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Léa Bou Sleiman

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Thèse de doctorat



# Essays in Urban and Environmental Economics

Thèse de doctorat de l'Institut Polytechnique de Paris  
préparée à l'École Polytechnique

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## Acknowledgments - Remerciements

This dissertation is inspired by a combination of my personal and professional experiences. I grew up in Beirut, a city that was destroyed and rebuilt 8 times. The history of this city has fueled my fascination with contemporary urbanism, and the intricate interplay between technical city designs and their social consequences. Moving to a developed city like Paris in 2014 prompted me to reflect on the key concepts that define a city, and the diverse array of social, economic, environmental, and political dynamics that shape it. This dissertation was written in part to quench my thirst for understanding the intricacies of urban dynamics.

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I am also honored to have had Pierre Boyer and Geoffrey Barrows as reference writers. Pierre

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## Summary

This dissertation lies at the intersection of Urban Economics and Environmental Economics. It combines quasi-experimental methods and theoretical models to better understand the impacts of transportation policies in today's cities.

There is a growing consensus in reducing the carbon use in transport in cities. Designing the optimal road network for urban mobility plays a central role in reaching this kind of sustainability. Increasing alternatives to car transportation such as walking, cycling or public transportation is usually proposed to decrease CO<sub>2</sub> emissions. Yet, compelling people to switch to greener means of transportation remains a difficult challenge. To meet the target, the government can influence individuals' choices by increasing the road usage cost, either through imposing an urban toll or through reducing the road supply. While the former remains socially unacceptable and politically difficult to implement, the public debate about the latter shows extreme positions, each party suggesting that the choices are obvious. Some argue that climate issues justify a major reform of the organization of cities. Others observe that the corresponding roads are widely used and that their removal surely comes at high cost. In reality, it is more of a complex problem, as the choice of solutions does not only depend on many parameters such as technical performance of expressways, characteristics of the demand of different users or scarcity of public space but also on traffic coordination explained by the road paradoxes. The first two chapters study the impacts of road-reduction policies on congestion and pollution.

Chapter 1, in collaboration with Dominique Bureau, analyzes how taking climate change into account justifies the re-examination of urban expressways as undertaken in various metropolises. We develop a theoretical model aiming at providing a framework for determining the cases in which the removal of express roads may be justified in the context of cities *decarbonation*. By introducing pollution externalities in the model, we show that in some cases, a marginal reduction in the road supply can increase the welfare cost. As such, the idea of a drastic adjustment is at the heart of the model.

Chapter 2 evaluates the different impacts of road-closing policies, focusing on a major road

closure that happened in Paris in 2016: the "Voie Georges Pompidou". Relying on a difference-in-difference strategy based on the direction and the timing of traffic, which is implemented on detailed road-sensor data; I show that the closure displaced congestion on two sets of roads: local roads and the ring road. Through an analysis of air quality data, I find that the displacement of congestion resulted in a significant increase in NO<sub>2</sub> concentrations. Despite the fact that only a small number of commuters diverted to the ring road, the U-shaped relationship between traffic speed and emissions caused a significant increase in pollution. Based on my estimates, up to 90% of the pollution costs were borne by lower-income residents who lived around the ring road, far from the new amenity created by the closure and outside the jurisdiction responsible for the decision to close the road.

Chapter 3, in collaboration with Benoit Schmutz, examines the role of politicians in influencing the share of car commuters. Specifically, we investigate how the political orientation of a municipality affects the implementation of transportation policies that promote sustainable transportation options, and how these policies in turn impact car usage patterns. Drawing data on French municipalities on commuting patterns over a decade and municipalities elections, we use a regression discontinuity design analysis (RDD) that exploits quasi-random variations in the political affiliation of the mayor as a consequence of close elections. We provide evidence that the political color of a municipality influences the share of car commuters in the municipality. In particular, electing a left-wing mayor compared to a right-wing mayor decreases the share of car commuters. This effect is stronger if we only consider within-city commuters.



## Résumé

Cette thèse se situe à l'intersection de l'économie urbaine et de l'économie de l'environnement. Elle combine des méthodes quasi-expérimentales et des modèles théoriques pour mieux comprendre les impacts des politiques de transport dans les villes d'aujourd'hui.

La réduction de la consommation de carbone dans les transports urbains fait l'objet d'un consensus de plus en plus large. La conception d'un réseau routier optimal pour la mobilité urbaine joue un rôle central dans la réalisation de ce type de durabilité. Pour réduire les émissions de CO<sub>2</sub>, il est généralement proposé d'augmenter les alternatives au transport automobile, telles que la marche, le vélo ou les transports publics. Pourtant, convaincre les gens d'adopter des moyens de transport plus écologiques reste un défi difficile à relever. Pour atteindre l'objectif, le gouvernement peut influencer les choix des individus en augmentant le coût d'utilisation des routes, soit en imposant un péage urbain, soit en réduisant l'offre de routes. Si la première solution reste socialement inacceptable et politiquement difficile à mettre en œuvre, le débat public sur la seconde fait apparaître des positions extrêmes, chaque partie suggérant que les choix sont évidents. Certains affirment que les enjeux climatiques justifient une réforme majeure de l'organisation des villes. D'autres observent que les routes correspondantes sont largement utilisées et que leur suppression a sûrement un coût élevé. En réalité, il s'agit d'un problème plus complexe, car le choix des solutions ne dépend pas seulement de nombreux paramètres tels que les performances techniques des voies rapides, les caractéristiques de la demande des différents usagers ou la rareté de l'espace public, mais aussi de la coordination des trafics expliquée par les paradoxes routiers. Les deux premiers chapitres se concentrent sur la réduction de voiries en ville et son impact sur la pollution et la congestion.

Le chapitre 1, en collaboration avec Dominique Bureau, analyse comment la prise en compte du changement climatique justifie le réajustement des voies express urbaines tel qu'il a été entrepris dans diverses métropoles. Nous développons un modèle théorique visant à fournir un cadre pour déterminer les cas dans lesquels la suppression des voies rapides peut être justifiée dans le contexte de la décarbonisation des villes. En introduisant des externalités de pollution

dans le modèle, nous montrons que dans certains cas, une réduction marginale de l'offre routière peut augmenter le coût du bien-être social. L'idée d'un ajustement radical est donc au cœur du modèle.

Le chapitre 2 évalue les différents impacts des politiques de fermeture de routes, en se concentrant sur une fermeture majeure qui a eu lieu à Paris en 2016 : la "Voie Georges Pompidou". En s'appuyant sur une stratégie de différence en différence basée sur la direction et le moment du trafic, qui est mise en œuvre sur des données détaillées de capteurs routiers, je montre que la fermeture a déplacé la congestion sur deux ensembles de routes : les routes locales et le périphérique. En analysant les données relatives à la qualité de l'air, je constate que le déplacement de la congestion a entraîné une augmentation significative des concentrations de NO<sub>2</sub>. Bien que seul un petit nombre de navetteurs se soit détourné vers le périphérique, la relation en U entre la vitesse de circulation et les émissions a entraîné une augmentation significative de la pollution. D'après mes estimations, jusqu'à 90% des coûts de pollution ont été supportés par les résidents à faible revenu qui vivaient autour du périphérique, loin des nouvelles aménités créées par la fermeture et en dehors de la juridiction responsable de la décision de la piétonisation de la voie "Georges pompidou".

Le chapitre 3, en collaboration avec Benoît Schmutz, examine le rôle des politiciens dans l'influence de la part des navetteurs en voiture. Plus précisément, nous étudions comment l'orientation politique d'une municipalité affecte la mise en œuvre de politiques de transport qui favorisent les options de transport durable, et comment ces politiques influencent à leur tour les schémas d'utilisation de la voiture. En nous appuyant sur des données relatives aux municipalités françaises concernant les déplacements domicile-travail sur une décennie et les élections municipales, nous utilisons une analyse de discontinuité de la régression (RDD) qui exploite les variations quasi-aléatoires de l'affiliation politique du maire à la suite d'élections rapprochées. Nous démontrons que la couleur politique d'une municipalité influence la part des navetteurs en voiture dans la municipalité. En particulier, l'élection d'un maire de gauche par rapport à un maire de droite diminue la proportion de navetteurs en voiture. Cet effet est d'autant plus important si nous ne prenons en compte que les navetteurs intra-muros.

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# General Introduction

Urban economics explores a range of topics related to urban areas, including the determinants of urban growth and decline, transportation policies, housing and real estate markets, urban poverty and inequality, urban labor markets or local public finance. By analyzing the economic dynamics of cities and the factors that shape their development, urban economics helps policymakers create sustainable and prosperous urban environments.

Environmental economics is a subfield concerned with the economic impact of policies aimed at addressing environmental problems such as climate change, pollution, and natural resource depletion.

This dissertation lies at the intersection of urban and environmental economics, aiming to provide a better understanding of the determinants and impacts of urban transportation policies. The first two chapters investigate the effects of road closures on congestion and pollution, using theoretical and empirical approaches. The third chapter examines the effects of local political elections on car usage.

The introduction is divided into four sections. The first section focuses on two main transportation issues addressed in this dissertation: congestion and air pollution. In the second section, various economic theories related to the regulation of these externalities are presented. The third section discusses the urban case of Paris and describes the different transportation policies implemented to combat the negative impacts of traffic in the city. The last section gives an overview of each chapter and highlights the dissertation's contribution to the existing literature.

## **Congestion and Pollution: two major challenges associated with urban traffic**

Private motorized transportation can have a range of negative externalities, which are costs that are not directly borne by those who cause them (Arnott and Small, 1994). On the one hand, having cars on the road can cause congestion which can in turn translate into time loss and decrease in productivity. Moreover, traffic congestion can also limit access to public services (Afrin and Yodo, 2020). On the other hand, private motorized transportation is responsible for increased air pollution, and congested traffic can lead to increased emissions of greenhouse gases and other pollutants, which can threaten public health.

These negative externalities highlight the importance of implementing efficient transportation policies as cities continue to grow and evolve. Although the design and implementation of effective transportation policies can have far-reaching impacts on the economy, environment, and on social inequalities, finding the right transportation policy remains a difficult challenge. In fact, the complexity and diversity of urban environments, the presence of political constraints, and the increasing technological transformation of the transportation industry make it all the more arduous to identify appropriate interventions for climate change mitigation.

**Urban Congestion** Traffic congestion occurs when there are too many vehicles on the roads, leading to slower travel times, longer commutes, and reduced productivity for individuals and businesses. It has been one of the major issues that most metropolises are facing (Bull et al., 2003). There are generally two factors that impact traffic congestion: the micro level and macro level (Rao and Rao, 2012). The micro level refers to the factors associated with the road demand. For example, many people wanting to move at the same time or excessive amount of cars for limited road space. The macro level refers to all factors associated with the road supply such as the number of roads available. The economic impact of congestion is substantial. Conservative estimates suggest that increasing the average speed of private car journeys by 1 km/hr and that of public transport by 0.5 km/hr would result in a reduction in journey times and operating costs

equivalent to 0.1% of the gross domestic product (GDP) (Bull and Thomson, 2002).

**Air Pollution** Air pollution is a major environmental issue, identified by the World Health Organization as the biggest environmental health risk in the world (WHO, 2016). Urban traffic is a significant contributor to overall air pollution in cities. Motorized-vehicles emit a variety of pollutants such as nitrogen dioxide or carbon monoxide that can cause severe health threats to individuals. It is worth to note that congested (or heavy) traffic is particularly bad for air pollution. In fact, as commuters are stuck in traffic, they may frequently break and accelerate. When a vehicle breaks, it releases particulate matter and other pollutants into the air. Thus, congested traffic tends to produce significantly higher levels of air pollution compared to uncongested traffic. Air pollution is responsible for the death of approximately 4.2 millions people per year (WHO, 2022). To this matter, the WHO has put in place air quality guidelines for several pollutants, aiming at serving as a benchmark for governments to measure and evaluate air quality levels in their respective regions. Air quality levels have gone better over the years, although a lot of regions are still above the recommended levels. The introduction of electric vehicles on the transportation market is definitely playing a crucial role in staying below the limits. In fact, EVs produce zero tailpipe emissions. In other words, they don't emit pollutants like particulate matter or nitrogen oxides. Of course, EVs cannot fully solve the air pollution problem associated with transportation since they depend on several factors such as the source of electricity used to charge them, the manufacturing process etc.

## **Traffic Regulation**

The transportation economic literature has identified a panoply of policy instruments that can be used to tackle externalities caused by traffic. Often, these regulations can be disciplined into two categories: demand-side policies and supply-side policies.

**Demand-side policies** On the demand-side, road pricing (or congestion pricing) is usually the most popular tool (Liu and McDonald, 1999; Santos et al., 2008; Tirachini and Hensher, 2012;



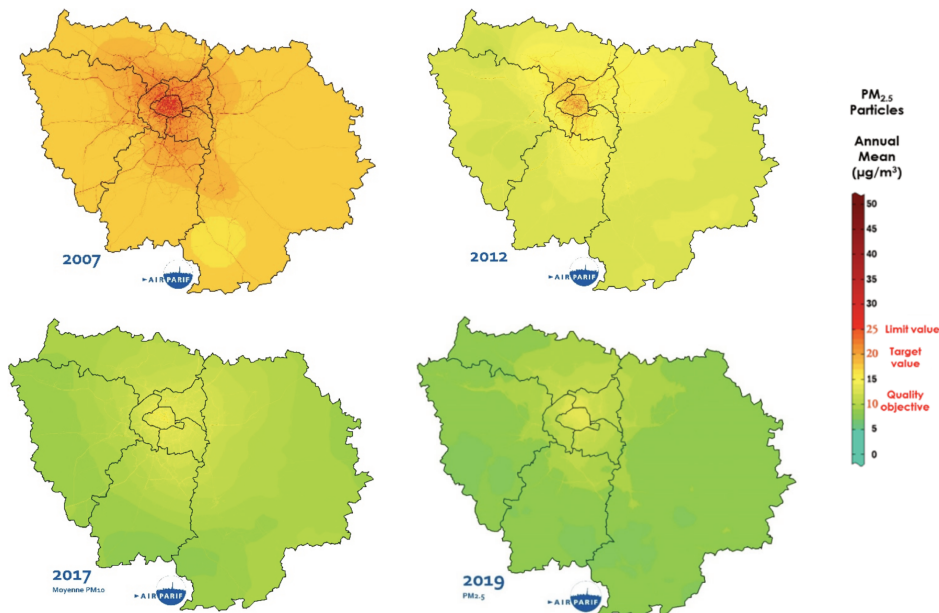
Winston and Langer, 2006). It is an instrument that charges drivers for using roads. It can be implemented during peak hours when congestion is the highest or during the whole day. Its objective is to hold drivers accountable for the negative externalities they cause, such as contributing to air pollution and traffic congestion. The problem lies in the fact that the effects of these externalities are not limited to those responsible for causing them, and others are forced to breathe the polluted air. By pricing roads, governments hope to discourage unnecessary car usage, encourage car-pooling or the use public transportation or even shift people's trips to off-peak hours. This instrument has been used in many cities such as London, Stockholm, Singapore or Milan.

**Supply-side policies** On the supply-side, there is a larger variety of policies. One possible policy consists in expanding the number of alternatives to car transportation by implementing new metro lines (Yang et al., 2018) or by multiplying the number of cycling and bus lanes (New York City, Beijing, Toronto). The purpose of these policies is to increase the relative cost of using the car compared to the alternatives. Some cities such as Beijing or Mexico City have used road space rationing by restricting the days or hours in which car users can drive on congested roads (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003). Others, including Paris, have opted for quantity-rationing by gradually reducing their road capacity. For example, Seoul transformed its main highway into an urban boulevard (Kang and Cervero, 2009) while New York has used *High Occupancy Vehicle* (HOV) lanes (Poole Jr and Orski, 2000) which are lanes designed on highways or urban roads that are reserved for vehicles with a certain minimum number of occupants. These policies are intended to encourage carpooling and promote the use of more sustainable modes of transportation. It is important to note that adding roads, bridges, and highways within urban areas may not be a beneficial long-term solution and could potentially exacerbate traffic congestion (Downs, 1962; Duranton and Turner, 2011a) by attracting some extra users on the road. Instead, removing road capacity is the new instrument that many cities have recently been using hoping to discourage existing users. Still, little is known about the efficiency of road-reduction policies. This is the focus of chapters 1 and 2 of this

dissertation.

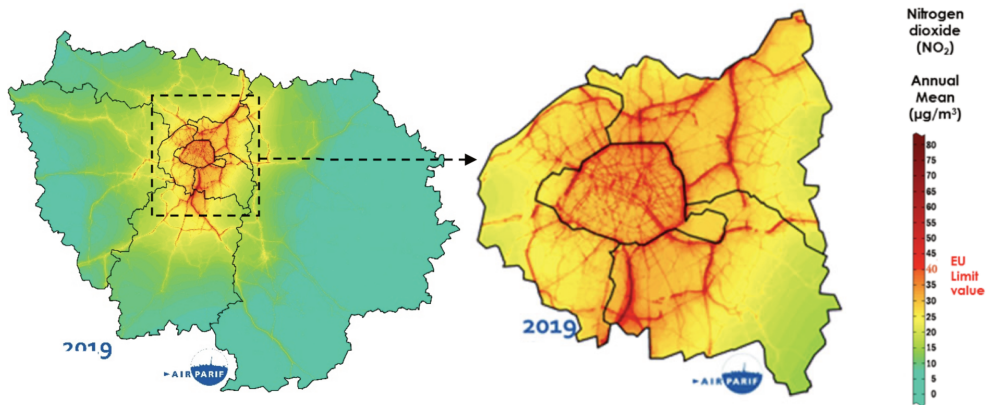
## The Case of Paris

The trend of pollution in Paris has been decreasing in recent years. According to data from the Airparif network, which monitors air quality in the Paris region, the concentration of fine particles (PM10 and PM2.5) has decreased significantly since 2007. As shown in Figure 1, there is a significant decline in the concentrations of  $PM_{2.5}$  from 2007 to 2019.



**Figure 1:** Annual mean concentrations of fine particles from 2007 to 2019 in the Paris Regions (Source: AirParif)

However, although there is a promising trend in air pollution, we can observe strong  $NO_2$  concentrations in the Paris region. These concentrations are particularly high - and above the recommended threshold - near major roads (see Figure 2); highlighting high levels of vehicle emissions.



**Figure 2:** Nitrogen Dioxide annual mean concentrations within the Paris region in 2019 (Source: AirParif)

These concerns led the Mayor of the city Anne Hidalgo to implement several urban modifications aiming at reducing traffic and pollution. These changes include the implementation of more than 700 km of bike lanes, the introduction of a low emission zone to restrict access to the most polluting vehicles in certain areas, the implementation of car-free days and the pedestrianization of several areas with the road along the river banks being the most emblematic one. The latter will be used as a case study in Chapter 2 to empirically evaluate the impacts of road reduction policies.

Knowing that road pricing is considered in the economic literature as the most efficient solution to deal with traffic externalities, one might wonder why Paris did not consider it. In fact, road pricing is often a controversial issue. Some people might see it as an unfair tax on drivers that could disproportionately impact low-income households. This scenario was already witnessed in Paris: When President Macron made the decision to impose a gasoline tax, it backfired on him and the *Gilets Jaunes* were quick to react and cause turmoil in the country (Boyer et al., 2020). The fear of having history repeat itself might make politicians reluctant to impose any sort of road pricing.

The high number of car commuters entering Paris has prompted the city's Mayor to consider using various methods to regulate external traffic and protect residents (and voters) from bearing the negative consequences of congestion. This political dimension is explored in the third chapter of this dissertation where I study the impacts of political elections in French municipalities

on car usage<sup>1</sup>. However, it is important to consider that the burden of these policies may not be equally distributed among the population, and low-income households may bear a disproportionate amount of the cost if no other alternatives are provided. This aspect is further examined in Chapter 2.

## **This Dissertation**

This dissertation builds on three economic essays on the theoretical implications of road reduction policies (chapter 1), the empirical evaluation of these policies (chapter 2) and the influence of political parties on car usage (chapter 3). My work mixes theory and empiric to better understand the determinants and consequences of transportation policies. While chapter 1 uses urban theoretical frameworks, the two other chapters mobilize data such as road sensors data (chapter 2), or a sample of French municipalities and detailed information on commuting patterns (chapter 3). The aim of this dissertation is twofold. First, evaluate the impacts of road reductions on pollution and congestion by providing a theoretical framework that determines in which cases the removal of express roads in cities are beneficial (chapter 1); and by empirically evaluating the pedestrianization of the "Georges Pompidou" riverbank in Paris on pollution and congestion (chapter 2). Second, understand how political parties can influence car usage by looking at close elections in French municipalities (chapter 3). In what follows, I summarize the three chapters of this dissertation focusing on the methods used and the contributions to the literature.

### **Chapter 1 - When Should Urban Roads be Removed to Lower Carbon Emissions? (with Dominique Bureau)**

Urban tolls have long been advocated to address the negative externalities associated with urban driving (Parry and Bento, 2002; Vickrey, 1969). However, its primary motivation is dealing with congestion externalities. Today, it is the *decarbonation* of cities that is fueling the debate. From this perspective, it is appropriate to analyze more generally how taking climate change into ac-

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<sup>1</sup>I exclude Paris from the analysis for several reasons mentioned in Chapter 3.

count justifies the re-examination of urban expressways as undertaken in various metropolises. This chapter (joint with Dominique Bureau), proposes a theoretical model aiming at providing a framework to determine when it is appropriate to remove roads in a context of scarce public space by integrating the cost of carbon. The model has been enriched by taking into account captive users (non-elastic) of the private car. This chapter should be useful for policy-makers since the public debate about the removal of roads in today's cities shows extreme positions, each party suggesting that its choices are obvious. Some argue that climate issues justify a major reform of the organization of cities. Others contend that the corresponding roads are widely used and that their removal surely comes at high cost. In reality, the road paradoxes suggest that the problem is more complex.

Our findings are fourfold. First, the idea of a drastic adjustment is at the heart of the model. In fact, by introducing individuals who can refer to alternative modes to car transportation, a jump occurs at the optimal road level. For certain values of public space, increasing the road capacity attracts non-captives on the road when they could have been using alternative means of transportation for an equivalent travel time. These roads are then of no interest. Second, we show how incentive pricing, that includes pollution externalities, can be used to improve the quality of service provided to road captives. However, this does not mean that any level of infrastructure could be legitimate if well-regulated because the opportunity cost of public space must be taken into account. Third, we compare two alternative strategies which are decarbonation through road reassessment or vehicle regulations. We then show that reallocating the urban expressways is preferable if the cost of using polluting means of transportation is higher than the abatement cost of pollution when adjusting the road infrastructure to road captives only. Last, we demonstrate that captives and non-captives of the car are equally impacted, the differences being capitalized in the land rents.

**Methodology.** We build a theoretical model with 2 types of individuals: the road captives and non-captives. On top of congestion, we introduce pollution externalities generated by road users.

The model is built around the Downs paradoxes<sup>2</sup> where climate issues are added. When the costs of air pollution are included, some extra roads become harmful (instead of just being useless), since some non-captives are attracted by the road and contribute not only to congestion but also to pollution, which worsens the paradox.<sup>3</sup>

**Contributions.** This paper contributes to several strands of the transportation and urban literature. To begin with, there is a large and growing literature developed around the theory of congestion and road equilibrium in the attempt to understand the dynamics of road traffic (Arnott, 2013; Arnott et al., 1993; Braid, 1996; Gonzales and Daganzo, 2012; Tabuchi, 1993; Vickrey, 1969), most of which strengthens the idea of tolling efficiency. However, the existing papers (i) only focus on access to the hyper-core area (ii) consider elastic road traffic demand, and (iii) do not take into account the acceptability of congestion charging. Yet, it is almost impossible to design a congestion charging scheme that is beneficial to any user group (Nakamura and Kockelman, 2002), which may create public tension. This being said, the costs of implementation and the problems of acceptability of congestion charging make it a solution that is likely to remain restricted to the business centers of the largest cities for some time to come. Above all, its primary motivation is congestion, whereas it is the decarbonation of cities that is driving current thinking. From this perspective, it is appropriate to analyze more generally how taking climate change into account justifies the re-examination of urban expressways, as is being undertaken in various metropolises. Second, a lot of studies have focused on measuring the effect of the supply of roads on traffic. Goodwin (1996) provides a synthesis of a wide range of evidence which identifies the so-called "induced-demand". In a similar vein, Duranton and Turner (2011b) document the effect of lane kilometers of roads on vehicle-kilometers traveled, showing that increasing the provision of roads is unlikely to relieve traffic congestion. While all of these papers reinforce the accuracy of road paradoxes when the road supply is increased, no study

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<sup>2</sup>The Downs Paradox states that improvements in the road network will not reduce traffic congestion.

