5) this last expression can be rewritten as:

$$[R_b] : 0 \leq \int_{\theta_b^{vr}}^{\theta_a^{vr}} \left[\kappa\theta^\alpha - h_p \left[e_a + \tfrac{\Delta}{2}\right] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta. \tag{A.2.3}$$

Following BGM (2019), there are three possibilities regarding the values for R_a and R_b: (i) $R_a < 1$ and $R_b < 1$, (ii) $R_a < 1$ and $R_b = 1$, (iii) $R_a = 1$ and $R_b \leq 1$. In what follows I analyze what happens when each of the previous possibilities is true. First, if case (i) is true, both (A.2.2) and (A.2.3) hold with equality. From (A.2.2) it follows that:

$$0 = \int_{\theta_a^{vr}}^{\bar{\theta}} \theta^\alpha \left[\kappa - \frac{h_p e_a}{\psi^\alpha}\right] f_p(\theta) d\theta.$$

Which means that $\kappa = h_p e_a \left(\frac{1}{\psi}\right)^\alpha$, this translates in (A.2.3) to:

$$0 = -\int_{\theta_b^{vr}}^{\theta_a^{vr}} \left[h_p \frac{\Delta}{2} \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta.$$

But since in the latter expression the term is negative and not equal to zero, case (i) is discarded. Second, if case (ii) is true, (A.2.2) holds with equality, thus $\kappa = h_p e_a \left(\frac{1}{\psi}\right)^\alpha$ which in (A.2.3) translates to:

$$0 \leq -\int_{\theta_b^{vr}}^{\theta_a^{vr}} \left[h_p \frac{\Delta}{2}\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta.$$

But since in the expression in question the term is negative and not equal nor greater than zero, case (ii) is also discarded.

Thus, I am left with case (iii) as the only possible scenario. Which means $R_a = 1$ and $R_b \leq 1$. Whether $R_b = 1$ or $R_b < 1$ depends on whether $\kappa > h_p \left[e_a + \frac{\Delta}{2}\right]\left(\frac{1}{\psi}\right)^\alpha$ or $\kappa = h_p \left[e_a + \frac{\Delta}{2}\right]\left(\frac{1}{\psi}\right)^\alpha$, respectively.

A.2.2. Mathematical Resolution for Section 4.3.2

Perfect Information

As mentioned in Section 4.3.2, the social planner determines the restriction upon low-polluting vehicles $R_l \leq 1$, the one upon high-polluting vehicles in circulation $R_h \leq 1$, and the threshold of emissions $\bar{e}$ to classify vehicles as l or h as to maximize:

$$\begin{aligned}
\mathbb{E}_{sc}[W] = \quad & - \quad \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\
& + \int_{\theta_a}^{\bar{\theta}} R_l \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^l]\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^h]\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta. \qquad \text{(A.2.4)}
\end{aligned}$$

Where θ_a, θ_l and θ_h are obtained as presented in the aforementioned Section 4.3.2 together with the rest of all relevant variables mentioned above.

To begin with, when differentiating (A.2.4) with respect to R_l, the following first order condition is obtained:

$$\begin{aligned}
0 \quad \leq \quad & \int_{\theta_a^{sc}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
+ \quad & \int_{\theta_l^{sc}}^{\theta_a^{sc}} \left[\kappa\theta^\alpha - h_p \left(\frac{e_a + \bar{e}}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
- \quad & R_l \left\{\kappa(\theta_l^{sc})^\alpha - h_p \left(\frac{e_a + \bar{e}}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc}) \frac{\partial \theta_l^{sc}}{\partial R_l} \\
+ \quad & R_h \left\{\kappa(\theta_l^{sc})^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc}) \frac{\partial \theta_l^{sc}}{\partial R_l}.
\end{aligned}$$

Which can be rewritten as follows when considering (4.3.6):

$$\begin{aligned} 0 &\leq \int_{\theta_a^{sc}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta + \int_{\theta_l^{sc}}^{\theta_a^{sc}} \left[\kappa\theta^\alpha - h_p\left(\frac{e_a+\bar{e}}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &+ \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial R_l}. \end{aligned} \tag{A.2.5}$$