<sup>3</sup>Of course, such configurations are described as paradoxical because it goes without saying that not all urban roads are useless. However, the situation has tended to stabilize, as cases of obvious uselessness have been reduced, either because of infrastructure development or regulation: access control to limit congestion, dynamic management of the number of lanes or better use of them, and, of course, road pricing.

has been found to this date on the role road paradoxes play when road capacity is reduced. Yet, most cities are now reassessing some roads in the aim of freeing up public space. It is therefore crucial to understand what mechanisms are at stakes once the road supply is adjusted downward. Finally, some papers have looked at grounded theory to estimate discrete transportation choice models (Ben-Akiva et al., 1985; de Palma and Picard, 2005; Domencich and McFadden, 1975; McFadden, 1976) where travelers are rational who are said to weigh the comparative travel times, costs, and other attributes when deciding which means of transportation they should opt for. This type of model is very hierarchical between the different stages (mode of transport, departure time, route choice) and its main shortcoming is that it is unfortunately not adapted to respond to non-conventional policies.

## **Chapter 2 - Displacing Congestion: Evidence from Paris**

Road-reduction policies have been widely spread across the developed metropolitan world (New York City, Seoul, Madrid, Oslo, San Francisco, Paris...) with a common goal of reducing the space occupied by private cars in a city and encouraging greener means of transportation. On the one hand, if the policy succeeds in reducing the overall number of cars in a city by initiating a shift to other means of transportation, it would be possible to observe an overall pollution decrease. On the other hand, in the absence of credible alternatives, traffic is likely to divert to other roads. Depending on how and where traffic is reallocated, the impacts on congestion and pollution might be increased and some residents might suffer from higher levels of negative externalities. As such, the overall benefits of this policy remain an open question. This chapter aims at filling that gap by providing some answers that would help us understand the different impacts of a road supply reduction.

I exploit a reform in Paris where a 3.3-km segment of the expressway along the Seine's right riverbank, the "Voie Georges Pompidou" (hereafter GP) got pedestrianized on September 1, 2016. Results suggest that traffic and pollution were displaced to (more) congested roads inside the city and at the periphery, lowering the average speed by over 15%. These reduced-form results are quantitatively consistent with a calibrated model of shortest route choice, which

confirms other suggestive evidence of a very limited mode switch. Overall, 90% of the pollution cost is borne by lower-income residents around the ring road, who live far away from the new amenity created by the closure and mostly outside the jurisdiction responsible for the closure decision. These results are of interest on two aspects. First, from a theoretical point of view, they suggest that, even if car usage were to decrease in the short-run, a road closure might still generate consequent costs in commuting time and air pollution if (some) traffic is displaced to (more) congested roads. The explanation behind this stems from the non-linear relationship between traffic flows and congestion: a small input can be greatly magnified if the road is already highly congested. Second, from a policy point of view, I provide several counterfactual scenarios suggesting a course for implementing less harmful closures.

**Methodology.** The biggest challenges when evaluating a change in the road supply are accounting for (i) network effects (ii) simultaneity, and (iii) selection. These issues make it arduous to find the best setting in which the impact of a road closure on traffic can be causally identified and isolated from any other alteration in the city. This chapter overcomes these challenges by exploiting the 2016 closure of the Voie Georges Pompidou, a one-way expressway crossing downtown Paris. To evaluate the causal impact of this policy, I rely on a difference-in-difference strategy based on the direction and the timing of traffic, which I implement on detailed road-sensor data.

**Contributions.** This chapter builds on and contributes to several strands of literature.

First, road reduction is part of a wide array of congestion policies implemented in cities, which have been studied in numerous works (Adler and van Ommeren, 2016; de Grange and Troncoso, 2011; Gallego et al., 2013; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021; Kornhauser and Fehlig, 2003; Liu and McDonald, 1999; Santos et al., 2008; Tirachini and Hensher, 2012; Winston and Langer, 2006). Some cities such as Paris, have opted for quantity-rationing policies by gradually reducing their road capacity. In the case of Paris, the choice of road reduction rather than road pricing takes on a political dimension due to the low levels of consent to taxation among French car users. This chapter adds to this literature as it is, to the best of my knowledge,



the first paper to causally identify the impacts of a road-reduction policy on traffic and congestion in a city.

Second, ever since the Downs (1962) paradox, a general consensus in the literature has emerged, whereby increasing the road supply is unlikely to reduce congestion: *If you build it, they will come*. This principle, known as the *fundamental law of road congestion* comes from the induced-demand. Although the elasticity of traffic to roadway lane kilometers is well-known to be close to 1 in the literature (Duranton and Turner, 2011a), no study to this date has sought to evaluate the symmetry of such elasticity. The question that arises here is whether *reduced-demand* reacts the same way: *If you demolish it, will they not come?* There are many reasons to believe this elasticity is not symmetrical. I contribute to this literature by evaluating the short-run impacts of a road closure on traffic congestion. My results show that reducing the road capacity does not reduce congestion, at least in the short run.

Third, this paper provides causal estimates of a marginal change in the road supply on both congestion and air pollution. On one hand, there is an extensive literature documenting the relationship between road restrictions and traffic congestion (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003). On the other hand, a large body of work in urban studies and transportation economics is devoted to the quantification of the negative consequences of urban road traffic on health through pollutant emissions, although causal assessments are rather scarce (Anderson, 2020; Currie and Walker, 2011; Gibson and Carnovale, 2015; Prud'homme et al., 2011). A common finding of many studies is that congestion policies may only have a positive impact on air quality if they do not increase congestion on untargeted roads (Bhalla et al., 2014). For example, Davis (2008) shows that banning some drivers from using their cars in Mexico City failed to decrease the use of car, thus providing no evidence that the restrictions have improved air quality. However, results have yet to be combined into a setting that evaluates the impacts of a traffic policy on both of these externalities.

Last, this paper contributes to the literature on the characterization of traffic congestion. Engineering studies find a convex relationship between traffic volume and travel time which suggests large marginal costs when congestion is already high. Economists have focused on two

approaches to model congestion: the static speed-flow curve and the dynamic deterministic bottleneck model (See Small and Verhoef (2007) for a selected review of studies). Several papers have measured the effect of vehicle density on travel flows either on selected segments (Ardekani and Herman, 1987; Geroliminis and Daganzo, 2008) or for an entire city (Akbar and Duranton, 2017). In this paper, I use the congestion model developed by Akbar and Duranton (2017) and extend it to the case of a road closure. By estimating the congestion elasticity of each treated road, I am able to predict the impacts of a road closure on substitute roads.

### **Chapter 3 - Can Politicians Make People Drop Their Cars? (with Benoit Schmutz)**

The transportation sector is an important contributor to greenhouse gas emissions, and reducing car usage is crucial for mitigating the effects of climate change (European Environmental Agency, 2020; WHO, 2005). Municipalities play an important role in shaping transportation policies and promoting non-polluting transportation alternatives, but the implementation and effectiveness of these policies can depend on the political orientation of the municipality. In this paper, we examine the role of politicians in influencing the share of car commuters among all commuter types. Specifically, we investigate how the political orientation of a municipality affects the implementation of transportation policies that promote sustainable transportation options, and how these policies in turn impact car usage patterns. Using data from French municipalities on commuting patterns over a decade and municipalities elections, we provide evidence that the political color of a municipality influences the share of car commuters in the municipality.

Our study reveals that the share of car commuters declines significantly faster (by 1 percentage point) in municipalities with left-wing mayors compared to those with right-wing mayors. When analyzing only within-city commutes, this effect becomes more substantial (3.5 percentage points), which corresponds to a decrease of 5.7% in car usage compared to 2014. We also find a decrease in the number of cars owned by 1.1 p.p. The impact is stronger among out-of-the city commuters (-1.9 p.p.) and within-city commuters (-1.4 p.p.). However, these results are not statistically significant. Last, we test whether electing a left-wing mayor in close elections affects the share of car commuters homogeneously across all municipalities. Results suggest that the

impacts of electing a left- relative to right wing mayor is stronger (i) in larger cities, (ii) in municipalities with a lower initial share of car commuters and (iii) in municipalities with a higher share of net car migration.

**Methodology.** To identify the effects of elections on local policies, we follow Ferreira and Gyourko (2009) and use a regression discontinuity design analysis (RDD) that exploits quasi-random variations in the political affiliation of the mayor as a consequence of close elections. We focus on one election that occurred in 2014 and restrict the sample to municipalities for which information on the mode of transportation is available every year from 2006 to 2019 in the French census. Our sample is composed of 1,622 municipalities. In our sample, 781 elections were won by the left, and 841 by the right. Thus, our data allow us to investigate the effects of elections on the share of car commuters after the 2014 election.

**Contributions.** First, this paper contributes to the literature that seeks to understand the link between voting and public policies. In recent years, there have been several studies examining the factors that influence individuals to vote for environmentally friendly policies and candidates. Hoffmann et al. (2022) found that experiencing extreme weather conditions such as temperature anomalies, heat episodes or dry spells makes you more likely to vote for candidates who prioritize environmental policies. This is consistent with the findings of Baccini and Leemann (2021), who observe a positive association between experiencing a flood and pro-climate voting among individuals. A separate body of literature examines the relationship between transportation policies and voting behavior. For example, Hansla et al. (2017) investigate how the implementation of a congestion tax affects public opinion, while Colantone et al. (2022) assess the impact of a ban on polluting cars, implemented in Milan, on the probability of voting for a right-wing political party. In contrast, our study examines how political elections can influence transportation and environmental outcomes.

Second, many papers look at the impact of transportation policies on pollution and car-usage, in different contexts. For example, a large set of papers evaluates the impacts of road pricing on congestion and pollution , such as those conducted by Liu and McDonald (1999); Santos

et al. (2008); Tirachini and Hensher (2012); Winston and Langer (2006). Others look at the effectiveness of car bans during certain hours or days (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003) or at the impacts of urban rail-transit expansions (Adler and van Ommeren, 2016; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021). In our paper, we contribute to this literature by evaluating the aggregate effect of all traffic-calming policies done in a municipality through left-wing elections.

Finally, our study contributes to the existing literature on "Beggars-thy-neighbor" policies, particularly in the context of green policies. (Liu et al., 2022; Zhong and Pei, 2022). By distinguishing between into-the-city commuters and out-of-the-city commuters, we evaluate whether the election results have spatial spillover effects that could either benefit or harm neighboring areas.

# Introduction Générale

L'économie urbaine explore une série de sujets liés aux zones urbaines, notamment les déterminants de la croissance et du déclin des villes, les politiques de transport, le logement et les marchés immobiliers, la pauvreté et les inégalités en milieu urbain, les marchés du travail urbains ou les finances publiques locales. En analysant la dynamique économique des villes et les facteurs qui façonnent leur développement, l'économie urbaine aide les décideurs politiques à créer des environnements urbains durables et prospères. L'économie de l'environnement est un sous-domaine qui s'intéresse à l'impact économique des politiques visant à résoudre les problèmes environnementaux tels que le changement climatique, la pollution et l'épuisement des ressources naturelles.

Cette thèse se situe à l'intersection de l'économie urbaine et de l'économie de l'environnement et vise à mieux comprendre les déterminants et les impacts des politiques de transport urbain. Les deux premiers chapitres étudient les effets des fermetures de routes sur la congestion et la pollution, en utilisant des approches théoriques et empiriques. Le troisième chapitre examine les effets des élections politiques locales sur l'utilisation de la voiture.

L'introduction est divisée en quatre sections. La première section se concentre sur les deux principaux problèmes de transport abordés dans cette thèse : la congestion et la pollution de l'air. La deuxième section présente diverses théories économiques liées à la régulation de ces externalités. La troisième section aborde le cas urbain de Paris et décrit les différentes politiques de transport mises en œuvre pour lutter contre les effets négatifs de la circulation dans la ville. La dernière section donne une vue d'ensemble de chaque chapitre et souligne la contribution de la thèse à la littérature existante.

## **Congestion et Pollution : deux défis majeurs liés au trafic urbain**

Les transports motorisés privés peuvent avoir une série d'externalités négatives, c'est-à-dire des coûts qui ne sont pas directement supportés par ceux qui les causent (Arnott and Small, 1994). D'une part, la présence de voitures dans les villes peut provoquer des embouteillages qui peuvent à leur tour se traduire par des pertes de temps et une baisse de la productivité. Les embouteillages peuvent également limiter l'accès aux services publics (Afrin and Yodo, 2020). D'autre part, le transport motorisé privé est responsable de l'augmentation de la pollution de l'air, et les embouteillages peuvent entraîner une augmentation des émissions de gaz à effet de serre et d'autres polluants, ce qui peut menacer la santé publique.

Ces externalités négatives soulignent l'importance de mettre en œuvre des politiques de transport efficaces à mesure que les villes continuent à se développer et à évoluer. Bien que la conception et la mise en œuvre de politiques de transport efficaces puissent avoir des répercussions considérables sur l'économie, l'environnement et les inégalités sociales, trouver la bonne politique de transport reste un défi difficile à relever. En effet, la complexité et la diversité des environnements urbains, la présence de contraintes politiques et la transformation technologique croissante de l'industrie des transports rendent d'autant plus ardue l'identification d'interventions appropriées pour l'atténuation du changement climatique.

**La Congestion Urbaine** Les embouteillages surviennent lorsqu'il y a trop de véhicules sur les routes, ce qui ralentit les temps de déplacement, allonge les trajets et réduit la productivité des individus et des entreprises. C'est l'un des principaux problèmes auxquels la plupart des métropoles sont confrontées (Bull et al., 2003). Deux facteurs influencent généralement les embouteillages : le niveau micro et le niveau macro (Rao and Rao, 2012). Le niveau micro fait référence aux facteurs associés à la demande routière. Par exemple, de nombreuses personnes souhaitant se rendre au travail en même temps ou un nombre excessif de voitures pour un espace routier limité. Le niveau macro fait référence à tous les facteurs associés à l'offre routière tels que le nombre de routes disponibles. L'impact économique de la congestion est considérable. Selon des estimations, l'augmentation de la vitesse moyenne des voitures particulières

de 1 km/h et de celle des transports publics de 0,5 km/h entraînerait une réduction de la durée des trajets et des coûts d'exploitation équivalente à 0,1% du produit intérieur brut (PIB) (Bull and Thomson, 2002).

**La Pollution de l'Air** La pollution de l'air est un problème environnemental majeur, identifié par l'Organisation mondiale de la santé comme le plus grand risque environnemental pour la santé dans le monde (WHO, 2016). Le trafic urbain contribue de manière significative à la pollution globale de l'air dans les villes. Les véhicules motorisés émettent une variété de polluants tels que le dioxyde d'azote ou le monoxyde de carbone, qui peuvent constituer une grave menace pour la santé des individus. Il convient de noter que les embouteillages (ou les trafics importants) sont particulièrement néfastes pour la pollution de l'air. En effet, lorsque les navetteurs sont coincés dans les embouteillages, il arrive fréquemment qu'ils freinent et accélèrent. Lorsqu'un véhicule freine, il libère des particules et d'autres polluants dans l'air. Ainsi, les embouteillages ont tendance à produire des niveaux de pollution atmosphérique nettement plus élevés que la circulation normale. La pollution atmosphérique est responsable de la mort d'environ 4,2 millions de personnes par an (WHO, 2022). À cet égard, l'OMS a mis en place des lignes directrices sur la qualité de l'air pour plusieurs polluants, afin de servir de référence aux gouvernements pour mesurer et évaluer les niveaux de qualité de l'air dans leurs régions respectives. Les niveaux de qualité de l'air se sont améliorés au fil des années, bien que de nombreuses régions soient encore au-dessus des niveaux recommandés. L'introduction des véhicules électriques sur le marché des transports joue sans aucun doute un rôle crucial dans le maintien de la qualité de l'air en deçà des limites fixées. En effet, les VE ne produisent aucune émission de gaz d'échappement. En d'autres termes, ils n'émettent pas de polluants tels que les particules ou les oxydes d'azote. Bien entendu, les VE ne peuvent pas résoudre entièrement le problème de la pollution atmosphérique associée aux transports, car ils dépendent de plusieurs facteurs tels que la source d'électricité utilisée pour les recharger, le processus de fabrication, etc.

## La Régulation du Trafic

La littérature sur l'économie des transports a identifié une panoplie d'instruments politiques qui peuvent être utilisés pour lutter contre les externalités causées par le trafic. Souvent, ces réglementations peuvent être classées en deux catégories : les politiques axées sur la demande et les politiques axées sur l'offre.

**Les Politiques Axées sur la Demande** Du côté de la demande, la tarification routière (ou tarification de la congestion) est généralement l'outil le plus populaire (Liu and McDonald, 1999; Santos et al., 2008; Tirachini and Hensher, 2012; Winston and Langer, 2006). Il s'agit d'un instrument qui fait payer les conducteurs pour l'utilisation des routes. Elle peut être mise en œuvre pendant les heures de pointe, lorsque les embouteillages sont les plus importants, ou pendant toute la journée. Son objectif est de responsabiliser les conducteurs pour les externalités négatives qu'ils causent, telles que la pollution de l'air et la congestion. Le problème réside dans le fait que les effets de ces externalités ne se limitent pas à ceux qui en sont responsables, et que d'autres sont obligés de respirer l'air pollué. En tarifant les routes, les gouvernements espèrent décourager l'utilisation inutile de la voiture, encourager le covoiturage, inciter à l'utilisation des transports publics ou même déplacer les déplacements vers les heures creuses. Cet instrument a été utilisé dans de nombreuses villes telles que Londres, Stockholm, Singapour ou Milan.

**Les Politiques Axées sur l'Offre** Du côté de l'offre, il existe une plus grande variété de politiques. Une politique possible consiste à augmenter le nombre d'alternatives au transport automobile en mettant en place de nouvelles lignes de métro (Yang et al., 2018) ou en multipliant le nombre de pistes cyclables et de voies de bus (New York, Pékin, Toronto). L'objectif de ces politiques est d'augmenter le coût relatif de l'utilisation de la voiture par rapport aux autres solutions. Certaines villes comme Pékin ou Mexico ont eu recours au rationnement de l'espace routier en limitant les jours ou les heures pendant lesquels les automobilistes peuvent circuler sur les routes encombrées (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003). D'autres, dont Paris, ont opté pour un rationnement quantitatif en réduisant

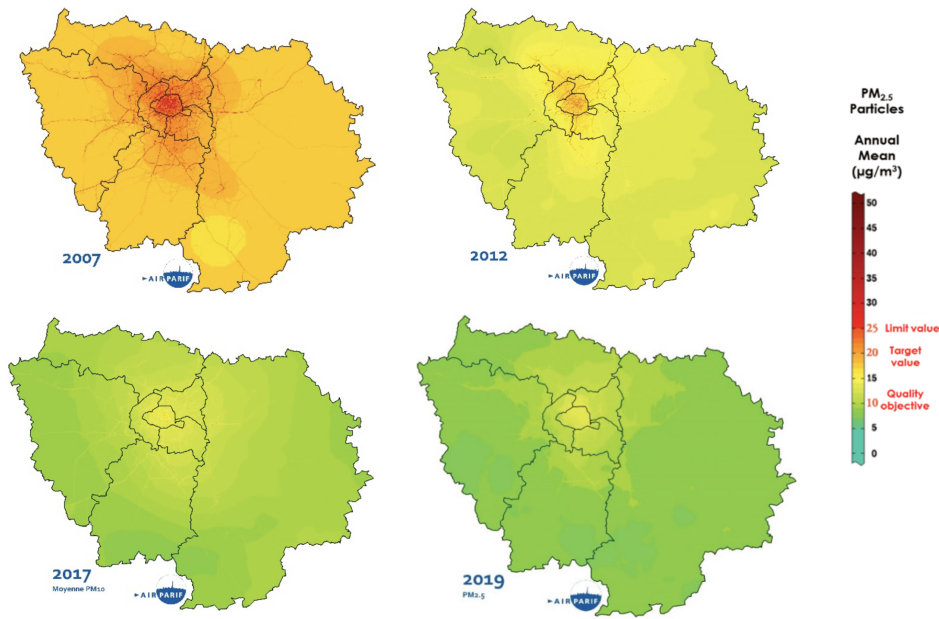


progressivement leur capacité routière. Par exemple, Séoul a transformé son autoroute principale en boulevard urbain (Kang and Cervero, 2009) tandis que New York a utilisé des voies réservées aux véhicules à haut taux d'occupation (Poole Jr and Orski, 2000), c'est-à-dire des voies conçues sur les autoroutes ou les routes urbaines et réservées aux véhicules ayant un certain nombre minimum d'occupants. Ces politiques visent à encourager le covoiturage et à promouvoir l'utilisation de modes de transport plus durables. Il est important de noter que l'ajout de routes, de ponts et d'autoroutes dans les zones urbaines n'est pas forcément une solution bénéfique à long terme et pourrait même aggraver la congestion du trafic. (Downs, 1962; Durranton and Turner, 2011a) en attirant des usagers supplémentaires sur la route. Au contraire, la suppression de la capacité routière est le nouvel instrument que de nombreuses villes ont récemment utilisé dans l'espoir de décourager les usagers existants. Cependant, on sait peu de choses sur l'efficacité des politiques de réduction des routes. C'est l'objet des chapitres 1 et 2 de cette thèse.

## **Le Cas de Paris**

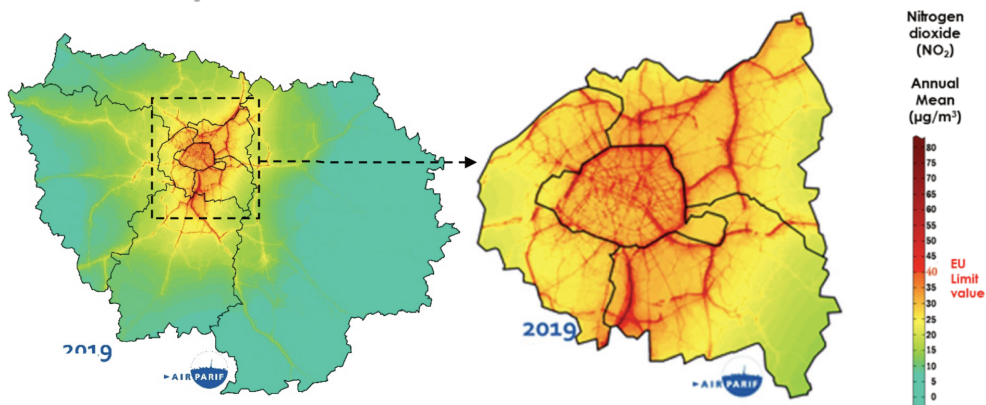
La tendance de la pollution à Paris est à la baisse ces dernières années. Selon les données du réseau Airparif, qui surveille la qualité de l'air en région parisienne, la concentration de particules fines (PM10 et PM2,5) a diminué de manière significative depuis 2007.

Comme le montre la Figure 3, on observe une baisse significative des concentrations de  $PM_{2,5}$  de 2007 à 2019.



**Figure 3:** Concentrations moyennes annuelles de particules fines de 2007 à 2019 en région parisienne (Source: AirParif)

Cependant, bien que l'évolution de la pollution atmosphérique soit prometteuse, on observe de fortes concentrations de  $NO_2$  en région parisienne. Ces concentrations sont particulièrement élevées - et supérieures au seuil recommandé - à proximité des grands axes routiers (see Figure 4); mettant en évidence des niveaux élevés d'émissions de véhicules.



**Figure 4:** Concentrations moyennes annuelles de dioxyde d'azote en région parisienne en 2019 (Source: AirParif)

Ces préoccupations ont conduit le maire de la ville, Anne Hidalgo, à mettre en œuvre plusieurs modifications urbaines visant à réduire le trafic et la pollution. Ces changements comprennent

la création de plus de 700 km de pistes cyclables, l'introduction d'une zone à faibles émissions pour restreindre l'accès aux véhicules les plus polluants dans certaines zones, la mise en place de journées sans voiture et la piétonisation de plusieurs zones: la route longeant la Seine étant la plus emblématique. C'est cette politique que j'utiliserai comme étude de cas dans le chapitre 2 pour évaluer empiriquement les impacts des politiques de réduction des routes.

Sachant que la tarification routière est considérée dans la littérature économique comme la solution la plus efficace pour traiter les externalités du trafic, on peut se demander pourquoi Paris ne l'a pas envisagée. En fait, la tarification routière est souvent une question controversée. Certains pourraient la considérer comme une taxe injuste pour les conducteurs qui pourrait avoir un impact disproportionné sur les ménages à faible revenu. Ce scénario a déjà été observé à Paris : Lorsque le président Macron a pris la décision d'imposer une taxe sur l'essence, cela s'est retourné contre lui et les Gilets Jaunes n'ont pas tardé à réagir et à provoquer des troubles dans le pays. (Boyer et al., 2020). La crainte de voir l'histoire se répéter pourrait rendre les décideurs politiques réticents à l'idée d'imposer une quelconque forme de tarification routière.

Le nombre élevé d'automobilistes entrant dans Paris a incité le maire de la ville à envisager diverses méthodes pour réguler le trafic extérieur et protéger les résidents (et les électeurs) des conséquences négatives de la congestion. Cette dimension politique est explorée dans le troisième chapitre de cette thèse, où j'étudie les impacts des élections politiques dans les municipalités françaises sur l'utilisation de la voiture.<sup>4</sup> Toutefois, il est important de considérer que le coût de ces politiques peut ne pas être réparti de manière égale au sein de la population, et que les ménages à faibles revenus peuvent supporter une part disproportionnée du coût si aucune autre solution n'est proposée. Cet aspect est examiné plus en détail au chapitre 2.

## **Cette Thèse**

Cette thèse s'appuie sur trois essais économiques portant sur les implications théoriques des politiques de réduction du trafic routier (chapitre 1), l'évaluation empirique de ces politiques (chapitre 2) et l'influence des partis politiques sur l'utilisation de la voiture (chapitre 3). Mon tra-

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<sup>4</sup>J'exclus Paris de l'analyse pour plusieurs raisons mentionnées au chapitre 3.

vail mêle théorie et empirique afin de mieux comprendre les déterminants et les conséquences des politiques de transport. Alors que le chapitre 1 utilise des cadres théoriques urbains, les deux autres chapitres mobilisent des données telles que les données des capteurs routiers (chapitre 2), ou un échantillon de municipalités françaises et des informations détaillées sur les schémas de déplacement domicile-travail (chapitre 3). L'objectif de cette thèse est double. Premièrement, évaluer les impacts de la réduction des routes sur la pollution et la congestion en fournissant un cadre théorique qui détermine dans quels cas la suppression des voies express dans les villes est bénéfique (chapitre 1) ; et en évaluant empiriquement la piétonisation des berges "Georges Pompidou" à Paris sur la pollution et la congestion (chapitre 2). Deuxièmement, comprendre comment les partis politiques peuvent influencer l'utilisation de la voiture en examinant les élections rapprochées dans les municipalités françaises (chapitre 3). Dans ce qui suit, je résume les trois chapitres de cette thèse en mettant l'accent sur les méthodes utilisées et les contributions à la littérature.

### **Chapitre 1 - Quand faut-il supprimer les routes urbaines pour réduire les émissions de carbone ? (avec Dominique Bureau)**

Les péages urbains sont depuis longtemps préconisés pour remédier aux externalités négatives associées à la voiture en ville (Parry and Bento, 2002; Vickrey, 1969). Cependant, sa motivation première est de traiter les externalités de la congestion. Aujourd'hui, c'est le *décarbonation* des villes qui alimente le débat. Dans cette perspective, il convient d'analyser plus généralement comment la prise en compte du changement climatique justifie la réévaluation des voies rapides urbaines tel qu'il a été entrepris dans diverses métropoles. Ce chapitre (en collaboration avec Dominique Bureau), propose un modèle théorique visant à fournir un cadre pour déterminer quand il est approprié de supprimer des routes dans un contexte de rareté de l'espace public et en intégrant le coût du carbone. Le modèle a été enrichi par la prise en compte des utilisateurs captifs (non élastiques) de la voiture. Ce chapitre devrait être utile aux décideurs politiques car le débat public sur la suppression des routes dans les villes d'aujourd'hui montre des positions

extrêmes, chaque partie suggérant que ses choix sont évidents. Certains affirment que les questions climatiques justifient une réforme majeure de l'organisation des villes. D'autres affirment que les routes correspondantes sont largement utilisées et que leur suppression a sûrement un coût élevé. En réalité, les paradoxes routiers suggèrent que le problème est plus complexe.

Nos conclusions sont au nombre de quatre. Premièrement, l'idée d'un ajustement drastique est au cœur du modèle. En effet, en introduisant des individus qui peuvent se référer à des modes alternatifs à la voiture, un saut se produit au niveau optimal de la route. Pour certaines valeurs de l'espace public, l'augmentation de la capacité routière attire des non-captifs sur la route alors qu'ils auraient pu utiliser des moyens de transport alternatifs pour un temps de trajet équivalent. Ces routes ne présentent alors aucun intérêt. Deuxièmement, nous montrons comment la tarification incitative, qui inclut les externalités de la pollution, peut être utilisée pour améliorer la qualité du service fourni aux captifs de la route. Toutefois, cela ne signifie pas que n'importe quel niveau d'infrastructure pourrait être légitime s'il était bien réglementé, car le coût d'opportunité de l'espace public doit être pris en compte. Troisièmement, nous comparons deux stratégies alternatives, à savoir la décarbonation par le biais d'une réévaluation des routes ou d'une réglementation des véhicules. Nous montrons ensuite que la réaffectation des voies rapides urbaines est préférable si le coût de l'utilisation de moyens de transport polluants est plus élevé que le coût de réduction de la pollution lors de l'ajustement de l'infrastructure routière aux seuls captifs routiers. Enfin, nous démontrons que les captifs et les non-captifs de la voiture sont également affectés, les différences étant capitalisées dans les rentes foncières.

**Méthodes.** Nous construisons un modèle théorique avec deux types d'individus : les captifs de la route et les non-captifs. En plus de la congestion, nous introduisons des externalités de pollution générées par les usagers de la route. Le modèle est construit autour des paradoxes de Downs<sup>5</sup> en ajoutant les questions climatiques. Lorsque les coûts de la pollution atmosphérique sont inclus, certaines routes supplémentaires deviennent nuisibles (au lieu d'être simplement inutiles), car certains non-captifs sont attirés par la route et contribuent non seulement à la

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<sup>5</sup>Le paradoxe de Downs affirme que les améliorations du réseau routier ne réduiront pas la congestion du trafic.

congestion mais aussi à la pollution, ce qui aggrave le paradoxe.<sup>6</sup>

**Contributions.** Ce chapitre contribue à plusieurs volets de la littérature sur les transports et l'urbanisme. Tout d'abord, il existe une littérature importante et croissante développée autour de la théorie de la congestion et de l'équilibre routier dans le but de comprendre la dynamique du trafic routier (Arnott, 2013; Arnott et al., 1993; Braid, 1996; Gonzales and Daganzo, 2012; Tabuchi, 1993; Vickrey, 1969), dont la plupart renforce l'idée de l'efficacité des péages. Cependant, les papiers existants (i) se concentrent uniquement sur l'accès à la zone hypercentre (ii) considèrent une demande élastique du trafic routier, et (iii) ne prennent pas en compte l'acceptabilité de la tarification de la congestion. Cependant, il est pratiquement impossible de concevoir un système de tarification de la congestion qui soit bénéfique à tous les groupes d'utilisateurs (Nakamura and Kockelman, 2002), ce qui risque de créer des tensions au sein de la population. Cela dit, les coûts de mise en œuvre et les problèmes d'acceptabilité du péage urbain en font une solution qui risque de rester limitée aux centres d'affaires des plus grandes villes pendant un certain temps encore. Surtout, sa motivation première est la congestion, alors que c'est la décarbonation des villes qui anime les réflexions actuelles. Dans cette perspective, il convient d'analyser plus généralement comment la prise en compte du changement climatique justifie la réévaluation des voies rapides urbaines, comme cela est entrepris dans différentes métropoles. Deuxièmement, de nombreuses études se sont dévouées à mesurer l'effet de l'offre de routes sur le trafic. Goodwin (1996) fournit une synthèse d'un large éventail de données qui identifient ce que l'on appelle la "demande induite". Dans le même ordre d'idées, Duranton and Turner (2011b) documentent l'effet des kilomètres de voies routières sur les véhicules-kilomètres parcourus, montrant qu'il est peu probable que l'augmentation de l'offre de routes réduise la congestion du trafic. Alors que tous ces papiers confirment l'exactitude des paradoxes routiers lorsque l'offre de routes est accrue, aucune étude n'a été trouvée à ce jour sur le rôle que jouent les paradoxes routiers lorsque la capacité des routes est réduite. Pourtant, la plupart des villes

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<sup>6</sup>Bien sûr, ces configurations sont qualifiées de paradoxales car il va de soi que toutes les voies urbaines ne sont pas inutiles. Cependant, la situation tend à se stabiliser, les cas d'inutilité manifeste se réduisant, soit par le développement des infrastructures, soit par la réglementation : contrôle d'accès pour limiter la congestion, gestion dynamique du nombre de voies ou meilleure utilisation de celles-ci, et, bien sûr, tarification routière.

réévaluent actuellement certaines routes dans le but de libérer l'espace public. Il est donc crucial de comprendre quels sont les mécanismes en jeu lorsque l'offre routière est ajustée à la baisse. Enfin, certains articles se sont penchés sur la théorie ancrée pour estimer les modèles de choix discrets en matière de transport (Ben-Akiva et al., 1985; de Palma and Picard, 2005; Domencich and McFadden, 1975; McFadden, 1976) où les voyageurs sont rationnels et sont censés peser les temps de trajet comparatifs, les coûts et d'autres attributs lorsqu'ils décident du moyen de transport qu'ils doivent choisir. Ce type de modèle est très hiérarchisé entre les différentes étapes (mode de transport, heure de départ, choix de l'itinéraire) et son principal défaut est qu'il n'est malheureusement pas adapté pour répondre à des politiques non conventionnelles.

## **Chapitre 2 - Déplacer la Congestion : L'expérience de Paris**

Les politiques de réduction de la voirie ont été largement répandues dans le monde métropolitain développé (New York, Séoul, Madrid, Oslo, San Francisco, Paris...) avec pour objectif commun de réduire l'espace occupé par les voitures particulières dans une ville et d'encourager des moyens de transport plus écologiques. D'une part, si la politique réussit à réduire le nombre total de voitures dans une ville en initiant un transfert vers d'autres moyens de transport, il serait possible d'observer une diminution globale de la pollution. D'autre part, en l'absence d'alternatives crédibles, le trafic est susceptible d'être détourné vers d'autres routes. En fonction de la manière dont le trafic est réaffecté et de l'endroit où il l'est, les effets sur la congestion et la pollution pourraient être accrus et certains résidents pourraient souffrir de niveaux plus élevés d'externalités négatives. En tant que tels, les avantages globaux de cette politique restent une question ouverte. Ce chapitre vise à combler cette lacune en apportant des réponses qui nous aideraient à comprendre les différents impacts d'une réduction de l'offre routière.

J'exploite une réforme à Paris où un segment de 3,3 km de la voie express le long de la rive droite de la Seine, la "Voie Georges Pompidou" (ci-après GP), a été piétonnisé le 1er septembre 2016. Les résultats suggèrent que le trafic et la pollution ont été déplacés vers des routes (plus) congestionnées à l'intérieur de la ville et à la périphérie, réduisant la vitesse moyenne de plus de 15%. Ces résultats de forme réduite sont quantitativement cohérents avec un modèle calibré de

choix de l'itinéraire le plus court, qui confirme d'autres preuves suggestives d'un changement de mode très limité. Dans l'ensemble, 90% du coût de la pollution est supporté par les résidents à faible revenu vivant autour du périphérique, qui habitent loin des nouvelles aménités créées par la fermeture et, pour la plupart, en dehors de la juridiction responsable de la décision de fermeture. Ces résultats sont intéressants à deux égards. Premièrement, d'un point de vue théorique, ils suggèrent que, même si l'utilisation de la voiture devait diminuer à court terme, la fermeture d'une route pourrait encore générer des coûts conséquents en termes de temps de trajet et de pollution de l'air si (une partie) du trafic est déplacée vers des routes (plus) congestionnées. Cela s'explique par la relation non linéaire entre les flux de trafic et la congestion : une petite contribution peut être considérablement amplifiée si la route est déjà très encombrée. Deuxièmement, d'un point de vue politique, je propose plusieurs scénarios contrefactuels suggérant une marche à suivre pour mettre en œuvre des fermetures moins dommageables.

**Méthode.** Les plus grands défis lors de l'évaluation d'un changement dans l'offre routière sont la prise en compte (i) des effets de réseau (ii) de la simultanéité, et (iii) de la sélection. Ces questions font qu'il est difficile de trouver le meilleur cadre dans lequel l'impact d'une fermeture de route sur le trafic peut être identifié de manière causale et isolé de toute autre modification dans la ville. Ce chapitre relève ces défis en exploitant la fermeture en 2016 de la Voie Georges Pompidou, une voie express à sens unique traversant le centre de Paris. Pour évaluer l'impact causal de cette politique, je m'appuie sur une stratégie de différence en différence basée sur la direction et le moment du trafic, que je mets en œuvre sur des données détaillées de capteurs routiers.

**Contributions.** Ce chapitre s'appuie sur plusieurs sources de documentation et y contribue.

Tout d'abord, la réduction des routes fait partie d'un large éventail de politiques de congestion mises en œuvre dans les villes, qui ont été étudiées dans de nombreux ouvrages (Adler and van Ommeren, 2016; de Grange and Troncoso, 2011; Gallego et al., 2013; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021; Kornhauser and Fehlig, 2003; Liu and McDonald, 1999; Santos et al., 2008; Tirachini and Hensher, 2012; Winston and Langer, 2006). Certaines villes, comme



Paris, ont opté pour des politiques de rationnement quantitatif en réduisant progressivement leur capacité routière. Dans le cas de Paris, le choix de la réduction des routes plutôt que de la tarification revêt une dimension politique en raison du faible niveau de consentement à la taxation parmi les automobilistes français. Ce chapitre apporte une contribution à cette littérature puisqu'il s'agit, à ma connaissance, du premier document à identifier de manière causale les impacts d'une politique de réduction des routes sur le trafic et la congestion dans une ville.

Deuxièmement, depuis le paradoxe de Downs (1962), un consensus général s'est dégagé dans la littérature, selon lequel il est peu probable que l'augmentation de l'offre routière réduise la congestion : *Si vous les construisez, ils viendront*. Ce principe, connu sous le nom de *loi fondamentale de la congestion routière*, découle de la demande induite. Bien que l'élasticité du trafic par rapport au nombre de kilomètres de voies routières soit connue pour être proche de 1 dans la littérature (Duranton and Turner, 2011a), aucune étude à ce jour n'a cherché à évaluer la symétrie de cette élasticité. La question qui se pose ici est de savoir si *la demande réduite* réagit de la même manière : *si vous démolissez, ne viendront-ils pas?* Il existe de nombreuses raisons de penser que cette élasticité n'est pas symétrique. Je contribue à cette littérature en évaluant les impacts à court terme d'une fermeture de route sur la congestion du trafic. Mes résultats montrent que la réduction de la capacité routière ne réduit pas la congestion, du moins à court terme.

Troisièmement, ce chapitre fournit des estimations causales d'un changement marginal de l'offre routière sur la congestion et la pollution de l'air. D'une part, il existe une littérature abondante qui documente la relation entre les restrictions routières et la congestion du trafic (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003). D'autre part, un grand nombre de travaux dans le domaine des études urbaines et de l'économie des transports sont consacrés à la quantification des conséquences négatives du trafic routier urbain sur la santé par le biais des émissions de polluants, bien que les évaluations causales soient plutôt rares (Anderson, 2020; Gibson and Carnovale, 2015; Prud'homme et al., 2011; ?). Une conclusion commune à de nombreuses études est que les politiques de congestion ne peuvent avoir un impact positif sur la qualité de l'air que si elles n'augmentent pas la congestion sur les

routes non ciblées (Bhalla et al., 2014). Cependant, les résultats n'ont pas encore été combinés dans un cadre qui évalue les impacts d'une politique de circulation sur ces deux externalités.

Enfin, ce document contribue à la littérature sur la caractérisation de la congestion du trafic. Des études révèlent une relation convexe entre le volume de trafic et le temps de déplacement, ce qui suggère des coûts marginaux importants lorsque la congestion est déjà élevée. Les économistes se sont concentrés sur deux approches pour modéliser la congestion : la courbe statique débit-vitesse et le modèle dynamique déterministe des goulets d'étranglement (voir Small and Verhoef (2007) pour une sélection d'études). Plusieurs articles ont mesuré l'effet de la densité des véhicules sur les flux de déplacements, soit sur des segments sélectionnés (Ardekani and Herman, 1987; Geroliminis and Daganzo, 2008), soit pour une ville entière (Akbar and Duranton, 2017). Dans ce chapitre, j'utilise le modèle de congestion développé par (Akbar and Duranton, 2017) et l'étend au cas d'une fermeture de route. En estimant l'élasticité de la congestion de chaque route traitée, je suis en mesure de prédire les impacts d'une fermeture de route sur les routes de substitution.

### **Chapitre 3 - Les politiciens peuvent-ils inciter les gens à abandonner leur voiture ? (avec Benoit Schmutz)**

Le secteur des transports contribue de manière importante aux émissions de gaz à effet de serre, et la réduction de l'utilisation de la voiture est cruciale pour atténuer les effets du changement climatique (European Environmental Agency, 2020; WHO, 2005). Les municipalités jouent un rôle important dans l'élaboration de la politique des transports et la promotion de solutions de transport non polluantes, mais la mise en œuvre et l'efficacité de ces politiques peuvent dépendre de l'orientation politique de la municipalité. Dans cet article, nous examinons le rôle des politiciens dans l'influence de la part des navetteurs en voiture. Plus précisément, nous étudions comment l'orientation politique d'une municipalité affecte la mise en œuvre de politiques de transport qui favorisent les options de transport durable, et comment ces politiques influencent à leur tour les schémas d'utilisation de la voiture. En utilisant les données des municipalités

françaises sur les habitudes de déplacement sur une décennie et les élections municipales, nous prouvons que la couleur politique d'une municipalité influence la part des navetteurs en voiture dans la municipalité. Notre étude révèle que la part des navetteurs en voiture diminue beaucoup plus rapidement (d'un point de pourcentage) dans les municipalités dirigées par des maires de gauche que dans celles dirigées par des maires de droite. Si l'on analyse uniquement les déplacements à l'intérieur de la ville, cet effet devient plus important (3,5 points de pourcentage), ce qui correspond à une diminution de 5,7% de l'utilisation de la voiture par rapport à 2014. Nous constatons également une diminution du nombre de voitures possédées de 1,1 p.p. L'impact est plus fort chez les navetteurs hors de la ville (-1,9 p.p.) et les navetteurs intra-urbains (-1,4 p.p.). Toutefois, ces résultats ne sont pas statistiquement significatifs. Enfin, nous testons si l'élection d'un maire de gauche lors d'élections serrées affecte la part des navetteurs en voiture de manière homogène dans toutes les municipalités. Les résultats suggèrent que l'impact de l'élection d'un maire de gauche par rapport à un maire de droite est plus fort (i) dans les grandes villes, (ii) dans les municipalités où la part initiale des navetteurs en voiture est plus faible et (iii) dans les municipalités où la part de la migration nette en voiture est plus élevée.

**Méthode.** Pour identifier les effets des élections sur les politiques locales, nous suivons Ferreira and Gyourko (2009) et utilisons une analyse de discontinuité de la régression (RDD) qui exploite les variations quasi-aléatoires de l'affiliation politique du maire à la suite d'élections rapprochées. Nous nous concentrons sur une élection qui a eu lieu en 2014 et nous restreignons l'échantillon aux municipalités pour lesquelles des informations sur le mode de transport sont disponibles chaque année de 2006 à 2019 dans le recensement français. Notre échantillon est composé de 1 622 communes. Dans notre échantillon, 781 élections ont été remportées par la gauche et 841 par la droite. Ainsi, nos données nous permettent d'étudier les effets des élections sur la part des navetteurs en voiture après les élections de 2014.

**Contributions.** Tout d'abord, ce chapitre contribue à la littérature qui cherche à comprendre le lien entre le vote et les politiques publiques. Ces dernières années, plusieurs études ont examiné les facteurs qui incitent les individus à voter pour des politiques et des candidats re-

spectueux de l'environnement. Hoffmann et al. (2022) a constaté que le fait de connaître des conditions météorologiques extrêmes, telles que des anomalies de température, des épisodes de chaleur ou des périodes de sécheresse, augmente la probabilité de voter pour des candidats qui accordent la priorité aux politiques environnementales. Ces résultats sont cohérents avec ceux de Baccini and Leemann (2021), qui observe une association positive entre le fait de subir une inondation et le vote en faveur du climat parmi les individus. Un autre type de littérature examine la relation entre les politiques de transport et le comportement électoral. Par exemple, Hansla et al. (2017) étudient comment la mise en œuvre d'une taxe sur les embouteillages affecte l'opinion publique, tandis que Colantone et al. (2022) évalue l'impact d'une interdiction des voitures polluantes, mise en œuvre à Milan, sur la probabilité de voter pour un parti politique de droite. En revanche, notre étude examine comment les élections politiques peuvent influencer les résultats en matière de transport et d'environnement.

Deuxièmement, de nombreux articles examinent l'impact des politiques de transport sur la pollution et l'utilisation de la voiture, dans différents contextes. Par exemple, un grand nombre d'études évaluent l'impact de la tarification routière sur la congestion et la pollution, comme celles menées par Liu and McDonald (1999); Santos et al. (2008); Tirachini and Hensher (2012); Winston and Langer (2006). D'autres s'intéressent à l'efficacité des interdictions de circulation automobile à certaines heures ou certains jours (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003) ou aux impacts de l'expansion des transports ferroviaires urbains (Adler and van Ommeren, 2016; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021). Dans notre étude, nous contribuons à cette littérature en évaluant l'effet global de toutes les politiques de réduction de la circulation mises en œuvre dans une municipalité à l'occasion d'élections de gauche.

Enfin, notre étude contribue à la littérature existante sur les politiques de "chacun pour soi", en particulier dans le contexte des politiques vertes. (Liu et al., 2022; Zhong and Pei, 2022). En faisant la distinction entre les navetteurs qui se rendent dans la ville et ceux qui en sortent, nous évaluons si les résultats des élections ont des effets de débordement spatial qui pourraient bénéficier ou nuire aux zones voisines.

# Chapter 1

## When Should Urban Roads be Removed to Lower Carbon Emissions?<sup>1</sup> (with Dominique Bureau)

### Abstract

The public debate about the removal of roads in a city shows extreme positions, each party suggesting that the choices are obvious. Some argue that climate issues justify a major reform of the organization of cities. Others observe that the corresponding roads are widely used and that their removal surely comes at high cost. However, the road paradoxes suggest that the problem is more complex. In this sense, one might wonder to what extent should the road supply be reduced. In this paper, we develop a theoretical model aiming at providing a framework for determining the cases in which the removal of express roads may be justified in the context of cities *decarbonization*. In addition to the possibilities of mode switch and the scarcity of public space, its specificity is based on the introduction of two groups of users: the "captives" of the car (or inelastic car-commuters) who do not have access to alternative solutions, and the "non-captives" (elastic car-commuters) who can switch to other modes of transport (public transport or new alternative modes). By introducing pollution externalities in the model, we show that in some cases, a marginal reduction in the road supply can increase the welfare cost. As such, the idea of a drastic adjustment is at the heart of the model.

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<sup>1</sup>This paper has benefited from comments by Geoffrey Barrows, Pierre Boyer, Heloise Clolery, Julien Combe, Patricia Crifo, Xavier D'Haultfoeuille, Gilles Duranton, Antoine Ferey, Francis Kramartz, Raphael Lafrogne-Joussier, Guillaume Monchambert, Mathis Nunez, Laurent Linnemer, Bérangère Patault, Benoit Schmutz, and Emmanuelle Taugourdeau as well as many seminar and conference participants.

## 1.1 Introduction

There is a growing consensus in reducing the carbon use in transport in cities. Designing the optimal road network for urban mobility plays a central role in reaching this kind of sustainability. Increasing alternatives to car transportation such as walking, cycling or public transportation is usually proposed to decrease CO<sub>2</sub> emissions (Brand et al., 2021). Yet, compelling people to switch to greener means of transportation remains a difficult challenge. To meet the target, the government can influence individuals' choices by increasing the road usage cost, either through imposing an urban toll or through reducing the road supply. While the former remains socially unacceptable and politically difficult to implement, the public debate about the latter shows extreme positions, each party suggesting that the choices are obvious. Some argue that climate issues justify a major reform of the organization of cities. Others observe that the corresponding roads are widely used and that their removal surely comes at high cost. In reality, it is more of a complex problem, as the choice of solutions does not only depend on many parameters such as technical performance of expressways, characteristics of the demand of different users or scarcity of public space but also on traffic coordination explained by the road paradoxes.