Next, differentiating (A.2.4) with respect to R_h yields:

$$\begin{aligned} 0 &\leq \int_{\theta_h^{sc}}^{\theta_l^{sc}} \left[\kappa\theta^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &- R_l\left\{\kappa(\theta_l^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial R_h} \\ &+ R_h\left\{\kappa(\theta_l^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial R_h} \\ &+ \left[c - R_h\left\{\kappa(\theta_h^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_h^{sc}}{\psi}\right)^\alpha\right\}\right] f_p(\theta_h^{sc})\frac{\partial\theta_h^{sc}}{\partial R_h}. \end{aligned}$$

Which can be rewritten as follows when considering both (4.3.6) and (4.3.7):

$$\begin{aligned} 0 &\leq \int_{\theta_h^{sc}}^{\theta_l^{sc}} \left[\kappa\theta^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &+ \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial R_h}. \end{aligned} \tag{A.2.6}$$

Last, differentiating (A.2.4) with respect to $\bar{e}$ (keeping in mind that $\bar{e} \geq e_a > 0$) yields:

$$\begin{aligned} 0 &= -R_l\int_{\theta_l^{sc}}^{\theta_a^{sc}} \left[\frac{h_p}{2}\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta - R_h\int_{\theta_h^{sc}}^{\theta_l^{sc}} \left[\frac{h_p}{2}\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &- R_l\left\{\kappa(\theta_l^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial\bar{e}} \\ &+ R_h\left\{\kappa(\theta_l^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial\bar{e}} \\ &+ \left[c - R_h\left\{\kappa(\theta_h^{sc})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_h^{sc}}{\psi}\right)^\alpha\right\}\right] f_p(\theta_h^{sc})\frac{\partial\theta_h^{sc}}{\partial\bar{e}}. \end{aligned}$$

Which can be rewritten as follows when considering both (4.3.6) and (4.3.7):

$$\begin{aligned} 0 &= -\frac{1}{2}\,h_p\int_{\theta_h^{sc}}^{\theta_a^{sc}} \left[\left(R_l\,\mathbb{1}[\theta \geq \theta_l^{sc}] + R_h\,\mathbb{1}[\theta \leq \theta_l^{sc}]\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &+ \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{sc})\frac{\partial\theta_l^{sc}}{\partial\bar{e}}. \end{aligned} \tag{A.2.7}$$

Note that $\partial\theta_l^{sc}/\partial R_l < 0$, $\partial\theta_l^{sc}/\partial R_h > 0$ and $\partial\theta_l^{sc}/\partial\bar{e} < 0$. Given that the first term in (A.2.7) is negative and $\partial\theta_l^{sc}/\partial\bar{e} < 0$, then to have (A.2.7) holding with equality, the following expression must be negative:

$$A := \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{sc}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] < 0.$$

There are three possibilities regarding the values for R_l and R_h: (i) $R_l < 1$ and $R_h < 1$, (ii) $R_l < 1$ and $R_h = 1$, (iii) $R_l = 1$ and $R_h \leq 1$. In what follows I analyze what happens when each of the previous possibilities is true.

First, if case (i) is true, both (A.2.5) and (A.2.6) hold with equality. Given that the first two terms in (A.2.5) are positive and that $\partial\theta_l^{sc}/\partial R_l < 0$, to have (A.2.5) holding with equality it must occur that $A > 0$, which hinders both (A.2.6) and (A.2.7) from holding with equality. In the same way, if case (ii) is true, (A.2.5) holds with equality. Again this means that $A > 0$, which contradicts that (A.2.7) holds with equality. Therefore, I am left with case (iii) as the only possible scenario, which means $R_l = 1$ and $R_h \leq 1$. Whether $R_h = 1$ or $R_h < 1$ depends on how negative A is.