The topic is not new and road paradoxes motivate most public policies aimed at reducing roadways. The economics of congested road networks has shown that there are situations in which road infrastructure may be intrinsically unnecessary, in the sense that its removal would be beneficial regardless of the use that might be made of the space thus freed up; only because it would actually reduce travel time (Ding and Song, 2012).

Of course, these situations are described as paradoxical because it is clear that not all urban roads are useless and the closure of the 42nd Street in New York - which eased traffic flow in Manhattan despite being a busy street - shows that they are possible (Gina, 1990). These results come from the fact that the road equilibrium is not optimal, mainly because users choose their routes based only on their travel time and ignore how that choice adversely affects the travel conditions of other users, known as the "selfish Wardrop equilibrium" (Wardrop, 1952). Luckily -

and after bitter controversy some 30 years ago - the situation has tended to stabilize with fewer cases of obvious inefficiency, either as a result of infrastructure development or as a result of regulation: access control to limit congestion, dynamic management of the number of lanes or better use of lanes, and of course pricing.

Still, roads were built back when public transportation was not well developed and the debate about climate less present, only to meet a high demand of car commuters. However, with the increasing supply of alternatives to car and the important concern of climate change one might wonder whether some established roads should still exist today and whether their usage is not the pure result of an induced-demand. This paper fills this gap by evaluating the cases in which reducing road capacity is beneficial. To this end, we develop a simplified model focusing on the modal shift between road and public transport (or other alternative modes), in which the road infrastructure is re-evaluated to take into account the automobile pollution - including greenhouse gas emissions. The model is also designed to shed light on the impacts on captive car users who need to access the city center and have no alternative to the road.

This paper contributes to several strands of the transportation and urban literature. To begin with, there is a large and growing literature developed around the theory of congestion and road equilibrium in the attempt to understand the dynamics of road traffic (Arnott, 2013; Arnott et al., 1993; Braid, 1996; Gonzales and Daganzo, 2012; Tabuchi, 1993; Vickrey, 1969), most of which strengthens the idea of tolling efficiency. However, the existing papers (i) only focus on access to the hyper-core area (ii) consider elastic road traffic demand, and (iii) do not take into account the acceptability of congestion charging. Yet, it is almost impossible to design a congestion charging scheme that is beneficial to any user group (Nakamura and Kockelman, 2002), which may create public tension. This being said, the costs of implementation and the problems of acceptability of congestion charging make it a solution that is likely to remain restricted to the business centers of the largest cities for some time to come. Above all, its primary motivation is congestion, whereas it is the decarbonization of cities that is driving current thinking. From this perspective, it is appropriate to analyze more generally how taking climate change into account justifies the re-examination of urban expressways, as is being undertaken in various metropolises. Second,

a lot of studies have focused on measuring the effect of the supply of roads on traffic. Goodwin (1996) provides a synthesis of a wide range of evidence which identifies the so-called "induced-demand". In a similar vein, Duranton and Turner (2011b) document the effect of lane kilometers of roads on vehicle-kilometers traveled, showing that increasing the provision of roads is unlikely to relieve traffic congestion. While all of these papers reinforce the accuracy of road paradoxes when the road supply is increased, no study has been found to this date on the role road paradoxes play when road capacity is reduced. Yet, most cities are now reassessing some roads in the aim of freeing up public space. It is therefore crucial to understand what mechanisms are at stakes once the road supply is adjusted downward. Finally, some papers have looked at grounded theory to estimate discrete transportation choice models (Ben-Akiva et al., 1985; de Palma and Picard, 2005; Domencich and McFadden, 1975; McFadden, 1976) where travelers are rational who are said to weigh the comparative travel times, costs, and other attributes when deciding which means of transportation they should opt for. This type of model is very hierarchical between the different stages (mode of transport, departure time, route choice) and its main shortcoming is that it is unfortunately not adapted to respond to non-conventional policies.

Our findings are fourfold. First, the idea of a drastic adjustment is at the heart of the model. In fact, by introducing individuals who can refer to alternative modes to car transportation, a jump occurs at the optimal road level. For certain values of public space, increasing the road capacity attracts non-captives on the road when they could have been using alternative means of transportation for an equivalent travel time. These roads are then of no interest. Second, we show how incentive pricing, that includes pollution externalities, can be used to improve the quality of service provided to road captives. However, this does not mean that any level of infrastructure could be legitimate if well-regulated because the opportunity cost of public space must be taken into account. Third, we compare two alternative strategies which are decarbonation through road reassessment or vehicle regulations. We then show that reallocating the urban expressways is preferable if the cost of using polluting means of transportation is higher than the abatement cost of pollution when adjusting the road infrastructure to road captives only. Last, we demonstrate that captives and non-captives of the car are equally impacted, the differences being capitalized



in the land rents.

After presenting the model (Section 2) and studying how taking the climate into account reinforces the possibility of the Pigou-Knight-Downs paradox (Section 3), we study the performance of a decarbonization strategy based on such a rescaling and its impacts, notably territorial (Section 4). Then, we address the issue of the Parisian debates (Section 5). Finally, we conclude by discussing the limitations of such an analysis (Section 6).

## 1.2 Analytical Framework

We construct a theoretical model with 2 types of individuals: the road captives and non-captives. On top of congestion, we introduce pollution externalities generated by road users.

### 1.2.1 Basic assumptions

We consider a transportation problem within a central area served by both (i) a network of public transport, and (ii) road infrastructure. We assume that transport speeds are homogeneous within each mode and unit transport costs are homogeneous within the central area. From the user's point of view, the transport costs are written in terms of generalized costs per kilometer, which essentially reflect "monetized" travel time. For road transport, the cost per kilometer ( $\theta$ ) depends on traffic density and the level of infrastructure, for example the number of kilometers of expressways in the area ( $n$ ). Here, the use of car is responsible for congestion problems on other commuters. Noting  $Q$  the total traffic within the area in passenger-km, and  $y$  the (endogenous) share of road traffic, we assume a linear relationship between travel time and road use of the type:<sup>2</sup>

$$\theta(y, n) = \frac{byQ}{n} \quad (1.1)$$

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<sup>2</sup>We consider a cost of congestion that is increasing in the demand for road travel and decreasing in the number of lanes as suggested by Duranton and Turner (2011b).

with  $b > 0$ , a characteristic parameter of the relationship between traffic and average road speeds.

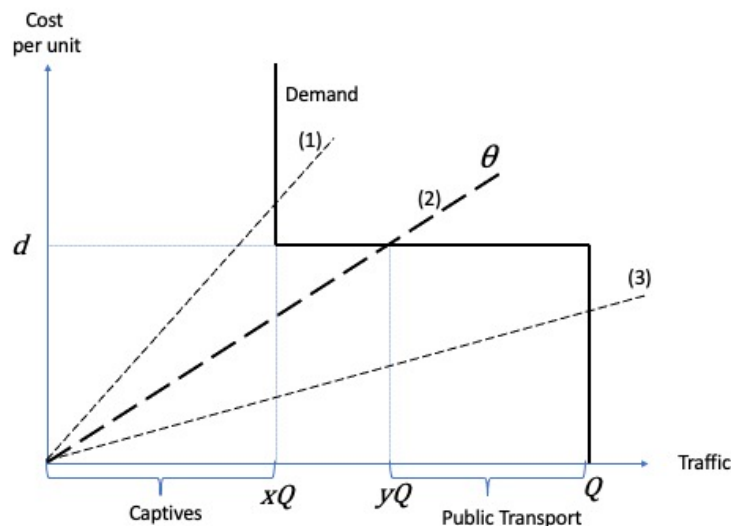
For public transport, we consider a constant cost per kilometer ( $d$ ).<sup>3</sup>

Assuming that pollutant emissions are proportional to road traffic and are associated to a unit social health and climate cost ( $\tau$ ), the social costs of transport use (TC) in this area are:

$$TC(y, n, \tau) = yQ(\theta(y, n) + \tau) + (1 - y)Qd \quad (1.2)$$

On the demand side, total traffic is assumed to be exogenous, and a share  $x$  is considered to be totally captive of the road. The non-captives choose their mode of transport by comparing the costs they would bear depending on the means of transportation selected<sup>4</sup>. In the absence of any pricing of road externalities (congestion and air pollution), the equilibrium of the transport system is therefore simply defined by the Nash-Wardrop conditions shown below (Figure 1.1).

**Figure 1.1:** Equilibrium of the transport system in the central area



Depending on the level of road infrastructure, three configurations are possible:

<sup>3</sup>In the short run, we could of course think of public transport congestion effects such as the ones described in de Palma et al. (2017). We disregard these effects since the public transport operator can adjust the frequencies to regulate the effects of congestion (Mohring, 1972) while the road is intrinsically subject to unregulated congestion.

<sup>4</sup>In this paper, we ignore the captives of public transportation.

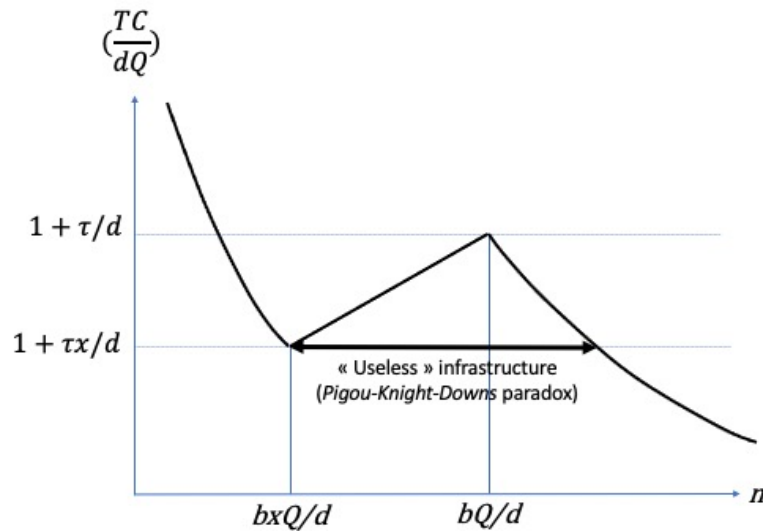
1. **Reduced road infrastructure.** Road traffic is restricted to captives. They incur higher costs per kilometer than non-captives, who opt for public transportation.
2. **Intermediate road infrastructure.** Non-captives are divided between the two modes, with the same unit costs for all users (captives and non-captives) equal to those of public transport.
3. **Large road infrastructure.** All users transfer to the road and benefit from a similar transport cost, lower than that of public transport.

The idea of the proposed exercise is to (i) start from a situation where the existing networks ( $n_0$ ) had been dimensioned without taking into account the issues related to air pollution -in particular CO<sub>2</sub> emissions- leading to an equilibrium of the latter type: "all road", and (ii) examine the suitable infrastructure adjustment when public policies now include the social costs of air pollution.

### 1.2.2 Optimal transport costs

Let us first ignore the value of the public space that may be freed up. The only costs that matter are the costs of transport use, borne by the users, and the associated pollution (Table 1.1).

The social costs of transportation vary according to the level of available expressways ( $n$ ) described in figure 1.2. This figure highlights an area of inefficiency (Pigou-Knight-Downs paradox) in which increasing the level of infrastructure actually increases the costs of transport use.

**Figure 1.2:** Generalized transport costs with respect to the level of road infrastructure

While the increase in the level of road infrastructure affects only the captives up to  $n = \frac{bxQ}{d}$ , a proportion of non-captives has an incentive to shift to the road when the level of road infrastructure exceeds this threshold. More precisely, for a given infrastructure, the transfer process continues until the road congestion is such that the average costs borne by users are equalized between modes at the level of the public transport cost. Thus, when non-captives split between the two modes, their access to that road is not actually beneficial. To reduce their transport cost, a higher level of infrastructure would be needed to provide a road usage cost lower than the one of public transport.

In the absence of external pollution costs, the total cost function therefore features a plateau between  $\frac{bxQ}{d}$  and  $\frac{bQ}{d}$ . In other words, if the existing infrastructure is in this range, there is no harm in reducing it to  $\frac{bxQ}{d}$ , neither for non-captives nor for captives. Indeed, the cost of transport for the captives in the reference situation was *in fine* determined by the congestion, which was in turn the result from the equilibrium with public transport for the non-captives.

When the costs of air pollution are included, the extra road becomes harmful, as the non-captives transferred to the road worsens the paradox. The range in which the inefficiency situ-

ation prevails is further extended to  $n = \frac{bQ}{d(1-\tau)}$ <sup>5</sup>. However, in this extended socially inefficient area, the downsizing of the road benefits the community because the gain in pollution is worth more than the loss in time. Note that the impact on the cost per kilometer borne by different users remains the same for non-captive and captive users as long as the level of equipment is not reduced below the  $n = \frac{bxQ}{d}$  threshold. Thus, a seemingly drastic adjustment of road supply to meet climate challenges should not be surprising in a context where road paradoxes are likely to prevail.

If  $n_0 \in ]\frac{bxQ}{d}, \frac{bQ}{d-(1-x)\tau}]$ , it is beneficial to bring the road supply back to  $n = \frac{bxQ}{d}$ . The corresponding transformation is Pareto-improving if  $n_0 \leq \frac{bQ}{d}$ . Otherwise, the reduction of damages related to air pollution outweighs the induced loss of time, which also affects both types of users.

This result is based on one particularly strong assumption: the inelasticity of road demands. However, we relax this assumption in Appendix 1.6.2 by taking a general form of the road demand and obtain similar results.

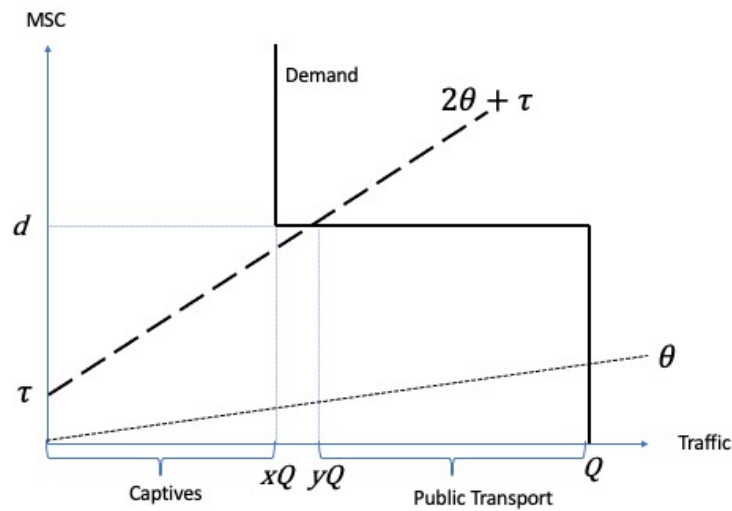
### 1.2.3 Congestion regulation

As mentioned in the introduction, road paradoxes are basically the result of users not taking into account the externalities to which they contribute: the impact on road congestion, which is the basis of the Pigou-Knight-Downs paradox at issue here; and the impact on air pollution (local and global), which thus aggravates it. Under these conditions, the previous result is valid only because we have ruled out the possibility of implementing an incentive road toll to internalize the costs of external damages in the behavior of users. In this case, this would consist of a kilometer-based toll summing the marginal external cost of congestion, here equal to  $\theta$ , and the unit cost of pollution  $\tau$ . The new equilibrium of the transportation system is described below (Figure 1.3).

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<sup>5</sup>If the denominator is negative, this means that the costs of pollution are so high (relative to the costs of public transport) that it is never justified to satisfy the demand of non-captives by road.

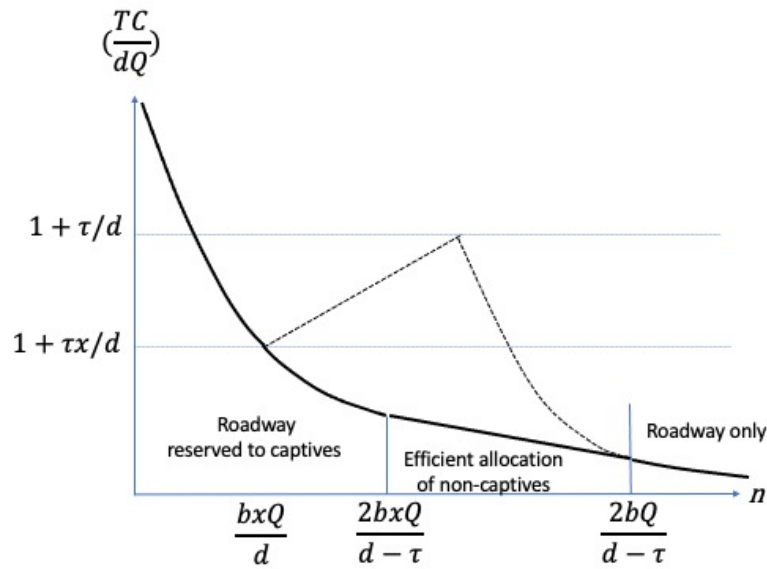
**Figure 1.3:** Equilibrium of the transport urban network with an urban toll  $\theta + \tau$



Provided that the pollution costs do not reach a level where any road transfer is socially harmful (i.e.,  $d > \tau$ ), in which case the road infrastructure should be restricted for captives only, the three previous possible configurations are recovered but with modified boundaries (see Table ??). The table also shows that the level of social user costs is reduced in the intermediate situation, because of the incentive regulation of road traffic which discourages excessive entry of non-captive users. In the extreme areas, the formulas are unchanged because the demands have been assumed to be inelastic: captive traffic in the first case; and total traffic in the third.

Figure 1.4 shows the resulting total social costs of transport as a function of  $n$ , and recalls the corresponding costs without incentive regulation.

**Figure 1.4:** Generalized transportation costs with an optimal toll



This figure shows, in particular, how incentive pricing can improve the quality of service provided to captive road users. However, road captives must also bear the burden of the toll, which explains the problems of acceptability that its implementation encounters since the social surplus that it generates benefits primarily the organization that collects the revenue. In order for it to be socially acceptable, it requires some form of redistribution of the surplus to potential losers.

In what follows, we assume that this instrument has been discarded, for example because of targeting difficulties or the cost of possible compensatory measures. Nevertheless, it is important to bear in mind that the road inefficiency analyzed above is conditional on this instrument.

If road congestion can be regulated by an incentive toll that also takes into account pollution externalities, any increase in infrastructure reduces the social costs of using the transport system.

Of course, this does not mean that any level of infrastructure could be legitimate if well regulated, as the opportunity cost of space in urban areas must be taken into account.

### 1.2.4 Social planner

In this section we consider a non-cooperative sequential game in which the authority or state first chooses the optimal level of road infrastructure and the travelers then opt for their means of transportation depending on the available number of expressways. The social planner bases its decision on the anticipated reaction of travelers. It is worth noting that the authority anticipates that commuters fail to coordinate which leads to a second best situation.

In the above, only the costs associated with transport use have been considered. However, the reuse of abandoned expressways in terms of public space or for alternative transport should not be excluded to determine the extent of the reallocation of express lanes that it is legitimate to carry out. To this end, we consider the opportunity cost of the space used by the express lanes  $V(n) \geq 0$  such as  $V(0) = 0, V' > 0, V'' \geq 0$ . If we ignore the fixed costs of public transport networks, then the optimal level of express lanes (which we will denote  $n^*$ ) minimizes the total social cost (TSC), defined by:

$$TSC(y^*, n, \tau) = TC(y^*, n, \tau) + V(n) \quad (1.3)$$

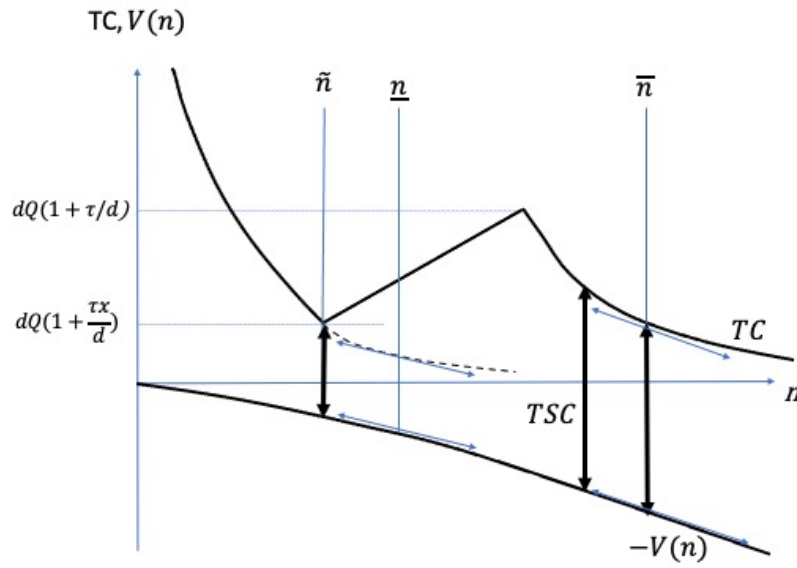
The objective function of the social planner is to minimize the total social costs given the transport mode decision functions of travelers, i.e:

$$\left\{ \begin{array}{l} \text{Min}_{(n)} TC(y^*, n, \tau) + V(n) \\ \text{s.t. } y^*(n) = \begin{cases} x \text{ if } n < \frac{bxQ}{d} \\ \frac{dn}{bQ} \text{ if } \frac{bxQ}{d} \leq n \leq \frac{bQ}{d} \\ 1 \text{ if } n > \frac{bQ}{d} \end{cases} \end{array} \right. \quad (1.4)$$

Figure 1.5 shows the variation of the total social cost as a function of  $n$ .



**Figure 1.5:** Optimal level of infrastructure



Notes: The optimal level of infrastructure corresponds to the difference between the curve TC, considered previously, and -V(n).

This figure highlights three possible local minima, associated with three particular levels of infrastructure, respectively denoted  $\underline{n}$ ,  $\bar{n}$ ,  $\tilde{n}$ : the first two correspond respectively to the levels of road infrastructure that would be optimal to satisfy captive users and all users in the absence of public transport; the third is the maximum level of infrastructure that can be offered to captives, without triggering a modal shift from public transport to road.

These three characteristic levels, independent of the social cost of pollution, are respectively defined by:

$$\left\{ \begin{array}{l} (\underline{n}) : \text{Min}_{(n)} \left[ \frac{bx^2Q^2}{n} + xQ\tau + (1-x)dQ + V(n) \right] = \text{Min}_{(n)} \left[ \frac{bx^2Q^2}{n} + xQ\tau + V(n) \right] \\ (\bar{n}) : \text{Min}_{(n)} \left[ \frac{bQ^2}{n} + Q\tau + V(n) \right] = \text{Min}_{(n)} \left[ \frac{bQ^2}{n} + V(n) \right] \\ (\tilde{n}) : \tilde{n} = \frac{bxQ}{d} \end{array} \right. \quad (1.5)$$

Given the assumptions, the functions to be minimized with respect to n have increasing

derivatives, which determine unique minima. However, they are not necessarily located in the interval that define the total social cost TSC (see Table 1.1). Moreover, we observe that the slopes of the tangents of TC as a function of  $n$ , on the left of  $(\tilde{n})$ , and on the right of  $(n = \frac{bQ}{d})$  are similar  $(\frac{-d^2}{b})$ . It follows that if  $\underline{n} < \tilde{n}$  then the function TSC is strictly decreasing up to  $\underline{n}$ , and strictly increasing beyond, so that  $\underline{n}$  is the optimum. In this case, express lanes are intrinsically inefficient and should be adjusted to the needs of captives only, with a quality level such that non-captives prefer to use public transport.

If  $\underline{n} \geq \tilde{n}$ , the total social cost is decreasing up to  $\tilde{n}$ . This level is optimal if:

$$dQ + xQ\tau + V\left(\frac{bxQ}{d}\right) \leq \frac{bQ^2}{\bar{n}} + Q\tau + V(\bar{n}) \quad (1.6)$$

Indeed, the left-hand side is the total social cost in  $\tilde{n}$  and grows up to  $n = \frac{bQ}{d}$ . The left term is lower than TSC for  $n \geq \frac{bQ}{d}$ , given (1.6.3). If the inequality (1.6) is reversed,  $\bar{n}$  is necessarily greater than  $\frac{bQ}{d}$ , so the right-hand side corresponds to the global minimum of TSC, at  $\bar{n}$ .

$n^* = \underline{n}$  if  $\underline{n} < \tilde{n}$ . If  $\underline{n} \geq \tilde{n}$ ,  $n^* = \tilde{n}$  if (1.6) is verified and  $n^* = \bar{n}$  otherwise.

## 1.3 Economic evaluation of the reallocation of urban expressways

We consider an initial level of expressroads  $n_0$  and evaluate in which cases it is optimal to reallocate a certain number of road infrastructure when both congestion and pollution are integrated in the model.

### 1.3.1 When should we reallocate urban expressways?

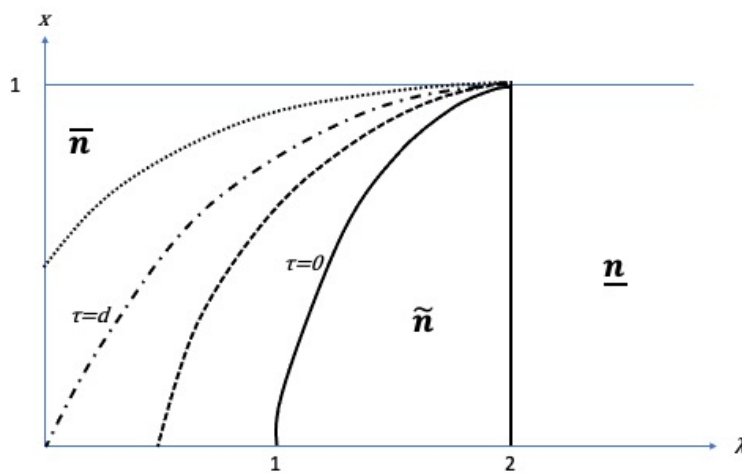
We consider a linear public space opportunity cost:  $V(n)=rn, r>0$ . The total marginal cost of road traffic development excluding pollution is then  $2\sqrt{br}$ , equally divided between transport costs and opportunity cost of public space. Furthermore, we have:

$$\begin{cases} \bar{n} = \sqrt{\frac{b}{r}}Q \\ \underline{n} = x\bar{n} \\ \tilde{n} = \frac{bxQ}{d} \end{cases}$$

Further details about computation can be found in Appendix 1.6.3. Let us denote  $\lambda = 2\frac{\sqrt{br}}{d}$  the long-term cost of road traffic development relatively to the user cost of public transport. The optimal infrastructure defined in Proposition (1.2.4) then verifies the following proposition: If  $\lambda > 2, n^* = \underline{n} = x\bar{n}$  and  $\frac{TSC}{dQ} = (\lambda + \frac{\tau}{d})x + (1 - x)$   
 If  $\lambda \leq 2, 1 + (\frac{\lambda^2}{4} + \frac{\tau}{d})x \leq \lambda + \frac{\tau}{d}, n^* = \tilde{n}$  and  $\frac{TSC}{dQ} = 1 + (\frac{\lambda^2}{4} + \frac{\tau}{d})$   
 If  $\lambda \leq 2, 1 + (\frac{\lambda^2}{4} + \frac{\tau}{d})x \geq \lambda + \frac{\tau}{d}, n^* = \bar{n}$  and  $\frac{TSC}{dQ} = \lambda + \frac{\tau}{d}$

In particular, one can notice that the left-hand side of the condition when  $\lambda \leq 2$  is increasing with  $x$ . Indeed, the higher the share of captives, the more pollution is acquired, and the more costly the constraint of not generating inappropriate transfer to the road is, which relatively favors the choice of maintaining express lanes. The optimal type of road infrastructure as a function of the value of the parameters  $(\lambda, x, \tau)$  is illustrated below (Figure 1.6).

**Figure 1.6:** Optimal level with respect to the social cost of pollution



The question of how to adjust road lanes when the value of the social cost of pollution ( $\tau$ ) increases only makes sense when  $\lambda < 2$  since otherwise, road costs are such that express lanes must target the captives alone, with a quality level independent of the value of pollution. If we now assume  $\lambda < 2$ , then a threshold value emerges, which is:

$$\frac{\tau_l}{d} = \frac{1 - \lambda + \frac{\lambda^2 x}{4}}{1 - x} \quad (1.7)$$

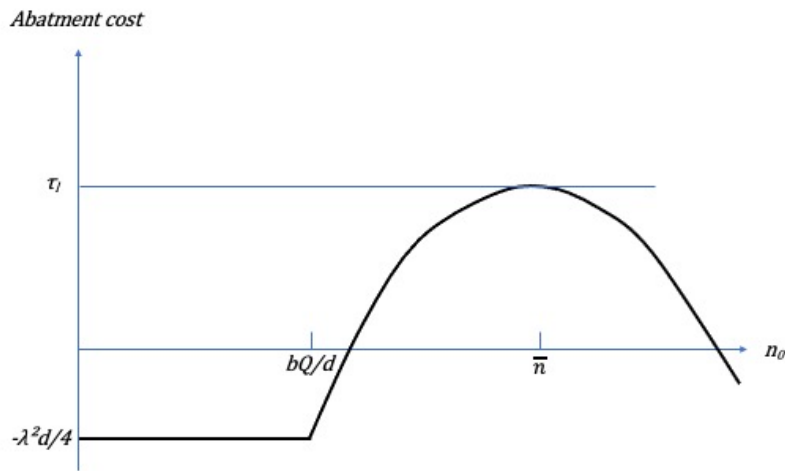
A high level of express lanes ( $\bar{n}$ ) is thus acceptable as long as  $\tau$  remains below this threshold value. However, the threshold may be negative, in which case the high level is in fact never justified since the opportunity cost of public space is sufficient to rule it out, regardless of the pollution issues. If the threshold value is positive, the high level is justified for low values of  $\tau$ . But when it reaches  $\tau_l$ , road infrastructure should be reallocated to  $\tilde{n}$ , with the downward adjustment being done by jump. Indeed, reductions that are too marginal do not trigger the modal shift that is necessary to reduce emissions. Also, the reduction must be sufficient to avoid falling into the inherently inefficient Pigou-Knight-Downs zone.

When  $\lambda < 2$ , a structural reduction of the road supply from  $\bar{n} = \sqrt{\frac{b}{r}}Q$  to  $\tilde{n} = \frac{bxQ}{d}$  is justified if  $\tau > \tau_l$ .

### 1.3.2 Comparison of alternative strategies

The pollution cost  $\tau_l$  represents the abatement cost per unit of emission of the adjustment from  $\bar{n}$  to  $\tilde{n}$ . More generally, one could calculate the unit abatement cost associated with a reduction in road infrastructure from a baseline  $n_0 > n$  to  $\tilde{n}$  by relating the corresponding social cost premium excluding pollution (transport user costs and opportunity cost of public space) to the realized gain in emissions. However, it is important to be clear about the meaning of this type of computation. Indeed, the degree of efficiency (or inefficiency) of the reference situation is decisive as illustrated in Figure 1.7 below. In the case  $\tau_l \geq 0$  that we now retain, the optimum is  $\bar{n}$  in the absence of externalities.

**Figure 1.7:** Impact of the reallocation of urban expressways from  $n_0$  to  $\tilde{n}$



The abatement cost thus calculated appears negative when the reference level is between  $\tilde{n}$  and  $\frac{bQ}{d}$ . But this is not surprising since we are then in the road paradox zone, where restricting road infrastructure does not affect the costs of transport use. In addition, it reduces the use of public space and reduces pollutant emissions. Compared with the baseline situation, the proposed reduction in road use undoubtedly reduces the total social cost. But this does not mean that this reduction is justified since it depends on the level of the social cost of externalities. Indeed, if the latter remains low, proposition (1.3.1) has established that the optimal level of infrastructure is  $\bar{n}$ , and therefore higher than the reference level: it would then be necessary to build more expressways than to reallocate them. Symmetrically, the abatement cost may also be negative if the initial oversizing of the express lanes is large.

In other words, these negative abatement costs essentially reflect the inefficiency of the baseline situation, but they do not tell us much about the optimal strategy. To do this, one must compare the removal of the express lanes to the best alternative strategy, i.e. to the reference level  $\bar{n}$ . It is therefore important to distinguish between (i) what reflects the non-optimality of the initial situation; and (ii) what intrinsically reflects the cost of reducing externalities. The latter must be calculated by reference to the optimized situation ( $\bar{n}$ ) when the externalities were not taken into

account. The corresponding abatement cost is equal to  $\tau_l$ , and is to be compared with the social cost of the externalities used to justify the strategy (Bureau, Quinet and Schubert, 2020).

In addition, the analysis should also consider possible alternative strategies to decarbonize urban transport, among which is the regulation of vehicle emissions. In this respect, various states and cities are considering the eventual banning of polluting vehicles. However, this alternative strategy is not without costs either since users must equip themselves with non-polluting vehicles, which are more expensive because of the cost of batteries, for example, in the case of electric vehicles.

This then suggests comparing two alternative strategies:

1. decarbonization through roadway reallocation,
2. or by regulating vehicles.

The first approach mobilizes the potential of public transport and generates co-benefits in terms of rights-of-way reduction. But it does not change the emissions of car captives. On the contrary, the second approach eliminates all polluting emissions. Regarding the costs, the former increases user costs, while the latter increases equipment costs.

Obviously, each of these strategies must be optimized, with reallocation of express lanes in particular only occurring if  $\tau > \tau_l$ . Similarly, if we assume that the use of non-polluting vehicles represents an additional cost per kilometer ( $e$ ), the authority should impose it only when the social cost of externalities is greater. The choice then depends on the relative levels of these three parameters:

- **First case:**  $e \leq \tau_l$ . As long as  $\tau$  remains below  $e$ , neither instruments can be mobilized to effectively regulate pollution, as the abatement costs to be borne are greater than its social cost. For  $\tau \geq e$ , banning polluting vehicles is justified and preferable to the alternative strategy in terms of social cost. However, it imposes an additional kilometer cost on all users, equal to  $e$  if  $\tau \leq \tau_l$ .
- **Second case:**  $e > \tau_l$ . If  $\tau = \frac{e-(1-x)\tau_l}{x} = \tau'_l$ , the social cost of the two strategies is equal. If

the social cost is lower, reallocation of express lanes is preferable while banning polluting vehicles is preferable in the opposite case.

Starting from a situation where a high level of express lanes ( $\bar{n}$ ) is justified in the absence of pollution ( $\lambda < 2, \tau_l \leq 0$ ), the strategy of reallocating them to bring them down to ( $\tilde{n}$ ) is preferable to banning pollution vehicles when ( $e > \tau_l$ ), as long as  $\tau \in [\tau_l, \tau_l']$ .

However, this comparison has assumed the two strategies to be incompatible, the idea being that road reallocation can no longer be justified by decarbonization if the vehicles are non-polluting. Of course, it could be justified by an upward revaluation of the opportunity cost of public space.

Moreover, it should be noted that the two strategies may be complementary, modal shift being less costly to decarbonize the mobility of non-captives, and the banning of polluting vehicles being justified with respect to captives. From this perspective, the efficient combination of instruments - if failing to implement the ideal congestion charge ( $\theta + \tau$ ) - would be to price environmental externalities ( $\tau$ ) through fuel pricing for example and combine such pricing with a possible reallocation of express lanes. In this way, the effectiveness of the shift to non-polluting vehicles would be assured. And when modal shift remains the least costly option for non-captives, this provides a higher quality of service for captives ( $\tilde{n}' = \min(\underline{n}, \frac{bxQ}{d - \min(\tau, e)}) > \tilde{n}$ ).

However, this set of instruments has inconvenient distributional effects with respect to captives when they have no viable alternative, since they must then bear both the increased cost of transport and the burden of an additional tax. In this case, and provided of course that road supply is not reduced below  $\tilde{n}$ , road reallocation alone can be seen as a means of limiting the impact on the captives, since the only lever when modal shift is mobilized.

### 1.3.3 Distribution of the cost of abatement

The distributional impacts of a strategy of reallocating express lanes cannot be neglected. Indeed, apart from the cases where the reference situation would be intrinsically inefficient, the reduction of polluting emissions has a cost for transport users since the cost per kilometer increases from  $\frac{d\lambda}{2}$  to  $d$ , when the road supply is reduced from  $\bar{n}$  to  $\tilde{n}$ . Moreover, if the effect is

homogeneous for all users, captives will *in fine* be more impacted if the distance of their trips is greater.

In practice, this will be the case if captives are commuters coming from the suburbs. Under these conditions, the brutality of the debates raised by the reallocation of roads in Paris should not be surprising, especially since it is reasonable to imagine that the benefits in terms of public space are primarily for the central zone. Still, it is important to specify the spatial impacts of such a policy beyond the immediate effects, thus taking into account the interactions between transport and urban land markets.

To this end, we consider the simplest case of a monocentric urban model in which the land consumed per dwelling is fixed and transport costs are linear. Schematically (Bureau, 2012), public transport supply is assumed to extend to distance  $L$  from the center, with non-captives being residents within this area and captives being those on the periphery. For the latter, the total road transport cost must take into account - in addition to the cost in the central area - the cost of access to the central area.

Noting  $c$  the cost per kilometer in the central zone and  $\alpha$  the cost in the peripheral zone, the total transport cost  $\gamma(z)$  for a resident living  $z$  away from the center is:

$$\gamma(z) = \begin{cases} cz & \text{if } z \leq L \\ cL + \alpha(z - L) & \text{if } z \geq L \end{cases}$$

We denote  $f(z)$  the density (normalized by the land consumed by a dwelling) of available land at distance  $z$ <sup>6</sup>, and  $\bar{L}$  the city boundary.  $Q$  is the total population. The central area transportation requirements considered above are:

$$\begin{cases} (1 - x)Q = \int_0^L zf(z)dz \\ xQ = L \int_L^{\bar{L}} f(z)dz \end{cases} \quad (1.8)$$

---

<sup>6</sup>Here, we consider that each individual in the model consumes one unit of housing.



Moreover, note  $l$  the average distance of travel for residents of the central area:

$$l = \frac{\int_0^L z f(z) dz}{\int_0^L f(z) dz}$$

Assuming that residents can change location within the city, the equilibrium of land markets implies that the urban costs borne by residents are equal, regardless of their location. Noting  $K$  this cost,  $R(z)$  the land rents as a function of location and  $A(z)$  the value of amenities provided by public spaces, we then have:

$$\forall z, K = \gamma(z) + R(z) - A(z) \tag{1.9}$$

Thus, the fact that *ex ante* the increase in transport costs resulting from road reallocation weighs more heavily on (captive) commuters leads to an increase in land pressure in the center that ultimately evens out the impact on residents: captives and non-captives are thus equally impacted, with the differences being capitalized in land rents.

The gradient of land rents in the cities is determined by equation (1.8). Its modification due to the roadway reallocation would reflect the evolution of the transport costs and the way in which the benefits of freed up public spaces are spatially distributed  $V(\bar{n}) - V(\tilde{n}) = (\frac{d\lambda}{2})(1 - \frac{d\lambda}{2}x)Q$ . If we assume that the freed space benefits uniformly to the central area, the variation  $\Delta A(z)$  of amenities is:

$$v = \frac{(\frac{d\lambda}{2})(1 - \frac{d\lambda}{2}x)l}{1 - x}$$

The gradient of land rents will therefore be increased in the central zone because of the increase in the cost per kilometer within it. In addition, the capitalization of the amenities provided in the city center will determine a decrease in these amenities at its limit. The sharing of the net abatement cost between residents and landowners will ultimately depend on the external mobility of residents, which determines the change in the variable  $K$ . In the short term, urban costs  $K$  are low (a so-called closed city). The size and structure of the city will remain unchanged, and it is

the competition with agricultural land at the city's border that determines land prices in  $\bar{L}$ , which won't be altered. Residents, regardless of their location, will therefore bear increased urban costs:

$$\Delta K = (d - \frac{\lambda d}{2})L$$

Land rents will be unchanged in the peripheral zone and increased in the central zone by:  $\nu + (d - \frac{\lambda d}{2})L$  at the central point since residents located there bear no transport costs and by  $\nu$  at the edge of the central zone. The gain on average equals to  $\nu + (d - \frac{\lambda d}{2})(L - l)$ , corresponding to the capitalization of the value of the freed-up public spaces and the relative benefits enjoyed by non-captives in terms of transport costs.

This additional cost borne by residents makes the city less attractive, which tends to reduce overall land pressure within it. In the long term, the equilibrium is therefore constrained by the potential mobility of the residents. If we consider that this mobility is perfect in the long term (an "open" city), the increase in land rent in the center cannot exceed  $\nu$ . The land rent curve  $R(z)$  is shifted downwards by  $(d - \frac{\lambda d}{2})L$ , compared with that of the closed city and the urbanization at the city's margins becomes unprofitable, reflecting its lesser attractiveness. Thus, its size is reduced by<sup>7</sup>:

$$\Delta \bar{L} = -\frac{(d - \frac{\lambda d}{2})L}{\alpha}$$

As a consequence, the transport needs and the share of captives must be readjusted (equation 1.8) and  $\tilde{n} = \frac{bxQ}{d}$  established, by integrating the evolution of the urban structure.

Compared to the baseline, residents' urban costs are then unchanged and land rents capitalize in each location the changes in  $\gamma(z) - A(z)$ : land rents are reduced by  $(d - \frac{\lambda d}{2})L$  in the peripheral area; they increase by  $\nu$  at the central point and by  $\nu - (d - \frac{\lambda d}{2})L$  at the boundary of the central area. The average gain for landowners in this area equals to  $\nu - (\frac{\lambda d}{2})(L - l)$ .

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<sup>7</sup>Since we are in an open city, the transport costs at the limit of the city should remain constant. Therefore,  $cL + \alpha(\bar{L} - L)$  should be constant.

## 1.4 Putting the Parisian debates into perspective

In Paris, the riverbank expressways were closed to car traffic in the fall of 2016. The introduction of new restrictions has been at the heart of the election campaign for mayor in 2020. Particularly acute today, debates about metropolitan expressways are not entirely new. Indeed, while in 1967, the right banks were transformed into the "Georges Pompidou" expressway, the symmetrical project to ease traffic by a left bank expressway was abandoned in 1974 by the newly elected President Giscard d'Estaing, in order to preserve the Parisian heritage. The situation then remained static until the emergence of concerns about climate change and the recognition of the role of cities in this regard.

Today, the objective of most cities is to keep the roads to the car-captives alone by fostering new alternatives to car transportation. It is worth to note that the situation today is quite different from that of the 1970s when the captives were more likely to be public transport users, particularly households that could not yet afford a car. Of course, there are still some captive or quasi-captive public transport users, notably commuters who live on the lines of the regional wide-gauge rail network. However, they are not affected by the reallocation strategies that interest us here unlike the car-captives i.e. residents of peripheral areas poorly served by public transport and inherited from 50 years of urban sprawl and vans providing urban logistics. In this respect, the proposed analytical framework is relevant to the Paris case.

Indeed, the closure of the Georges Pompidou riverbank has provoked much debate since it has been accused of having displaced, not reduced, road traffic and consequently polluting emissions. However, this pedestrianization is not very costly if credible alternatives are proposed, at least for part of the population. The question then is: has the closure of the expressways caused a shift to alternative transport?

This is the perspective of our model, which assumes an available supply of public transport of a given quality to which individuals can switch. However, the Paris case suggests, at least initially, an intensive marginal shift to other routes (Bou Sleiman, 2021), as well as an increase in nitrogen dioxide emissions on major Parisian roads. This was suggested by the Urban Planning

Institute<sup>8</sup>.

Our study suggests that this may be due to the abundant presence of captives of the private car. Nevertheless, it is also likely that we have not yet reached the point where the switch-over will take place, despite the increasing spectrum of alternatives to the private car in the Paris region<sup>9</sup>.

Thus, this model suggests that, on the one hand, the captives cannot be ignored and, on the other, that the competitiveness of alternative transport is crucial but not limited to public transport. Thus, the attractiveness of public transport remains an issue: if policymakers want to induce a modal shift, they must first be able to reduce the cost of alternative transport "d" and then reallocate express lanes. This suggests that the two policies are at least complementary rather than alternatives.

## 1.5 Conclusion

This paper focuses on the public debate about the removal of roadway in a given city. To this end, we propose a theoretical model aiming at providing a reference to determine when it is appropriate to remove roads in a context of scarce public space and by integrating the cost of carbon. The model has been enriched by taking into account captive users of the private car. The results of this paper seem to be interesting since they suggest a jump adjustment of the roadway to avoid falling into the "paradoxical" zone, i.e. choosing a roadway capacity that pumps non-captive users onto the road - and thus increases emissions - when they could have used alternative transport for an equivalent travel time. These situations call into question the very principle of infrastructure, but the question of alternatives remains crucial in this context.

Yet the roadway is essential for some users, and special attention should be given to those who are captive of the car and who cannot be neglected. Therefore, the complete removal of

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<sup>8</sup>Institut d'Aménagement et d'Urbanisme (2017), Bilan du suivi et de l'évaluation un an après: [https://www.iau-idf.fr/fileadmin/DataStorage/SavoirFaire/NosTravaux/Amenagement/voiesberges/rapport\\_final.pdf](https://www.iau-idf.fr/fileadmin/DataStorage/SavoirFaire/NosTravaux/Amenagement/voiesberges/rapport_final.pdf)

<sup>9</sup>Enquête globale transport, Septembre 2012: [https://omnil.fr/IMG/pdf/egt2010\\_enquete\\_globale\\_transports\\_-\\_2010.pdf](https://omnil.fr/IMG/pdf/egt2010_enquete_globale_transports_-_2010.pdf)

roads cannot be considered, but the road can be limited by better traffic management. Both road removal and congestion charging affect peripheral commuters more severely. However, the differences are capitalized in land rents, so all agents are equally affected.

Finally, a range of instruments can be proposed to decongest and decarbonize the city (e.g., reallocation of express lanes, incentive pricing, vehicle regulation). It is then necessary to have a global vision and to find the right combination of instruments.

The aim of this paper is not to replace transport models that incorporate all trips - although they are ill-suited to the purpose of our study - but to have an evaluation exercise leading to different cases of equilibrium in the sense of the Wardrop principle.

## **1.6 Appendix**

### **1.6.1 Further results**

In this section, we show in detail how the different graphs in the paper are constructed.

Figure 1.2 represents the social costs of transport use with respect to  $n$ . It describes the 3 configurations of figure 1.1 when the cost of transports includes pollution and congestion externalities. In table 1.1, we compute the total social cost for the 3 configurations with and without road pricing.

$n$	Type	$y$	$\frac{TC}{dQ}$
<b>Without road pricing</b>			
$n < \frac{bxQ}{d}$	(1)	$x$	$\frac{bx^2Q}{dn} + \frac{x\tau}{d} + (1-x)$
$\frac{bxQ}{d} \leq n \leq \frac{bQ}{d}$	(2)	$\frac{dn}{bQ}$	$1 + \frac{n\tau}{bQ}$
$n > \frac{bQ}{d}$	(3)	1	$\frac{bQ}{dn} + \frac{\tau}{d}$
<b>With road pricing</b>			
$n < \frac{2bxQ}{d-\tau}$	(1)	$x$	$\frac{bx^2Q}{dn} + \frac{x\tau}{d} + (1-x)$
$\frac{bxQ}{d-\tau} \leq n \leq \frac{2bQ}{d-\tau}$	(2)	$\frac{(d-\tau)n}{2bQ}$	$1 - \frac{(d-\tau)^2n}{4bdQ}$
$n > \frac{2bQ}{d-\tau}$	(3)	1	$\frac{bQ}{dn} + \frac{\tau}{d}$

**Table 1.1:** Social costs of transport use with respect to  $n$

Notes: Type (1) represents the case of reduced road infrastructure, type (2) refers to intermediate infrastructure and type (3) refers to a large road infrastructure.  $y$  represents the endogenous share of road users,  $n$  the level of expressways and  $\frac{TC}{dQ}$  the cost of road use relatively to public transportation.

## 1.6.2 Generalization to an elastic demand

The model highlights that the consideration of air pollution reinforces the possibility of a road paradox, as the increase in road supply actually increases the social cost of road use. In such a context, the reduction of road use is justified irrespective of the use that can be made of the freed-up roads.

However, the analysis is carried out on the basis of realistic but schematic assumptions: that road demand comes from two segments corresponding respectively to two inelastic transport demands, the first of which is totally captive to road use; the second of which is transferable to alternative modes whose generalized unit cost has been assumed to be uniform for the whole demand considered. This last assumption determines by nature a road paradox zone, where the road supply attracts users and becomes so congested (again) that it does not ultimately benefit them in comparison with the use of alternative modes. Adding the unit pollution damages ( $\tau$ ) then determines a social loss.

To appreciate the significance of the results, it should be noted that these extreme assumptions are not necessary, which can be seen by specifying the conditions for such a paradox. For this purpose, we consider a general form for the demand on the road. We note  $q$  the road traffic,  $p(q)$  this inverse demand and its elasticity at the point considered:  $\sigma = -\frac{p(q)}{qp'(q)} > 0$

As before, we assume that the road cost to users is proportional to the road use rate, i.e.:  $\theta = \Theta(q, n) = \frac{bq}{n}$ . The marginal social cost of road use is then:  $MSC = \theta + \Theta'_q(q, n)q + \tau$ . The first term corresponds to the cost borne by the user, the second to the marginal external cost of congestion, and the third to pollution.