Moreover, when assuming that $p_l > p_h$ occurs as a consequence of efficient rationing such that higher type-θ drivers buy low-polluting cars instead of high-polluting ones, the model requires both that $R_l \neq R_h$ and $R_l > R_h$. In this scenario it would not be possible to have $R_l = 1$ and $R_h = 1$, for it would imply $R_l = R_h$; a contradiction. Therefore, in that event I have $R_l = 1$ and $R_h < 1$. Likewise, if the model requires $R_l > R_h$, this constraint could mathematically imply that the first order condition associated to R_h is always greater than zero. In which scenario the problem would have no solution, for the central planner would always want to increase R_h. This, ultimately converging to $R_h = R_l$, meaning that it would not be possible to reach an equilibrium. To account for this, I assume that the constraint $R_l > R_h$ is not costly for the central planner when considering $p_l > p_h$. Last, note that only if $p_l = p_h = c$ then $R_l = R_h = 1$.

Imperfect Information

In such context, the optimization problem of the social planner must be modified a little. In particular, her social welfare function changes to:

$$\begin{aligned}
\mathbb{E}_{scm}[W] = \quad & - \quad \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\
& + \quad \int_{\theta_a}^{\bar{\theta}} R_l \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_l] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
& + \quad \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right) \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta. \qquad \text{(A.2.8)}
\end{aligned}$$

Where $\mathbb{E}[e_l]$ denotes the expected emission value for a car that is labeled as low-polluting (i.e., $sc = l$) taking into account that a fraction λ of high-polluting cars is mislabeled as low-polluting. In this manner:

$$\begin{aligned}
\mathbb{E}[e_l] = & P_r[e_b \leq \bar{e}]\, \mathbb{E}[e_l | e_b \leq \bar{e}] \\
& + \lambda P_r[e_b > \bar{e}]\, \mathbb{E}[e_l | e_b > \bar{e} \wedge sc = l] \\
& + (1 - \lambda) P_r[e_b > \bar{e}]\, \mathbb{E}[e_l | e_b \leq \bar{e} \wedge sc = h],
\end{aligned}$$

where, given by the conditional distribution of $\mathbb{E}[e_l]$, it follows that $\mathbb{E}[e_l | e_b \leq \bar{e} \wedge sc = h] = 0$. Thus:

$$\mathbb{E}[e_l] = \left\{\frac{s_b{}^l}{\eta_l} \int_{e_a}^{\bar{e}} \left(\frac{e_b}{\bar{e} - e_a}\right) de_b + \lambda \frac{s_b^h}{\eta_l} \int_{\bar{e}}^{E_b} \left(\frac{e_b}{E_b - \bar{e}}\right) de_b\right\},$$

where $\eta_l = \left(s_b^l + \lambda s_b^h\right)$, is the share of type-$b$ cars that end up classified as low-polluting, either because they are actually low-polluting (i.e., share s_b^l) or because they got mislabeled (i.e., share λs_h^l), naturally $s_b^l + s_b^h = 1$.

To the same extent, $s_b^l = \dfrac{\bar{e} - e_a}{E_b - e_a}$ and $s_b^h = \dfrac{E_b - \bar{e}}{E_b - e_a}$. Again, given $e_b \sim U(e_a, E_b)$ and $E_b - e_a = \Delta$, it follows that:

$$\mathbb{E}[e_l] = \frac{1}{\eta_l}\left\{ \left(\frac{\bar{e} - e_a}{E_b - e_a}\right)\left(\frac{\bar{e} + e_a}{2}\right) + \lambda\left(\frac{E_b - \bar{e}}{E_b - e_a}\right)\left(\frac{\bar{e} + E_b}{2}\right) \right\}$$

$$\Rightarrow \mathbb{E}[e_l] = \frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}.$$

Along these lines, differentiating (A.2.8) with respect to R_l, the following first order condition is obtained:

$$\begin{aligned}
0 \quad &\leq \quad \int_{\theta_a^{scm}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
&+ \quad \int_{\theta_l^{scm}}^{\theta_a^{scm}} \left[\kappa\theta^\alpha - h_p \left(\frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
&- \quad R_l \left\{\kappa(\theta_l^{scm})^\alpha - h_p \left(\frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm}) \frac{\partial\theta_l^{scm}}{\partial R_l} \\
&+ \quad R_h \left\{\kappa(\theta_l^{scm})^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm}) \frac{\partial\theta_l^{scm}}{\partial R_l}.
\end{aligned}$$