Assuming that, for a road supply level  $n$ , road traffic is  $\tilde{q}(n)$ , this function having locally an elasticity noted  $\epsilon$ , the total cost of transport use (incorporating the cost of alternative transport in case of postponement or the opportunity cost if the adjustment is made on the number of trips) is then:

$$CT(n) = \Theta(\tilde{q}(n), n)\tilde{q}(n) + \tau\tilde{q}(n) + \int_{\tilde{q}(n)}^{\infty} p(u)du$$

If traffic were independent of  $n$ , an increase in road supply would provide each user with a gain  $-\Theta'_n\tilde{q}$ . In relation to this reference, the impact on the total cost of use is therefore :

$$\frac{CT'}{\Theta'_n\tilde{q}(n)} = 1 + \frac{\Theta(\tilde{q}(n), n) - MSC}{\Theta(\tilde{q}(n), n)}\epsilon$$

The second term thus combines the "subsidy rate" of the road with respect to its marginal social cost and the elasticity of road traffic with respect to road facilities. Obviously, if the road were perfectly priced, through a congestion incentive toll that also included pollution damages, the second term would be zero: the envelope theorem prevails and the value of a marginal road extension is equal to the quality of service gain for a given traffic.

On the other hand, if the road is open access, the subsidy is equal to the non-pricing of the marginal external cost of congestion and pollution. The benefit of an increase in road capacity is then reduced - or even negative - especially as the subsidy is large and the elasticity of traffic to road supply is high. In this case, the road equilibrium is defined by:  $p(\tilde{q}(n)) = \Sigma(\tilde{q}(n), n)$ , from which we derive the elasticity of traffic to road supply:

$$\epsilon = \frac{1}{1 + \frac{1}{\sigma}}$$

The latter depends only on the characteristics of road demand. It tends to 0 if demand is

inelastic, and to 1 if it is infinitely price-elastic, with any new road being immediately congested at the level previously prevailing on the existing network. More precisely, the reduction in the user cost gain is equal to:

$$\frac{CT'}{\Theta'_n \tilde{q}(n)} = 1 + -\frac{\Theta(\tilde{q}(n), n) + \tau}{\Theta(\tilde{q}(n), n)} \epsilon$$

In general, the increase in pollution makes road paradox situations more likely (in the absence of pricing for the external costs of road use).

The total cost of transport use increases with the level of roads if:

$$\tau \geq \Theta(\tilde{q}(n), n) \left( \frac{1}{\epsilon} - 1 \right)$$

In particular, this condition is always satisfied in an area where there is competition with a perfectly elastic alternative mode (i.e., road demand such that  $\epsilon = 1$ ), the case highlighted by the Pigou-Knight-Thomson paradox. However, its primary origin remains the (un)regulation of road access, combined with a highly elastic road demand. But the result would hold regardless of the mechanisms determining this elasticity. On this basis, the model has a more general scope and could be enriched in terms of demand segmentation and alternatives to road.

### 1.6.3 Proofs of propositions

**Proof 1 (Proof of proposition 1)** First, let us compute the derivatives of the relative transport costs in each configurations. If  $n < \frac{bxQ}{d}$ , as in configuration (1), then:

$$\frac{\partial \frac{TC}{dQ}}{\partial n} = -\frac{bx^2Q}{dn^2} < 0$$

Hence, the higher the level of infrastructure, the lower the transport costs. Therefore,  $n = \frac{bxQ}{d}$  is level of infrastructure that minimizes the transport costs in the first configuration. If  $\frac{bxQ}{d} \leq n \leq \frac{bQ}{d}$ ,



as in configuration (2), then:

$$\frac{\partial \frac{TC}{dQ}}{\partial n} = \frac{\tau}{bQ} > 0$$

In the second configuration, the transport costs are increasing with respect to the level of infrastructure. Therefore,  $n = \frac{bxQ}{d}$  is the level of infrastructure minimizing the 2 configurations. Therefore whenever the initial level of infrastructure  $n_0 \in ]\frac{bxQ}{d}, \frac{bQ}{d}]$ , it is beneficial to bring the road supply back to  $n = \frac{bxQ}{d}$  since  $\frac{TC}{dQ}|_{n=\frac{bxQ}{d}} < \frac{TC}{dQ}|_{n \in ]\frac{bxQ}{d}, \frac{bQ}{d}]}$ . This transformation is therefore Pareto-improving and the corresponding total cost is:  $\frac{TC}{dQ} = 1 + \frac{\tau x}{d}$ .

If  $n > \frac{bQ}{d}$ , as in configuration (3), then:

$$\frac{\partial \frac{TC}{dQ}}{\partial n} = -\frac{bQ}{dn^2} < 0$$

The derivative is decreasing with respect to  $n$  in the last configuration. Therefore, whenever  $\frac{TC}{dQ} > 1 + \frac{\tau x}{d}$  i.e.  $n_0 < \frac{bQ}{d-(1-x)\tau}$ , we should bring back the road supply to  $n = \frac{bxQ}{d}$ . As a result, we get the Proposition 1.

**Proof 2 (Proof of proposition 3)** The objective function of the social planner is to minimize the total social costs given the transport mode decision functions of travelers, i.e:

$$\left\{ \begin{array}{l} \text{Min}_{(n)} TC(y^*, n, \tau) + V(n) \\ \text{s.t. } y^*(n) = \begin{cases} x & \text{if } n < \frac{bxQ}{d} \\ \frac{dn}{bQ} & \text{if } \frac{bxQ}{d} \leq n \leq \frac{bQ}{d} \\ 1 & \text{if } n > \frac{bQ}{d} \end{cases} \end{array} \right.$$

These three characteristic levels, independent of the social cost of pollution, are respectively defined by:

$$\left\{ \begin{array}{l} (\underline{n}) : \text{Min}_{(n)} \left[ \frac{bx^2Q^2}{n} + xQ\tau + (1-x)dQ + V(n) \right] = \text{Min}_{(n)} \left[ \frac{bx^2Q^2}{n} + xQ\tau + V(n) \right] \\ (\tilde{n}) : \text{Min}_{(n)} \left[ \frac{n\tau d}{b} + V(n) \right] \\ (\bar{n}) : \text{Min}_{(n)} \left[ \frac{bQ^2}{n} + Q\tau + V(n) \right] = \text{Min}_{(n)} \left[ \frac{bQ^2}{n} + V(n) \right] \end{array} \right.$$

By solving the first minimization problem we get:

$$\begin{aligned} bx^2Q^2 &= V'(n)n^2 \\ \underline{n} &= \sqrt{\frac{b}{V'(n)}}xQ \end{aligned}$$

However,  $\underline{n}$  should be located in the interval where the function is determined i.e.  $\underline{n} < \frac{bxQ}{d}$ .

If  $\underline{n} > \frac{bxQ}{d}$  meaning that  $\sqrt{V'(n)} < \frac{d}{\sqrt{b}}$ , then the local minimum would be a corner solution equal to  $\frac{bxQ}{d}$ .

The second minimization problem has an increasing derivative with respect to  $n$ . Hence, the local minimum is the inferior corner solution  $\tilde{n} = \frac{bxQ}{d}$ .

By solving the third minimization problem, we get:

$$\begin{aligned} bQ^2 &= V'(n)n^2 \\ \bar{n} &= \sqrt{\frac{b}{V'(n)}}Q \end{aligned}$$

Therefore, the local minima that can be summarized by:

$$\left\{ \begin{array}{l} (\underline{n}) : \underline{n} = \sqrt{\frac{b}{V'(n)}} xQ \text{ if } \underline{n} < \frac{bxQ}{d} \text{ and } \underline{n} = \frac{bxQ}{d} \text{ otherwise.} \\ (\tilde{n}) : \tilde{n} = \frac{bxQ}{d} \\ (\bar{n}) : \bar{n} = \sqrt{\frac{b}{V'(n)}} Q \end{array} \right.$$

which gives:

$$\left\{ \begin{array}{l} TSC(\underline{n}) = \sqrt{bV'(\underline{n})} xQ + V(\underline{n}) \\ TSC(\tilde{n}) = xbQ + V\left(\frac{bxQ}{d}\right) \\ TSC(\bar{n}) = \sqrt{bV'(\bar{n})} Q + V(\bar{n}) \end{array} \right.$$

Finally, we want to know what is the global minimum ( $n^*$ ):

- If  $\underline{n} < \frac{bxQ}{d}$ ,  $\underline{n} = \sqrt{\frac{b}{V'(n)}} xQ$ .  $TSC(\underline{n}) < TSC(\tilde{n})$  (by construction) and  $TSC(\underline{n}) < TSC(\bar{n})$  since  $V' > 0$  and  $\underline{n} < \bar{n}$ . Hence,  $\boxed{n^* = \underline{n}}$ .
- If  $\underline{n} > \frac{bxQ}{d}$ ,  $\underline{n} = \tilde{n}$ . In order to know the global minimum one needs to compare  $TSC(\tilde{n})$  with  $TSC(\bar{n})$ . We get  $\boxed{n^* = \bar{n}}$  if  $\sqrt{bV'(\bar{n})} Q + V(\bar{n}) < xbQ + V\left(\frac{bxQ}{d}\right)$  and  $\boxed{n^* = \tilde{n}}$  otherwise.

### 1.6.4 Further computation

**Abatement costs** The abatement cost per unit of emission of the adjustment from any level of infrastructure  $n_0 > \tilde{n}$  to  $\tilde{n}$  can be computed by equalizing  $\frac{TSC(n_0)}{dQ}$  and  $\frac{TSC(\tilde{n})}{dQ}$ . Since the TSC function depends on the level of infrastructure we have two cases:

1.  $n_0 < \frac{bQ}{d}$  and  $\frac{TSC(n_0)}{dQ} = 1 + \frac{\tau n}{bQ} + \frac{rn}{dQ}$
2.  $n_0 > \frac{bQ}{d}$  and  $\frac{TSC(n_0)}{dQ} = \frac{bQ}{dn} + \frac{\tau}{d} + \frac{rn}{dQ}$

Taking the first case, we can compute the abatement cost per unit of emission from  $n_0 > \tilde{n}$  to  $\tilde{n}$ :

$$\begin{aligned}\frac{TSC(n)}{dQ} &= \frac{TSC(\tilde{n})}{dQ} \\ 1 + \frac{n\tau}{bQ} + \frac{rn}{dQ} &= 1 + \frac{x\tau}{d} + \frac{rbx}{d^2} \\ \tau\left(\frac{n}{bQ} - \frac{x}{d}\right) &= \frac{r}{d}\left(\frac{bx}{d} - \frac{n}{Q}\right) \\ \tau &= -\frac{rb}{d}\end{aligned}$$

Thus, if  $n_0 < \frac{bQ}{d}$ , the abatement cost is negative and constant.

In the second case, we have:

$$\begin{aligned}\frac{TSC(n)}{dQ} &= \frac{TSC(\tilde{n})}{dQ} \\ \frac{bQ}{dn} + \frac{\tau rn}{d dQ} &= 1 + \frac{x\tau}{d} + \frac{rbx}{d^2} \\ \frac{\tau}{d}(1-x) &= 1 + \frac{rbx}{d^2} - \frac{bQ}{dn} - \frac{rn}{Qd} \\ \tau &= \frac{d}{1-x} + \frac{rbx}{d(1-x)} - \frac{bQ}{n(1-x)} - \frac{rn}{Q(1-x)}\end{aligned}$$

We can now differentiate the abatement cost with respect to the level of infrastructure (n) and compute the optimum:

$$\begin{aligned}\frac{\partial \tau}{\partial n} &= \frac{bQ}{(1-x)n^2} - \frac{r}{Q(1-x)} \\ \frac{\partial \tau}{\partial n} &= 0 \text{ for } n = Q\sqrt{\frac{b}{r}} = \bar{n}\end{aligned}$$

We now differentiate it twice, we get:

$$\frac{\partial^2 \tau}{\partial n^2} = -\frac{bQ}{(1-x)n^3} < 0$$

Hence, the Abatement cost is concave when  $n_0 > \frac{bQ}{d}$  and the optimum is a maximum. The

function is illustrated in figure 1.7.

## Chapter 2

# Displacing Congestion: Evidence from Paris<sup>1</sup>

### Abstract

This paper shows that road-closing policies may have adverse short-run effects on pollution by reallocating traffic toward more congested roads. I study the impact of the 2016 closure of the Voie Georges Pompidou, a one-way expressway crossing downtown Paris, on traffic and pollution displacement. To do so, I rely on a difference-in-difference strategy based on the direction and the timing of traffic, which I implement on detailed road-sensor data. I show that the closure lowered average speed by over 15% on two sets of substitute roads: central streets nearby and the already congested southern ring road. Using air quality data, I show that NO<sub>2</sub> concentrations increased by 6% near the ring road and by 1.5% near local roads. The reduced-form results on traffic are quantitatively consistent with a calibrated model of shortest route choice, which allows me to recover the underlying rerouting patterns. Even though few displaced commuters diverted to the ring road, they triggered a massive pollution increase because of the U-shaped relationship between emissions and traffic speed. Overall, I estimate that up to 90% of the pollution cost was borne by lower-income residents around the ring road, who lived far away from the new amenity created by the closure and mostly outside the jurisdiction responsible for the closure decision. Finally, I study counterfactual closure scenarios to assess under which conditions those adverse effects could have been mitigated.

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## 2.1 Introduction

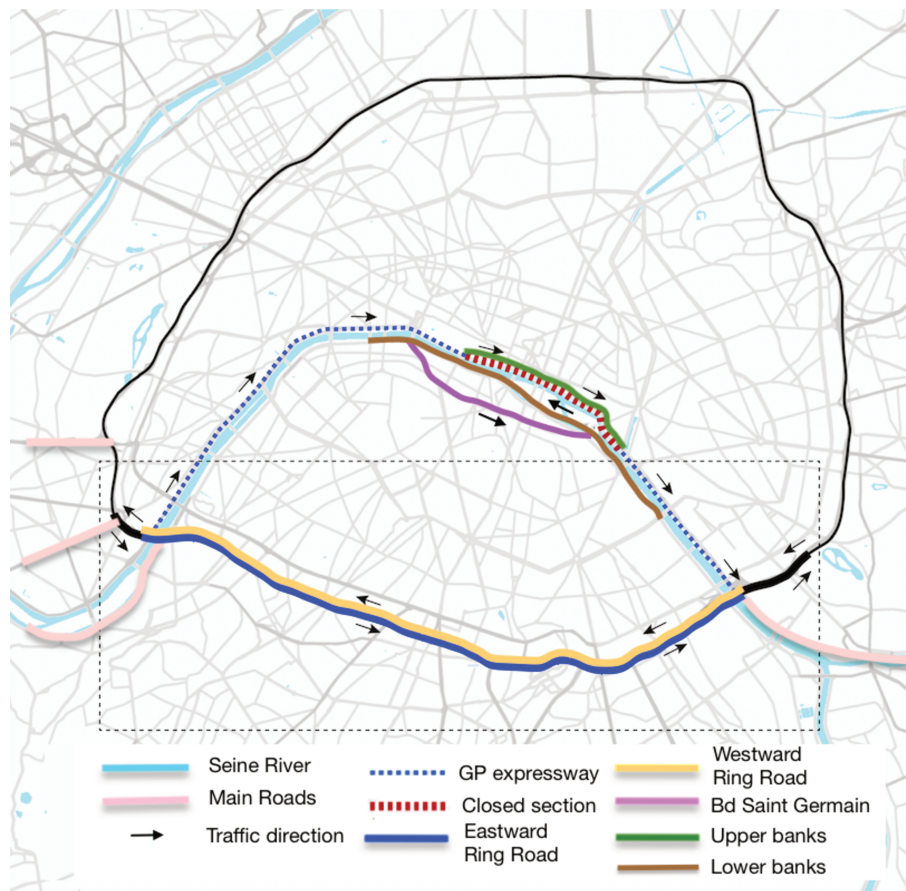
Traffic congestion represents an undoubted threat to the quality of urban life, and keeping it under control has been an ongoing process (European Environmental Agency, 2020; WHO, 2005). In response, various traffic-calming policies have been used worldwide, some more readily received than others. Today, car-free streets have become the paradigm of contemporary urbanism. Many cities in developed countries have started reducing their road supply to curb air pollution. Often-times, traffic is diverted to other roads, displacing congestion and pollution to other areas.<sup>2</sup> As such, even if the total number of commuters is reduced, the overall effect of road closures on the environment remains an open question due to the non-linear impact of traffic flow on emissions.

This paper provides quantitative evidence on the impacts of road closures in a city and the distributional effects thereof. While the idea of road construction is well-established to be counter-productive as it may actually make congestion worse (Downs, 1962; Duranton and Turner, 2011a), no study to this date has evaluated the impacts of road "destruction". I exploit a reform in Paris where a 3.3-km segment of the expressway along the Seine's right riverbank, the "Voie Georges Pompidou" (hereafter GP) got pedestrianized on September 1, 2016. The GP was the only expressway to cross the city. As shown in Figure 2.1, it was part of a 13-km road that crossed Paris from southwest to southeast. The closed segment was near Notre Dame Cathedral, the geographical and tourist center of the city. Until 2016, this road was used by approximately 40,000 vehicles every day. It was partly used for traveling within the city but also acted as a possible substitute for the ring road, especially its heavily congested southern section, for suburb-to-suburb traffic (Bouleau, 2013). As such, the riverbank was part of a road network that was of general interest to the region.

First, I empirically estimate the impacts of this closure on substitute roads. A given road can be considered as a substitute if it is of almost same length and serves the same itinerary as the one considered (same starting point and exit point). The biggest challenges when evaluating a change in the road supply are accounting for (i) network effects (ii) simultaneity, and (iii) selection. These issues make it arduous to find the best setting in which the impact of a road closure on

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<sup>2</sup><https://www.nytimes.com/2022/09/12/nyregion/nyc-congestion-pricing-manhattan-bronx.html>

**Figure 2.1:** The Empirical Setting: The Case of Paris

*Notes:* This figure represents a map of Paris. The dashed line represents the riverbank used by cars to cross Paris. The black line represents the limit of the city which corresponds to the ring road. I focus on the southern part of the ring roads, represented in the map by two thick lines. The thick section of the ring roads with an eastward flow direction corresponds to the south outer ring road. The thick section with a westward flow direction corresponds to the south inner ring road. The two local roads with an eastward flow direction represent the detour routes. The local road with a westward flow direction will serve as a control. The different main roads outside the city and leading to the GP are highlighted.

traffic can be causally identified and isolated from any other alteration in the city. This paper overcomes these challenges by implementing a difference-in-difference strategy based on the direction and the timing of traffic. To identify the effect of the pedestrianization, I make use of one particular feature of the GP: its unique flow direction. Given the unique flow direction of the GP, the direction of roads provides me with a natural selection of treatment and control groups: roads with the same flow direction as the riverbank are likely to be directly impacted by the GP closure by receiving a fraction of the displaced GP users. In contrast, the impact of the closure on the westward lanes, in the absence of alternative westward expressways within the city, may



only have been indirect through a global decrease in traffic. I also use the timing of traffic to ensure comparability between treatment and control groups, knowing that one direction is used in the morning and the other in the evening. In addition, each eastward substitute road has a similar westward road in the city with similar architecture (same type of steel and strip, presence or absence of traffic lights, outward/inward exit lanes). This makes it likely that traffic flows in either directions are independent. These different features allow for an evaluation of the GP closure by comparing its effect on the eastward roads to its effect on the westward roads in a difference-in-difference framework.

To measure traffic, I make use of the 2013-2019 road sensor data of the Paris City Hall. These data provide the occupancy rate (the percentage of time that vehicles occupy a given segment of the road) and the flow of vehicles, for every hour of the day. I also use a collection of dozens of road segments that match the substitute roads to the riverbank almost exhaustively. As shown in figure 2.1, the GP expressway presents at least 3 itineraries of substitution, two of which are local roads with the same flow direction that circumvent the closed section: "Boulevard Saint Germain" and the upper banks. However, the third itinerary of substitution is the south outer ring road - serving as an alternative for the 13-km expressway road - forcing people to abandon the full riverbank.

In my main specification, I compare, before and after September 1<sup>st</sup> 2016, the occupancy rates and flow of cars of the roads with the same flow direction as the riverbank to roads with the opposite flow direction, controlling for segment and day×hour fixed effects. I run this estimate separately for local roads and ring roads since both sets of roads are likely to be impacted differently. The former will most possibly attract inner-city commuters while the latter will capture commuters intending to cut across Paris. Furthermore, they both have different technical road performances. While ring roads are made of continuous steel with no traffic lights or pedestrian crosswalks and a speed limit of 70km/h, local roads present several lights and pedestrian crossings with a speed limit of 50km/h at that time.<sup>3</sup>

I first look at the impact of the GP closure on the two main outcomes: flow of cars and

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<sup>3</sup>The speed limit on local roads was lowered to 30km/h citywide in 2022.

occupancy rates. I show that the flow of cars decreased by 6% on the ring road and increased by 26% on local roads. The difference in signs comes from the non-linear character of traffic flows since the same level of flow can be observed at two different speeds. For instance, a negative impact on traffic flows can indicate a decrease in the number of cars provided that the road is uncongested (at freeflow speed). It can also indicate an increase in the number of cars entering the road if downstream bottleneck is at capacity. In other words, a queue forms at the entrance of the road and grows with additional vehicles, which lowers the average speed on the road and decreases the number of cars counted in a given time span. To this matter, I turn my analysis to the impact on occupancy rates. I show that occupancy rates increased by 11.2% on the ring roads and by 34% on local roads, with the highest impact during evening hours. This is consistent with the fact that the GP expressway was mainly used during evening hours, since the west of Paris is an employment hub while the east of Paris is a highly-dense residential area.

I then look at congestion and average speed that I deduce using the occupancy rates and the flow of cars. I first compute an indicator of congestion by using the quadratic relationship between traffic flow and occupancy rate, described by the *fundamental diagram* well-known in the transportation literature. Second, relying on simple parametric assumptions, I can comment on the impact of the closure on the average speed of vehicles on the roads. I find that the ring roads are 21% more congested due to the GP closure while local ring roads show an increase in the probability of congestion of 50%. Both results are consistent with the conclusions I get from running the difference-in-difference on the average speed. Namely, I find a decrease in the average speed by 16.5% on the ring road and 17.5% on local roads.

I extend my work to the evaluation of the negative externalities of traffic. I make use of two permanent pollution monitors located near the periphery and near the upper banks. Using pre-closure data, I estimate the elasticity of  $NO_2$  concentrations with respect to the average speed on nearby road segments, controlling for weather characteristics and the flow of cars. I multiply this elasticity by the impact on the average speed to impute the effect on  $NO_2$  emissions, both near the upper banks and near the ring roads. With an elasticity of pollution to speed of -0.34% on the ring roads and -0.08% on local roads, I show that the emissions of nitrogen dioxide increased by

5.8% near the ring roads and by 1.5% near local roads. However,  $NO_2$  emissions are not the only consequence of increased traffic. Increased noise pollution or other particulate pollutants can also occur. To have a sense of the magnitude of the overall cost, I evaluate the causal impact of the GP closure on housing prices near the periphery bearing in mind that all amenities are capitalized in housing prices. I find a decrease of housing prices in the 700-meter vicinity of the periphery by 5%.

Although we all experienced traffic congestion, the traffic problem is far from easy to understand. This is a consequence of the chaotic nature of traffic flows. A small input can get greatly magnified, which makes the problem "non-linear". In other words, a reallocation of cars from one road to a more congested road generates a net increase in congestion - and hence pollution. As such, it is impossible to back out the number of drivers switching on each substitute road just by looking at the reduced-form results. Yet, knowing the number of extra cars on each road is essential for the cost analysis. For this purpose, the second part of my paper provides a simple model of shortest route with endogenous congestion based on Akbar and Duranton (2017) to quantify the costs of the policy. The model predicts that the overall impact on congestion and pollution depends on the elasticity of congestion of each substitute road - i.e., the degree to which the number of cars impacts speed on the road. Closing a less congested road than its substitute roads will generate an overall rise in congestion and pollution in the absence of a (sufficient) mode switch. By estimating each treated road's congestion elasticity and distinguishing between (i) inner-city commuters and (ii) suburban commuters, I back out the number of commuters diverting on each road. This allows me to compute the costs generated and speak to the distributional aspects of this policy.