Which can be rewritten as follows when considering (4.3.6):

$$\begin{aligned}
0 \quad &\leq \quad \int_{\theta_a^{scm}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
&+ \quad \int_{\theta_l^{scm}}^{\theta_a^{scm}} \left[\kappa\theta^\alpha - h_p \left(\frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
&+ \quad \left[\{p_h - p_l\} + h_p \left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha \left\{R_l \left(\frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}\right) - R_h \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\right\}\right] f_p(\theta_l^{scm}) \frac{\partial\theta_l^{scm}}{\partial R_l}.
\end{aligned} \tag{A.2.9}$$

Next, differentiating (A.2.8) with respect to R_h yields:

$$\begin{aligned}
0 \quad &\leq \quad \int_{\theta_h^{scm}}^{\theta_l^{scm}} \left[\kappa\theta^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta) d\theta \\
&- \quad R_l \left\{\kappa(\theta_l^{scm})^\alpha - h_p \left(\frac{(1-\lambda)(\bar{e}^2 - e_a^2) + \lambda\Delta(2e_a + \Delta)}{2\Delta\eta_l}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm}) \frac{\partial\theta_l^{scm}}{\partial R_h} \\
&+ \quad R_h \left\{\kappa(\theta_l^{scm})^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm}) \frac{\partial\theta_l^{scm}}{\partial R_h} \\
&+ \quad \left[c - R_h \left\{\kappa(\theta_h^{scm})^\alpha - h_p \left(\frac{e_a + \bar{e} + \Delta}{2}\right)\left(\frac{\theta_h^{scm}}{\psi}\right)^\alpha\right\}\right] f_p(\theta_h^{scm}) \frac{\partial\theta_h^{scm}}{\partial R_h}.
\end{aligned}$$

Which can be rewritten as follows when considering both (4.3.6) and (4.3.7):

$$\begin{aligned} 0 &\leq \int_{\theta_h^{scm}}^{\theta_l^{scm}} \left[\kappa\theta^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &+ \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha \left\{R_l\left(\frac{(1-\lambda)(\bar{e}^2-e_a^2)+\lambda\Delta(2e_a+\Delta)}{2\Delta\eta_l}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{scm})\frac{\partial\theta_l^{scm}}{\partial R_h}. \end{aligned} \tag{A.2.10}$$

Last, differentiating (A.2.8) with respect to $\bar{e}$ (keeping in mind that $\bar{e} \geq e_a > 0$) yields:

$$\begin{aligned} 0 &= -R_l h_p \int_{\theta_l^{scm}}^{\theta_a^{scm}} \left[\frac{\xi_l}{2}\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta - R_h h_p \int_{\theta_h^{scm}}^{\theta_l^{scm}} \left[\frac{1}{2}\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &- R_l\left\{\kappa(\theta_l^{scm})^\alpha - h_p\left(\frac{(1-\lambda)(\bar{e}^2-e_a^2)+\lambda\Delta(2e_a+\Delta)}{2\Delta\eta_l}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm})\frac{\partial\theta_l^{scm}}{\partial\bar{e}} \\ &+ R_h\left\{\kappa(\theta_l^{scm})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha\right\} f_p(\theta_l^{scm})\frac{\partial\theta_l^{scm}}{\partial\bar{e}} \\ &+ \left[c - R_h\left\{\kappa(\theta_h^{scm})^\alpha - h_p\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta_h^{scm}}{\psi}\right)^\alpha\right\}\right] f_p(\theta_h^{scm})\frac{\partial\theta_h^{scm}}{\partial\bar{e}}. \end{aligned}$$

Which can be rewritten as follows when considering both (4.3.6) and (4.3.7):

$$\begin{aligned} 0 &= -\frac{1}{2}\, h_p \int_{\theta_h^{scm}}^{\theta_a^{scm}} \left[\left(\xi_l\, R_l\, \mathbb{1}[\theta \geq \theta_l^{scm}] + R_h\, \mathbb{1}[\theta \leq \theta_l^{scm}]\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\ &+ \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha \left\{R_l\left(\frac{(1-\lambda)(\bar{e}^2-e_a^2)+\lambda\Delta(2e_a+\Delta)}{2\Delta\eta_l}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{scm})\frac{\partial\theta_l^{scm}}{\partial\bar{e}}. \end{aligned} \tag{A.2.11}$$

Where ξ_l is twice the partial derivative of η_l with respect to $\bar{e}$, namely:

$$\xi_l = \frac{(1-\lambda)\Big[(e_a-\bar{e})^2 - \lambda(e_a+\Delta-\bar{e})^2\Big]}{\Big[(e_a-\bar{e}) - \lambda(e_a+\Delta-\bar{e})\Big]^2}.$$

There are three possibilities regarding the values for R_l and R_h: (i) $R_l < 1$ and $R_h < 1$, (ii) $R_l < 1$ and $R_h = 1$, (iii) $R_l = 1$ and $R_h \leq 1$. In what follows I analyze what happens when each of the previous possibilities is true. First, let B be defined as follows:

$$B := \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{scm}}{\psi}\right)^\alpha \left\{R_l\left(\frac{(1-\lambda)(\bar{e}^2-e_a^2)+\lambda\Delta(2e_a+\Delta)}{2\Delta\eta_l}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right].$$

Again, if case (i) is true, both (A.2.9) and (A.2.10) hold with equality. Given that the first two terms in (A.2.9) are positive and that $\partial\theta_l^{scm}/\partial R_l < 0$, to have it holding with equality it follows that $B > 0$, which contradicts both (A.2.10) and (A.2.11) holding with equality. In the same way, if case (ii) is true, (A.2.9) holds with equality. Again, this means that $B > 0$, which contradicts that (A.2.11) holds with equality. Therefore, I am left with case (iii) as the only possible scenario, which means $R_l = 1$ and $R_h \leq 1$. Whether $R_h = 1$ or $R_h < 1$ depends on how negative B is.

In such a scenario, the central planner solves:

$$\begin{aligned}
\max_{\bar{e},R_a,R_l,R_h} \mathbb{E}_{vs}[W] = \; & - \; \left(c\left[F_p(\bar{\theta}) - F_p(\theta_h)\right] + C_s\right) \\
& + \int_{\theta_a}^{\bar{\theta}} R_a \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\
& + \int_{\theta_l}^{\theta_a} R_l \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^l] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\
& + \int_{\theta_h}^{\theta_l} R_h \left[\kappa\theta^\alpha - h_p \mathbb{E}[e_b^h] \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta.
\end{aligned} \tag{A.2.12}$$

First when differentiating (A.2.12) with respect to R_a, the following first order condition is obtained:

$$0 \;\leq\; \int_{\theta_a^{vs}}^{\bar{\theta}} \left[\kappa\theta^\alpha - h_p e_a \left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \tag{A.2.13}$$

Next, differentiating (A.2.12) with respect to R_l yields:

$$\begin{aligned}
0 \;\leq\; & \int_{\theta_l^{vs}}^{\theta_a^{vs}} \left[\kappa\theta^\alpha - h_p \left(\frac{e_a+\bar{e}}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\
+ & \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{vs}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{vs})\frac{\partial\theta_l^{vs}}{\partial R_l}.
\end{aligned} \tag{A.2.14}$$

Then, differentiating (A.2.12) with respect to R_h yields:

$$\begin{aligned}
0 \;\leq\; & \int_{\theta_h^{vs}}^{\theta_l^{vs}} \left[\kappa\theta^\alpha - h_p \left(\frac{e_a+\bar{e}+\Delta}{2}\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\
+ & \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{vs}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{vs})\frac{\partial\theta_l^{vs}}{\partial R_h}.
\end{aligned} \tag{A.2.15}$$

Last, differentiating (A.2.12) with respect to $\bar{e}$ (keeping in mind that $\bar{e} \geq e_a > 0$) yields:

$$\begin{aligned}
0 \;=\; & -\frac{1}{2}\, h_p \int_{\theta_h^{vs}}^{\theta_a^{vs}} \left[\left(R_l\, \mathbb{1}[\theta \geq \theta_l^{vs}] + R_h\, \mathbb{1}[\theta \leq \theta_l^{vs}]\right)\left(\frac{\theta}{\psi}\right)^\alpha\right] f_p(\theta)d\theta \\
+ & \left[\{p_h - p_l\} + h_p\left(\frac{\theta_l^{vs}}{\psi}\right)^\alpha \left\{R_l\left(\frac{e_a+\bar{e}}{2}\right) - R_h\left(\frac{e_a+\bar{e}+\Delta}{2}\right)\right\}\right] f_p(\theta_l^{vs})\frac{\partial\theta_l^{vs}}{\partial \bar{e}}.
\end{aligned} \tag{A.2.16}$$