I show that higher-income commuters bear 60% of the time costs while lower-income residents bear 90% of the pollution costs, most of them living outside the local jurisdiction responsible for this closure. This brings into question the political economy behind the adoption of this kind of policy, which was implemented by the Mayor of Paris but ended up hurting people who live outside her jurisdiction. Finally, I use the model to study several counterfactual scenarios of interest from a theoretical or a policy point of view. They suggest that (i) closing only half of the segment

would have drastically mitigated pollution externalities (ii) for the policy to yield zero pollution cost, more than 50% of inner-city commuters and 10% of suburban commuters should have had to switch to (uncongested) alternative transportation and (iii) a wider car-free zone (planned to take place by 2030) would lead to a slight decrease in pollution cost but a substantial increase in time cost, if no mode shift occurs.

**Relation to the literature** This project builds on and contributes to several literatures.

First, road reduction is part of a wide array of congestion policies implemented in cities, which have been studied in numerous works. On the demand-side, road pricing is seen as the most efficient and reasonable solution to deal with congestion (Liu and McDonald, 1999; Santos et al., 2008; Tirachini and Hensher, 2012; Winston and Langer, 2006). However, with little social acceptance, many cities have instead used supply-side policies such as road space rationing, restricting the days or hours in which car users can drive on congested roads (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003) or urban rail-transit expansions (Adler and van Ommeren, 2016; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021). Other cities, including Paris, have opted for quantity-rationing by gradually reducing their road capacity. For example, Seoul transformed its main highway into an urban boulevard (Kang and Cervero, 2009) while New York has used *High Occupancy Toll* (HOT) lanes (Poole Jr and Orski, 2000). In the case of Paris, the choice of road reduction rather than road pricing takes on a political dimension due to the low levels of consent to taxation among French car users.<sup>4</sup> This paper adds to this literature as it is, to the best of my knowledge, the first paper to causally identify the impacts of a road-reduction policy on traffic and congestion in a city.

Second, ever since the Downs (1962) paradox, a general consensus in the literature has emerged, whereby increasing the road supply is unlikely to reduce congestion: *If you build it, they will come*. This principle, known as the *fundamental law of road congestion* comes from the induced-demand. Although the elasticity of traffic to roadway lane kilometers is well-known to be close to 1 in the literature (Duranton and Turner, 2011a), no study to this date has sought

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<sup>4</sup>When President Macron made the decision to impose a gasoline tax, it backfired on him and the yellow vests (*Gilets Jaunes*) were quick to react and cause turmoil in the country (Boyer et al., 2020).

to evaluate the symmetry of such elasticity. The question that arises here is whether *reduced-demand* reacts the same way: *If you demolish it, will they not come?* There are many reasons to believe this elasticity is not symmetrical. In fact, road expansion is implemented on heavily-used roads to relieve congestion, while road reduction is made to free up some high-amenity potential roads. In addition, road expansions lead to new home constructions next to a new highway or a major road, which would feed once again the induced demand. However, road reduction is unlikely to lead to homes being torn down.<sup>5</sup> I contribute to this literature by evaluating the short-run impacts of a road closure on traffic congestion. My results show that reducing the road capacity does not reduce congestion, at least in the short run.<sup>6</sup>

Third, this paper provides causal estimates of a marginal change in the road supply on both congestion and air pollution. On one hand, there is an extensive literature documenting the relationship between road restrictions and traffic congestion (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003). On the other hand, a large body of work in urban studies and transportation economics is devoted to the quantification of the negative consequences of urban road traffic on health through pollutant emissions, although causal assessments are rather scarce (Anderson, 2020; Currie and Walker, 2011; Gibson and Carnovale, 2015; Prud'homme et al., 2011). A common finding of many studies is that congestion policies may only have a positive impact on air quality if they do not increase congestion on untargeted roads (Bhalla et al., 2014). For example, Davis (2008) shows that banning some drivers from using their cars in Mexico City failed to decrease the use of car, thus providing no evidence that the restrictions have improved air quality. However, results have yet to be combined into a setting that evaluates the impacts of a traffic policy on both of these externalities.

Last, this paper contributes to the literature on the characterization of traffic congestion. Engineering studies find a convex relationship between traffic volume and travel time which suggests large marginal costs when congestion is already high. Economists have focused on two

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<sup>5</sup>The only channel through which the demand might be reduced is through reallocation of residents or mode switch.

<sup>6</sup>My results would have been comparable to a *short-run* evaluation of a road expansion. However, papers looking at road constructions focus on the long-run impacts with data less precise than the one I use. In this sense, I cannot really provide an elasticity of road kilometers to road traffic that would allow for a comparison between road expansion and road reduction.

approaches to model congestion: the static speed-flow curve and the dynamic deterministic bottleneck model (See Small and Verhoef (2007) for a selected review of studies). Several papers have measured the effect of vehicle density on travel flows either on selected segments (Ardekani and Herman, 1987; Geroliminis and Daganzo, 2008) or for an entire city (Akbar and Duranton, 2017). In this paper, I use the congestion model developed by Akbar and Duranton (2017) and extend it to the case of a road closure. By estimating the congestion elasticity of each treated road, I am able to predict the impacts of a road closure on substitute roads.

The remainder of the paper is structured as follows: Section 2.2 describes the background and data sources. Section 2.3 presents the main empirical analyses on traffic. Section 2.4 documents evidence of pollution increase. Section 2.5 sets up a theoretical model of pollution and congestion that I use to analyze the case of the GP closure, to quantify the costs of the policy and to report some policy counterfactual scenarios. Section 2.6 concludes by providing some policy insights.

## 2.2 Context and data

### 2.2.1 Commuting in Ile-de-France and the riverbank shutdown of 2016

The Ile-de-France region is in north-central France. It is divided into eight departments and surrounds Paris. In the Ile-de-France region, job concentration follows a decreasing gradient, with Paris City as its core (see Figure 2.7), consistent with the monocentric model (Chapelle et al., 2020).<sup>7</sup> Most individuals commute to the center of the region either by car or by public transportation, depending on access to train stations. Municipalities located in the east or west of Ile-de-France have the highest share of car commuters (Figure 2.8 (a)) and car use is particularly dominant for suburb-to-suburb journeys (Figure 2.8 (b)).

The urge to transform the city into a greener one was at the heart of the 2014 municipal

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<sup>7</sup>The resident gradient is reversed within Paris: densities are higher on the outskirts of the city, particularly around the ring roads.

elections, won by Mayor Hidalgo.<sup>8</sup> Her campaign mainly focused on environmental and urban strategies that reversed previous schemes based on increasing road capacities.<sup>9</sup> Her program was threefold: offer a greater role to nature within Paris proper; promote the creation of public housing; and improve the efficiency of urban logistics. This included reducing the number of cars in the city by pedestrianizing some roads and creating new bus and cycling lanes.

The GP riverbank was the object of her most contested reform even though in the 2000s the progressive pedestrianization of the riverbank had already taken place. While banning cars from this road was initially implemented every Sunday and during bank holidays, then an entire month in summertime dedicated to "Paris Plage" (Paris-by-the-beach), Mayor Hidalgo formally established it on September 1<sup>st</sup>, 2016. This policy was justified with the urge to decrease vehicle circulation by provoking a mode shift, thus reduce pollution in the city when around 40,000 vehicles were circulating on this expressway every day. After the Paris Plage event of summer 2016, the GP riverbank from the Tuileries to the Henry IV tunnel was never reopened although the shutdown was not yet official. This project was first implemented in autumn 2016, but went through many protests and disputes before it legitimately took place. I provide a detailed description of the timeline implementation of this policy in Appendix 2.7.1. Despite the struggles she had to face during her first term, Mayor Hidalgo was re-elected in 2020.

## 2.2.2 Data description

This study makes use of several databases:

**Comptage routier -Données trafic issues des capteurs permanents.** This is the main dataset for the study. The City Hall (Mairie de Paris) monitors the traffic situation on the main roads of

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<sup>8</sup>Mayor Hidalgo has been the Mayor of Paris since 2014. She has been a member of the Socialist Party since 1994. Her political view is mainly centered around environmental policies. To fight air pollution, she introduced in 2016 a scheme called "*Paris Respire*", literally "Paris Breathes" by banning some cars from certain areas in Paris on the first Sunday of every month.

<sup>9</sup>For example, the riverbanks along the Seine river (dashed line of Figure 2.1) were first open to vehicle circulation in the 1970s with the aim of reducing travel time. This expressway was inaugurated in December 1967 by the Prime Minister Georges Pompidou. Originally, the project was meant to gather different sections in order to create a continuous fast track across the city.

Paris by implementing electromagnetic loops endowed with sensors in its pavements.<sup>10</sup> Roads are decomposed into segments or "arcs". Each arc is monitored by one sensor and corresponds to the unit of observation. The sensors can detect two main types of data:

- Occupancy rate: This corresponds to the time vehicles are located above a loop as a percentage of an hour. For example, an occupancy rate of 25% indicates that cars were present in the loop for 15 minutes.
- Flow: This counts the number of cars that pass by a point in an hour. The same flow can correspond to either a saturated or a fluid traffic situation, depending on the corresponding occupancy rate level.

For each observation, I have hourly data of the occupancy rate and flow from 01/01/2013 00:00 until now. However, a public transportation strike happened in the last months of 2019 and the COVID-19 pandemic hit in 2020. Both events significantly impacted road traffic in Paris. To this matter, I restrict the dataset to observations until September 1, 2019.

I make use of these data to impute other variables which are important for my analysis. First, by assuming an average length of vehicles, I compute the average speed on each road section. I assume the average length of vehicles to be 4.5 meters.<sup>11</sup> Using the flow per lane as well as the occupancy rate, the average speed can be computed with Athol's formula (Hall, 1996):

$$Speed_{it} = \left( Flow_{it} \times (L + K_i) \right) / Occupancy_{it} \quad (2.1)$$

where  $Speed_{it}$  represents the average speed (km/h) on road section  $i$  at time  $t$ ,  $Flow_{it}$  and  $Occupancy_{it}$  are the flow per lane and the occupancy rate on section  $i$  at time  $t$ .  $L$  represents the average length of vehicles (here 0.0045 km) and  $K_i$  is the length in km of the road section  $i$ <sup>12</sup>.

<sup>10</sup><https://opendata.paris.fr/pages/home/>

<sup>11</sup>The length of vehicles passing can vary, especially when trucks are included in the sample. Therefore, the speed computed represents an approximation of the actual average speed.

<sup>12</sup>Since the sensor occupies the entire road section, the length of each road section is equal to the length of the sensor.



Second, with flow and speed measurements, density (vehicles per kilometer) is easily calculated by dividing the flow rate by the speed:

$$N_{it} = \frac{Flow_{it}}{Speed_{it}} \quad (2.2)$$

$$N_{it} \approx \frac{Occupancy_{it}}{L + K_i} \quad (2.3)$$

with  $N_{it}$  representing the number of vehicles per kilometer on road section  $i$  at time  $t$ .

Unfortunately, these data are only available for Paris' roads which enables me to only observe the traffic impact on roads in intramural Paris. I also lack socioeconomic data regarding road users and cannot track vehicles due to the aggregated shape of the data. I use other datasets to ballpark aggregate consequences of the GP closure such as exposure to pollution or the impact on housing prices.

**Population Census of 2013, 2014, 2015, 2016, 2017 and 2018 -Logements, individus, activité, mobilités scolaires et professionnelles, migrations résidentielles.** For each individual, information about home location, workplace, mode of transportation, age, and status are available from censuses conducted by the National Institute of Statistics and Economic Studies (INSEE). This allows me to determine the percentage of people commuting by car and public transportation. However, these data provide no information on precise itineraries of commuters.

**Pollution levels -Airparif.** Airparif is a nonprofit organization, linked to the Ministry of Environment, that monitors air quality in the Ile-de-France region. Different monitors across the region register emission levels of various pollutants ( $NO_2$ ,  $PM_{10}$ ,  $PM_{2,5}$  and  $O_3$ ). I am interested in the monitors near the ring roads and the one near the upper banks. Both register hourly emission levels of  $NO_2$  for the years 2013 to 2018, aiming at capturing pollution from traffic.

**Public transport traffic per entry - Validations sur le réseau ferré : Nombre de validations par jour.** Ile-de-France mobilités<sup>13</sup> provides data on the daily number of people entering each

<sup>13</sup> *Île-de-France Mobilités* is the Organizing Authority for sustainable mobility in Ile-de-France.

train station. For this analysis, I use data on the two RERs (regional express networks), which are the main train lines serving Paris and its surrounding suburbs.

**Demandes de Valeurs Foncières (DVF).** I use exhaustive data recording all housing transactions in France from January 2014 to December 2018, recorded by the French Treasury for tax purposes in the *DVF* database. It provides information on the price of the transaction, its location, the date the transaction happened as well as some characteristics of the house (built area, number of rooms, type of house).

### 2.2.3 The Georges Pompidou riverbank

The *Georges Pompidou* riverbank is 13 kilometers long and crosses Paris from southwest to southeast (see Figure 2.1) with a unique flow direction (eastward). Figure 2.9 provides some descriptive statistics of the riverbank traffic in 2015, a year before the pedestrianization of its center. The descriptive statistics of the pedestrianized segment (figure 2.9 (b)) suggest that this part of the riverbank is less congested or occupied than the average (lower flow and occupancy rate). In fact, the occupancy rate never exceeds 15%, which highlights the fluidity of the traffic on this segment. Furthermore, there is no obvious variability between peak hours and non peak hours. Instead, the flow of cars is always high from 8 AM to 9 PM. However, roads appear to be slightly more occupied during evening hours from 5 PM to 8 PM. This could imply that most users lived in the east and worked in the west.

In 2015, the average daily flow on the entire riverbank corresponds to 40,000 vehicles representing half of the daily flow of the south outer ring road. The 3.3 kilometers to be pedestrianized have a daily flow of around 35,000 cars. Although the shutdown was implemented on September 1<sup>st</sup> 2016, the pedestrianized area was already closed as of mid-July and throughout August for the *Paris Plage* event; hence, no traffic can be recorded during this period (figure 2.10). To obtain a sense of the impact of the closure on circulation, I plot the hourly mean of traffic flow of the riverbank when omitting the 3.3-kilometer stretch to be pedestrianized, before and after the closure (Figure 2.11). The non-pedestrianized stretch of the riverbank presents a lower flow aver-

age after the shutdown, which provides some suggestive evidence that some ex-riverbank users abandoned the whole riverbank itinerary once its center was closed. Indeed, former riverbank users could have either decided to change their means of transportation or to change itineraries. Had they decided to change routes, they could either circumvent the closed section using other local roads or abandon the whole riverbank and use another road. If so, a direct substitute would be the ring roads outside Paris. The eastward trip of the riverbank can be replaced by the south outer ring road.

### 2.2.4 The local roads

The closed section of the riverbank presents two clear substitute roads within 1-kilometer: the “*Boulevard Saint Germain*” and the *upper banks*. Both substitute roads have the same flow direction as the riverbank. However, they both differ in two particular dimensions: (i) they are interrupted by traffic lights and pedestrian crosswalks, and (ii) they are equipped with cycling and/or bus lanes. These two features make them slower and subject to higher time variability than the riverbank. In table 2.6, I provide some descriptive statistics on both roads.

Descriptive data of the riverbank suggests that only a fraction of the riverbank users abandoned the itinerary and the larger fraction are still using the non-pedestrianized stretch (Figure 2.11). Remaining users can only circumvent the closed section with local roads. In this paper, I estimate the impact of the GP closure on the substitute local roads within 1-kilometer of the closure.

### 2.2.5 The ring roads

Three main bypasses encircle Paris (Figure 2.12) and allow travelers to circumvent Paris. The first one is the *Boulevard Périphérique* (Ring Road), which separates the municipality of Paris, over which the Mayor has jurisdiction, from the rest of the metropolitan area. The second circle represents the A86 highway, sometimes called the *Super Périphérique*. It forms a complete circle at a variable distance between 8 and 16 kilometers from the center of Paris in which suburb-to-

suburb transit represents 87% of private vehicle commutes (Bouleau, 2013). The third bypass is called *La Francilienne*, which is an incomplete set of highways and express roads circling the Ile-de-France region; it is 160 kilometers long and approximately 30 kilometers away from the center of Paris.

In this paper, I evaluate the impact of the GP closure on the first bypass: The *Boulevard Périphérique*.<sup>14</sup> These ring roads are among the most commonly used urban roads of Europe. They are 35 kilometers long, which represents 20 times the length of the Champs-Élysées, and account for 2.5% of Paris' total linear roadway. Moreover, they take up to 40% of Paris' road traffic (Aur, 2016). Suburb-to-suburb transit represents almost 40% of the traffic on these roads, compared to 55% for Paris-Suburb journeys (Bouleau, 2013). I focus on its southern part since it represents a direct substitute to the riverbank (almost same length). It is of 10.5-kilometers and shares an entrance and exit with the GP expressway. Also, before the 2016 shutdown, using the ring road to cross Paris would deliver (almost) the same travel time as using the GP-expressway. In Table 2.6, I provide descriptive statistics of the ring roads traffic before and after the riverbank shutdown. During daytime, we can note saturated traffic conditions even in the pre-shutdown period. As a result, adding extra vehicles to these roads is very likely to generate traffic jams.

## 2.3 Impact on Traffic

In this section, I look at the impact of the GP shutdown on the traffic situation of substitute roads.

### 2.3.1 Empirical Strategy

#### Treatment and Control groups

Using a difference-in-difference strategy, I evaluate the impact of the GP closure on traffic conditions of (i) local substitute roads, and (ii) the south ring road around the city. More precisely, I compare, before and after September 1<sup>st</sup> 2016, substitute roads with the same flow direction as

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<sup>14</sup>The Boulevard Périphérique is composed of one outer ring road and one inner ring road.

the riverbank (treatment group) with similar roads of the opposite flow direction (control group). The main intuition behind my identification strategy stems from the idea that a GP-user is unlikely to divert to a westward road. In fact, since the GP has only one flow direction (eastward), ex-GP users are only impacted during the eastward trip of their commute. The westward trip is left unchanged, provided that they do not change means of transportation.

Since treatment and control groups must be comparable, I use the traffic on the same type of road with an opposite flow direction as a control for each treated road. First, I look at the impact of the riverbank closure on local substitute roads within 1-kilometer of the road closed, with the same flow direction as the riverbank and sharing and entrance and exit around the closed segment. This boils down to two treated roads: the “*Boulevard Saint Germain*” and the *Upper banks*. I use the lower banks with the opposite flow direction as the control group. Indeed, the lower bank has the exact same characteristics as the treated local roads (i.e. speed limit, presence of traffic lights, number of lanes), with one main difference: an opposite flow direction. I select a road length of 6.6-kilometers of the control group to have the same number of road kilometers in the treatment and control groups. The treated local roads are composed of 44 arcs of roads and the control local road of 41 arcs of roads.<sup>15</sup>

I also look at the impacts on roads that could serve as a substitute to the entire GP expressway. As previously argued, the road along the Seine River was part of an itinerary for western-based commuters to access the eastern suburbs and vice versa. Given that the GP expressway was used by some commuters to cross Paris, it is likely that part of the effect was reflected on the ring road since it also serves this purpose. To this matter, I study the impact on the southern part of the *Boulevard Périphérique*. The treated road would be the south outer ring road since it is the eastern road of the south ring road. The control group is the south inner ring road, both roads being comparable: they are arguably the only akin roads that are completely independent of each other in the urban area, with one particular difference being the flow direction. The treated ring road is composed of 22 arcs of roads and the control ring road of 21 arcs of roads.<sup>16</sup>

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<sup>15</sup>The average length of a local road segment is of 0.14 kilometers.

<sup>16</sup>The average length of a ring road segment is of 0.45 kilometers.

## Specifications

I first estimate the following specification over the period September 2013 - September 2019:

$$Y_{it} = \alpha + \gamma \mathbb{1}_{treated_i=1} \mathbb{1}_{post=1} + \lambda_t + \psi_i + \epsilon_{it} \quad (2.4)$$

where  $i$  represents the arc, a segment of a road, and  $t$  represents the time by the hour.  $Y_{it}$  denotes the outcome considered on arc  $i$  at date  $t$ . The indicator variable  $\mathbb{1}_{treated_i=1}$  equals 1 if arc  $i$  belongs to an eastward ring road (treatment group) and 0 if it belongs to a westward ring road (control group). The indicator variable  $\mathbb{1}_{post=1}$  equals 1 if the reform has been adopted (after September 1, 2016) and 0 otherwise.  $\psi_i$  and  $\lambda_t$  are arcs and  $day \times hour$  fixed effects, respectively. Standard errors are clustered at the arc level. Here, the causal inference I am interested in is captured by the coefficient  $\gamma$ . I expect this coefficient to be significant and have a positive sign on the occupancy rate if the policy displaces traffic to the substitute roads I restrict my analysis to.

I then estimate the following leads-and-lags regression to evaluate the impact of the policy several years after its implementation and test for the presence of pre-trends.

$$Y_{it} = \alpha + \sum_{k=-3}^{+2} \beta_k \mathbb{1}_{treated_i=1} \mathbb{1}_{T(t)=k} + \lambda_t + \psi_i + \epsilon_{it} \quad (2.5)$$

where  $T(t)$  represents the relative year compared to the year the GP riverbank was pedestrianized.<sup>17</sup>  $\beta_k$  represents the incremental impact of the policy on year  $k$ , compared to the reference year. All coefficient are normalized relative to year -1.

## Identification: Assumptions and Threats

In the absence of treatment, the identification assumption claims that the difference between the treatment and control groups is constant over time. Here, it implies that absent from the September 2016 reform, the occupancy rates and flow of cars in the treatment and control groups

<sup>17</sup>A year includes the period from the 1<sup>st</sup> of September to the 31<sup>st</sup> of July of the following year, since August is omitted.

would have evolved similarly. The trends of treatment and control groups are represented in figure 2.14, where the occupancy rates and flow of cars are represented by a yearly moving average. Control and treated units present, at least visually, parallel trends before 2016. In addition to graphical support, I test for the significance of the pre-treatment estimates. Figure 2.3 display the estimates of equation (2.5) and validates the presence of parallel trend. I portray below the three main threats to the identification strategy.

**Credibility of control group.** The main concern is the credibility of the control group. First, one might wonder whether the effects on the treated roads would spill over onto the non-treated roads. However, the control group has an opposite flow direction to the riverbank. Therefore, commuters are unlikely to substitute the riverbank itinerary with a road that has an opposite flow direction and eastward commuters would still keep the same path on their way back home (or westward commuters on their way to work). The only way the control group could have been impacted is through an overall decrease of traffic. If ex-GP users switch to alternative means of transportation, the control group would experience a decrease in the average traffic which would not be observed in the treated group. This would overestimate the impact of the GP closure. Second, the increase in traffic on substitute roads might have encourage some (non-GP) car users to shift away from car transportation. If it targets commuters who were initially on substitute road, the decrease in traffic would be similar in the treatment and control group; unless commuters do not use both sets of roads in their commuting trip. However, plotting the trend of the control group (figure 2.14) shows no clear decline in the occupancy rates over the years.

I make use of the timing of traffic to allow comparability between traffic in the control group and traffic in the treatment group for shorter time spans. Since commuters make use of one flow direction in the morning and its opposite in the evening, I use the evening traffic of westward roads as a control for morning traffic of eastward roads and vice-versa. This allows me to have approximately the same number of commuters in both groups when evaluating the impact of the GP on a subsample of hours.

Appendix 2.7.2 discusses whether the GP closure provoked a mode switch towards public transportation. I show that there is no significant evidence of an increase in the usage of the west-east public transportation lane. This results corroborates the idea that, at least in the short-run, the GP closure did not contribute to a mode switch among car-users.<sup>18</sup> In addition, the model developed in section 2.5 and calibrated on Paris is consistent with very limited mode shift.

**Anticipation effects.** The second worry boils down to anticipation effects: since the GP closure was announced in December 2015, commuters might have deviated from this itinerary before its official shutdown. Figure 2.13 provides evidence of a potential anticipatory effect showing that people googled this event at the end of 2015. However, Figure 2.3 shows no significant difference between the treatment and control prior to 2016.

**Other simultaneous urban policies.** Finally, Mayor Hidalgo's first mandate was crammed with urban modifications to promote alternatives to car. One of these was *Plan vélo 2015-2020*, which aimed for biking to represent 15% of the modal share of Paris and its nearby suburbs, versus 3% in 2014. If not taken into consideration, it could be responsible for part of the average treatment effect observed. However, this bias would exist if, for some reason, additional cycling and/or bus lanes were implemented on the eastward lanes differently than on the westward lanes. Other transportation programs such as new tramway lines were also implemented in recent years. To ensure that I disentangle the effect of the GP pedestrianization from these other programs, I perform a placebo test. I take a subsample including all the observations before the event from January 1<sup>st</sup>, 2013 to August 31<sup>st</sup>, 2016. I then perform a difference-in-difference with phantom events (every 30 days starting January 1, 2015 until September 29, 2015). Figure 2.15 represents the results of the placebo difference-in-differences. All the virtual treatment effects are statistically non-significant and close to zero, once again lending support to the identification strategy.