The analysis for this problem is analogous to the one presented in Section 4.3.2. The only possibility that cannot be discarded is $R_a = 1$, $R_l = 1$ and $R_h \leq 1$, where the optimal pollution standard $\bar{e}$ is obtained from (A.2.16).

A.3. *Additional Material for Section 5*

A.3.1. Figures and Tables

Table A5: Revenue per Station in Santiago

Code	**Price**	**Inspections**	**Revenue**
AB–1322	16,152	21,999	355
B–1302	14,646	144,622	2,120
B–1303	14,646	96,364	1,410
B–1304	14,646	128,887	1,890
B–1305	14,646	91,230	1,340
B–1307	19,186	72,692	1,390
B–1308	19,186	93,040	1,790
B–1309	19,186	123,438	2,370
B–1310	19,186	100,730	1,930
B–1312	17,219	84,668	1,460
B–1313	17,219	79,570	1,370
B–1314	17,219	88,414	1,520
B–1315	17,219	69,162	1,190
B–1317	17,179	84,148	1,450
B–1318	17,179	89,094	1,530
B–1319	17,179	66,717	1,150
B–1320	17,179	80,070	1,380
B–1321	15,988	37,344	597
Total	-	1,552,189	26,230
Average	16,948	86,233	1,457

Notes: Table A5 presents prices and number of inspections for all 18 smog check stations located in the Metropolitan Region in Chile for year 2014. All prices displayed correspond to the average price charged during 2014 in each station and are presented in Chilean pesos (CLP). Revenue corresponds to the product of the two preceding columns, namely the price and the number of inspections, and is presented in CLP MM.

Table A6: Revenue per Entrant Station in Santiago

Code	**Price**	**Inspections**	**Revenue**
B–1311	8,300	48,798	405
B–1325	13,200	76,407	1,008
B–1327	13,200	93,447	1,234
B–1328	9,542	42,967	409
B–1337	9,542	48,223	460
B–1338	9,542	52,545	501
Total	-	362,387	4,017
Average	10,554	60,398	670

Notes: Table A6 presents prices and number of inspections for all smog check stations located in the Metropolitan Region in Chile that entered the market during 2016. All prices displayed correspond to the average price charged during 2016 in each station and are presented in Chilean pesos (CLP). Revenue corresponds to the product of the two preceding columns, namely the price and the number of inspections, and is presented in CLP MM.

Table A7: Optimal Emission Standard: Alternative Corruption Value

Δ/e_a	$\bar{e}^{scm}/e_a$	**Optimal Emission Standard per Gas Test**					
		NO 2525 (1,072)	NO 5015 (1,186)	CO 2525 (0.82)	CO 5015 (0.85)	HC 2525 (147)	HC 5015 (152)
Panel (a) : Type-a: age $\leq$ 5 & Type-b: age > 5							
3.6	4.061	344.0	461.7	0.32	0.24	50.4	68.2
5.6	4.392	372.0	499.4	0.35	0.26	54.5	73.8
7.6	4.783	405.1	543.8	0.38	0.29	59.3	80.4
Panel (b) : Type-a: age $\leq$ 10 & Type-b: age > t 10							
3.5	4.041	497.4	746.0	0.44	0.40	67.9	98.2
4.7	4.242	522.2	783.1	0.47	0.42	71.3	103.1
5.8	4.427	545.0	817.2	0.49	0.44	74.4	107.6

Notes: Table A7 presents the optimal emission standards obtained from combining both the model simulation and the data presented in the second column in Table 8. Each panel is calculated multiplying the value from the $\bar{e}^{scm}$ column and the data from its homonym in the second column in Table 8. Optimal standards are computed for the six different dispersion values presented above, assuming a single value for corruption $\lambda = 0.5$. Limits are given in parts per million for NO and HC and in percentage of volume for CO.