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<sup>18</sup>Reluctance to switch transportation modes could have more than one explanation. The presence of subway congestion, especially during peak hours, increases the cost of shifting from car to public transportation (Haywood et al., 2018). It is also worth noting that individuals who purchased a car before 2016 may want to depreciate its cost over the years, so that any shift toward public transportation may only be visible over a longer time span.



### 2.3.2 Main results

In this section, I estimate the causal impact of the GP shutdown on the traffic situation of substitute roads. I first focus on the occupancy rate and flow of cars described in Section 2.2. Then, by imposing some assumptions, I look at the average speed and the probability of congestion. I separate the sample into three to capture time heterogeneity: morning hours (8AM to 10AM), evening hours (6PM to 8PM) and daytime (8AM to 8PM). I estimate equations (2.4) and (2.5) to evaluate the average impact of the riverbank shutdown on the traffic situation of (i) local roads and (ii) the south ring roads.

#### Flow of cars

I first look at the impact on traffic flow. The flow of cars represent the number of cars that are counted in an hour on a given road segment. Table 2.1 gather the estimates of equation (2.4). The average flow during an hour increased by at least 26% on local roads. On the contrary, the number of cars passing during an hour decreased by 6% on the ring roads. The impact is consistent and significant over time (Figure 2.2). The difference in signs on both roads does not necessarily indicate that traffic has been displaced on local roads and not on the ring roads. In fact, a tiny disruption in the flow can cause congestion. In other words, traffic flow is linear, until it no longer is. The flow increases linearly as everyone continues to drive the posted speed limit and there are more cars on the road. However, as vehicles on the road increase to a congested state, they start to drive slower. Therefore, traffic flow does not behave linearly after some point.

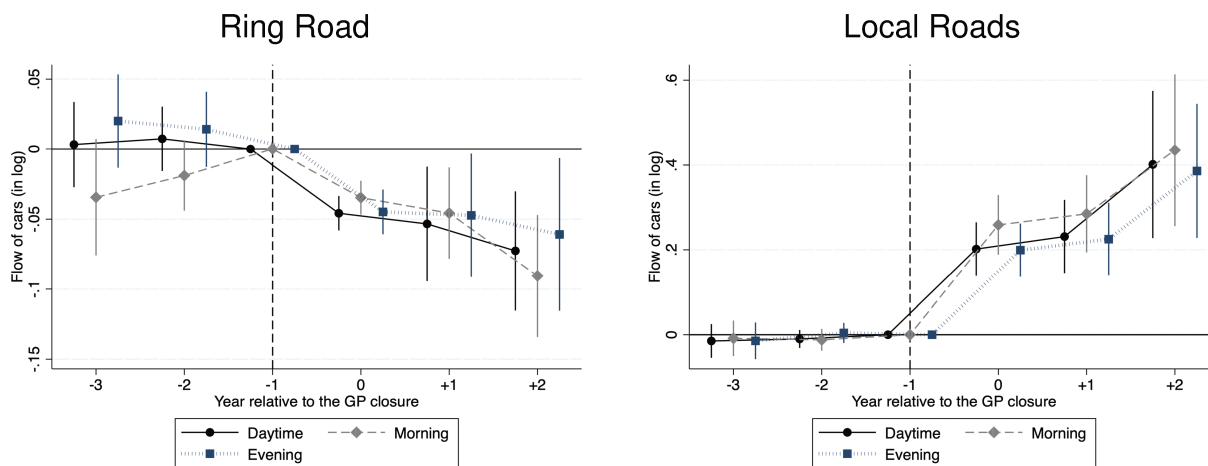
**Table 2.1:** Impact on the flow of cars

	(1)	(2)	(3)
	<b>Flow (in log)</b>		
	Morning	Evening	Daytime
<b>Ring Roads</b>			
Treatment	-0.061*** (0.013)	-0.081*** (0.020)	-0.061*** (0.013)
Constant	8.387*** (0.003)	8.366*** (0.005)	8.395*** (0.003)
Observations	14,4155	97,405	627,122
$R^2$	0.895	0.863	0.855
<b>Local Roads</b>			
Treatment	0.331*** (0.050)	0.212*** (0.051)	0.264*** (0.048)
Constant	7.125*** (0.017)	7.331*** (0.017)	7.189*** (0.017)
Observations	335,934	227,045	1,461,499
$R^2$	0.797	0.712	0.750
Arc FE	Yes	Yes	Yes
<i>Day</i> × <i>hour</i> FE	Yes	Yes	Yes

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$

standard errors clustered at the arc level

*Notes:* The outcome is the log of the flow of cars in an hour. Column (1) represents the estimation during morning hours, from 8Am to 10 AM. Columns (2) during evening hours from 6PM to 8PM and column (3) during daytime from 8Am to 8PM. The first part of the table shows the impact on the ring roads. The second part of the table shows the impact on the 2 local roads considered: the boulevard saint germain and the upper bank.

**Figure 2.2:** Impact on the flow of cars

Notes: These graphs plot the estimates and 95% confidence intervals from equation (2.5). The outcome is the log of the flow of cars in an hour: the count of cars that pass by a point in an hour. The straight line represents the estimates during daytime hours (from 8AM to 8PM). The dashed line represents the estimates during morning hours (from 8AM to 10AM) and the dotted line represents the estimates on evening hours (from 6PM to 8PM). All samples are restricted to the working days of the week (from Monday to Friday).

To understand what happens to the traffic situation on both roads, I then turn my analysis to the impact on the occupancy rates.

### Occupancy Rate

On the ring roads, the average impact is the highest for evening hours with an impact of 14.2% (compared to 9.4% for morning hours and 11.2% for the whole day). This is consistent with the traffic situation on the riverbank before its shutdown. Indeed, figure 2.9 shows that the riverbank was mostly taken during the evening, suggestive of a job/resident imbalance. However, the impacts on local roads do not vary much and remains around 33% (table 2.2). Figure 2.3 shows the impacts over time and suggests higher occupancy rates even three years after the GP shutdown. A decrease in the magnitude of the impact is observed on the ring road for morning hours. However, the impacts across the years are not statistically different from each other during morning hours. The increase in the occupancy rates on both sets of roads suggests that treated roads are denser, which caused a decrease in the flow of cars on the ring road due to traffic jams.

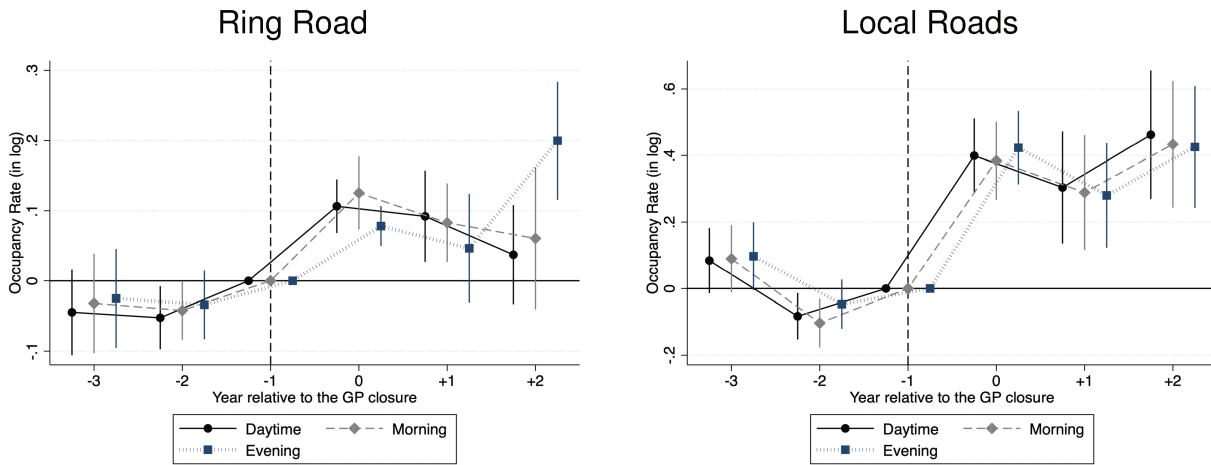
**Table 2.2:** Impact on the occupancy rate

	(1)	(2)	(3)
	<b>Occupancy rate (in log)</b>		
	Morning	Evening	Daytime
	<b>Ring Roads</b>		
Treatment	0.094*** (0.017)	0.142*** (0.026)	0.112*** (0.018)
Constant	3.141*** (0.004)	3.264*** (0.007)	3.146*** (0.005)
Observations	176,038	118,781	765,044
$R^2$	0.676	0.566	0.569
	<b>Local Roads</b>		
Treatment	0.321*** (0.078)	0.328*** (0.083)	0.339*** (0.080)
Constant	2.158*** (0.024)	2.365*** (0.025)	2.233*** (0.024)
Observations	397,931	268,689	1,729,726
$R^2$	0.613	0.580	0.579
Arc FE	Yes	Yes	Yes
<i>Day</i> × <i>hour</i> FE	Yes	Yes	Yes

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$

standard errors clustered at the arc level

*Notes:* The outcome is the log of the occupancy rate, which is a percentage of an hour. The occupancy rate represents the fraction of time a road section has been occupied by cars. Column (1) represents the estimation during morning hours, from 8Am to 10 AM. Columns (2) during evening hours from 6PM to 8PM and column (3) during daytime from 8Am to 8PM. The first part of the table shows the impact on the ring roads. The second part of the table shows the impact on the 2 local roads considered: the boulevard saint germain and the upper bank.

**Figure 2.3:** Impact on the occupancy rate

*Notes:* These graphs plot the estimates and 95% confidence intervals from equation (2.5). The outcome is the log of the occupancy rate: the percentage of an hour that vehicles stay on a loop. The straight line represents the estimates during daytime hours (from 8AM to 8PM). The dashed line represents the estimates during morning hours (from 8AM to 10AM) and the dotted line represents the estimates on evening hours (from 6PM to 8PM). All samples are restricted to the working days of the week (from Monday to Friday).

## Robustness Checks

In what follows, I perform a number of checks and tests to validate the robustness of the previous results.

**Fixed effects.** I check that the result is not the spurious outcome resulting from a too saturated model. To this end, I first add the dummy variable  $\mathbb{1}_{treated_i=1}$  to equation (2.4) and drop the arc fixed effects (Column (2) of Tables 2.8 and 2.9). The estimates for the treatment effect are barely affected and the significance remains the same. Second, instead of including time fixed effects that control for the differences between each hour of each day, I separately include year, month of the year, day of the week and hour of the day fixed effects. Column (3) of these same tables provide the estimates while changing the fixed effects. The inclusion of additive, instead of multiplicative time fixed effects decreases the R-squared but leaves the treatment effect virtually unaffected.

**Clustering.** Since road users are likely to drive on several sections of the same road, there might be reasons to believe that unobserved components of the traffic outcomes may be correlated between arcs of roads. For instance, we could think of accidents on a road that affect the occupancy rate of several sections of the same road. To address this concern, I construct clusters composed of arcs of road between two entries. Column (4) of Tables 2.8 and 2.9 show that the clustering at the road level increases the standard errors although the significance of the results remains unchanged.

**Outliers.** Some outliers can distort the outcomes and hence the estimates. We could think of two-wheelers exceeding the average speed of four-wheeled vehicles. This kind of behavior would appear at the bottom of the occupancy rate distribution. On the other hand, if a car stops on the road, say due to stalling, the sensor would register a very high occupancy rate on the relevant road sections. This would therefore appear on the top of the distribution. To take this into account, I winsorize the top and bottom of the occupancy rate and flow distribution at the 1% level. Results are shown in column (5) of tables 2.8 and 2.9. The estimates and standard errors do not vary, which indicates that outliers do not drive the results.

### **Further Results**

The results so far suggest that the riverbank shutdown is responsible for an increase in occupancy rates on the ring road as well as on 2 local roads within 1-kilometer of the riverbank. However, an increase in occupancy rates does not necessarily mean that the road is more congested or that the average speed on the road decreases. Indeed, consider a situation where only one car is on the road, driving at the speed limit. Adding another car on the same road will mechanically increase the occupancy rate. However, both cars can still drive at the speed limit, hence creating no traffic congestion. What matters on a broader economic scale is whether this policy is causing delays which result in the late arrival of workers. Since I cannot observe individually each commuter, I rely on the aggregated traffic data set to infer some conclusions about congestion and travel time. This section takes the analysis in this further direction by imposing

stronger assumptions.

**Probability of Congestion.** As previously mentioned, the increase in occupancy rates is not a problem per se. In fact, if the traffic is initially fluid, increasing the occupancy might not be harmful. The efficiency loss, if any, comes from congestion. To measure congestion, I make use of the fact that traffic flow per lane and occupancy rate are linked via a concave relationship known as the *fundamental diagram* in transportation economics (Immers and Logghe, 2002). When a traffic situation is initially fluid, adding more vehicles on the road increases their present time by less than when the situation is already congested. For each arc of road, I estimate a quadratic approximation of the relationship between flow per lane and occupancy rate and compute the optimum *Occupancy\**, above which a more occupied road is associated with a lower flow of cars. *Occupancy\** is a road-specific indicator of hyper-congestion.<sup>19</sup> I create a dummy variable that takes the value 1 if the road is hyper-congested and 0 otherwise. I therefore estimate the impact of the 2016 riverbank closure on the probability of (hyper)congestion.<sup>20</sup> If the road's occupancy rates are close to the threshold prior to 2016, I expect the impact to be significant and positive. Table 2.3 suggests that the probability of congestion increased by 12 percentage point on ring roads during the day and 10 percentage points on local roads. Although both results are quite similar, they do not have the same impacts. In fact, the probability of congestion increased by 21.4% on the ring road compared to the pre-reform period and by 50% on local roads. Figure 2.4 shows that the impact on the probability of congestion is always positive during evening hours on both type of roads, even 2 years after the GP closure.

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<sup>19</sup>See Figure 2.16 for an example.

<sup>20</sup>The outcome here is based on the estimated variable *Occupancy\**. This might cause some measurement errors. However, as shown in Table 2.3, the coefficients are quite precisely estimated.

**Table 2.3:** Impact on the probability of congestion

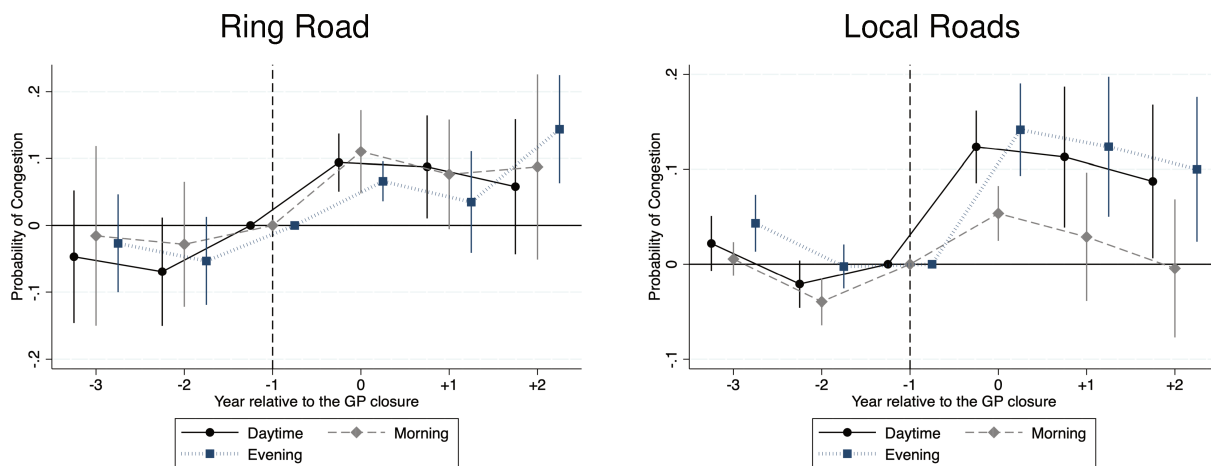
	(1)	(2)	(3)
	<b>Probability of Congestion</b>		
	Morning	Evening	Daytime
	<b>Ring Roads</b>		
Treatment	0.106*** (0.032)	0.107*** (0.018)	0.119*** (0.022)
Constant	0.359*** (0.009)	0.444*** (0.004)	0.421*** (0.005)
Observations	120,788	204,004	627,123
Mean DepVar	0.307	0.570	0.557
$R^2$	0.363	0.366	0.372
	<b>Local Roads</b>		
Treatment	0.033 (0.025)	0.100*** (0.031)	0.101*** (0.031)
Constant	0.053*** (0.010)	0.075*** (0.011)	0.079*** (0.011)
Observations	292,243	474,426	1,461,657
Mean DepVar	0.069	0.196	0.202
$R^2$	0.242	0.239	0.284
Arc FE	Yes	Yes	Yes
<i>Day</i> × <i>hour</i> FE	Yes	Yes	Yes

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$

standard errors clustered at the arc level

*Notes:* The outcome is a dummy variable that takes the value 1 if the occupancy rate is passed the threshold of the relevant road (*Occupancy\**), and 0 otherwise. On average, it represents the probability of congestion. The mean of the dependent variable gives the average of the outcome variable in the treatment group during the pre-reform period. Column (1) represents the estimation during morning hours, from 8AM to 10 AM. Columns (2) during evening hours from 6PM to 8PM and column (3) during daytime from 8AM to 8PM. The first part of the table shows the impact on the ring roads. The second part of the table shows the impact on the 2 local roads considered: the boulevard saint germain and the upper bank.



**Figure 2.4:** Impact on the probability of congestion

*Notes:* These graphs plot the estimates and 95% confidence intervals from equation (2.5). The outcome is the probability of congestion. The straight line represents the estimates during daytime hours (from 8Am to 8PM). The dotted dashed line represents the estimates during morning hours (from 8AM to 10AM) and the dotted line represents the estimates on evening hours (from 6PM to 8PM). All samples are restricted to the working days of the week (from Monday to Friday).

**Average Speed.** I now turn my analysis to the impact on average speed. The results are in line with those of the occupancy rates (cf. table 2.4). Namely, a decrease in the average speed is detected on the ring roads with the largest impact during the evening (21.6%). Average speed decreases by 16.5% during daytime for weekdays on the ring road and by 17.5% on local roads. Figure 2.5 plots the leads-and-lags regressions on the ring road as well as local roads. These results will allow me to compute the average time loss of commuters in section 2.5.3.

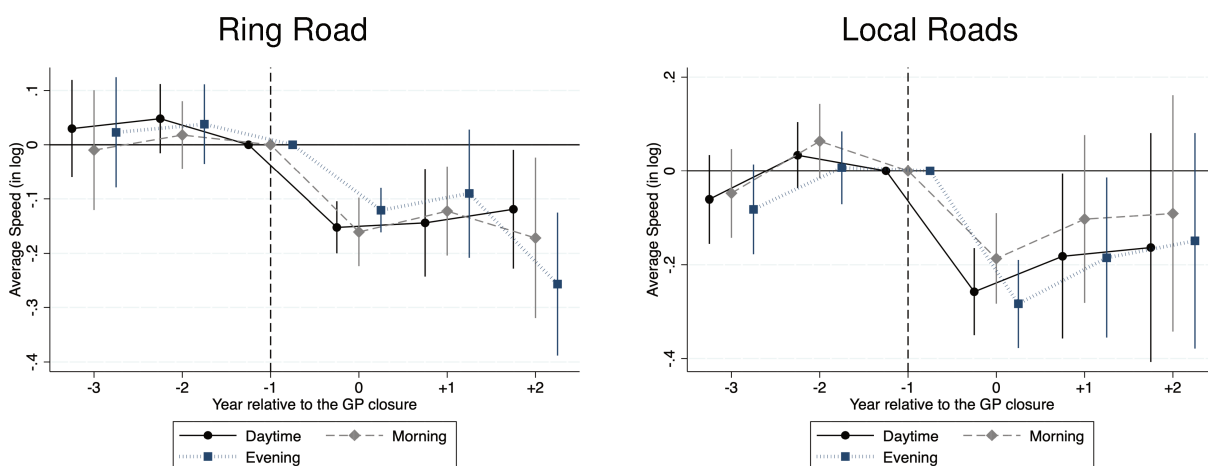
**Table 2.4:** Impact on the average speed

	(1)	(2)	(3)
	<b>Average Speed (in log)</b>		
	Morning	Evening	Daytime
<b>Ring Roads</b>			
Treatment	-0.154***	-0.175***	-0.165***
	(0.032)	(0.033)	(0.029)
Constant	3.325***	3.220***	3.243***
	(0.009)	(0.008)	(0.007)
Observations	120,788	204,004	627,122
R <sup>2</sup>	0.587	0.581	0.586
<b>Local Roads</b>			
Treatment	-0.113	-0.170**	-0.175**
	(0.083)	(0.080)	(0.083)
Constant	2.421***	2.480***	2.420***
	(0.033)	(0.027)	(0.028)
Observations	292,214	474,261	1,461,407
R <sup>2</sup>	0.698	0.665	0.692
Arc FE	Yes	Yes	Yes
Day × hour FE	Yes	Yes	Yes

\* p<.10, \*\* p<.05, \*\*\* p<.01  
standard errors clustered at the arc level

Notes: The outcome is the log of the average speed in kn/h. Column (1) represents the estimation during morning hours, from 8Am to 10 AM. Columns (2) during evening hours from 6PM to 8PM and column (3) during daytime from 8Am to 8PM. The first part of the table shows the impact on the ring roads. The second part of the table shows the impact on the 2 local roads considered: the boulevard saint germain and the upper bank.

**Figure 2.5:** Impact on the average speed



Notes: These graphs plot the estimates and 95% confidence intervals from equation (2.5). The outcome is the log of the average speed on a road section. The straight line represents the estimates during daytime hours (from 8Am to 8PM). The dashed line represents the estimates during morning hours (from 8AM to 10AM) and the dotted line represents the estimates on evening hours (from 6PM to 8PM). All samples are restricted to the working days of the week (from Monday to Friday).

## 2.4 Beyond Traffic: Pollution and Housing Prices

The closure of the GP expressway caused an increase in congestion on substitute roads as seen in section 2.3.2. An increase in congestion - which translates into a progressive reduction in traffic speeds and an uninterrupted traffic flow - affects the air quality due to the slow downs and stop operations. The increase in pollution - if any - harms city-dwellers living near the substitute roads. In this section, I look at the impact of a decrease in the average speed on the road on the concentration of nitrogen dioxide: particles that primarily gets in the air from the burning of fuel.<sup>21</sup>

### 2.4.1 Empirical Strategy

Ideally, I would want to study the causal impact of the riverbank shutdown on pollutant emission levels by comparing a set of pollution monitors near the ring roads with another set that is close to the unaffected roads, before and after September 1<sup>st</sup>, 2016. However, due to local dispersion of emissions, spillover effects would take place, which would prevent me from comparing the air quality near the treated roads to the air quality near the untreated roads in a difference-in-difference framework. To this matter, instead of seeking to estimate the causal impact of the GP closure on pollution, I estimate the elasticity of nitrogen dioxide concentrations with respect to the average speed on nearby roads in the pre-shutdown period. Using this elasticity, I impute the impact on nitrogen dioxide using the result on speed shown in section 2.3.2.

I use two pollution monitors in Paris: the first one is located on the upper banks and the second one is located on the east ring road. I select the road sections near each monitor (see figure 2.17).<sup>22</sup> I restrict the sample to the pre-shutdown period and I estimate the following

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<sup>21</sup>I focus on nitrogen dioxide since the concentration of this gas is particularly correlated with vehicle emissions (on the Health Effects of Traffic-Related Air Pollution, 2010), while fine particles PM2.5 are not affected by vehicle speed (Batterman et al., 2010). Also, exposures to  $NO_2$  over short periods can lead to severe health issues since it can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms (such as coughing, wheezing or difficulty breathing), hospital admissions and visits to emergency rooms. People with asthma, as well as children and the elderly are generally at greater risk for the health effects of  $NO_2$ .

<sup>22</sup>In order to account for the same length of road near each monitor, I select 6 road sections on the upper banks and 1 road section of 800 meters on the ring road since the road sections of the upper banks are smaller in length. In total, each road selected represents approximately 800 meters.

equation by assuming a log linear relationship between emissions and speed:<sup>23</sup>

$$\ln(NO_{2t}) = \alpha \ln(Speed_t) + \theta Q_t + \zeta W'_t + \delta_{h(t)} + \delta_{m(t)} + \epsilon_t \quad (2.6)$$

where  $NO_{2t}$  is the nitrogen dioxide concentration at time  $t$ ,  $Speed_t$  is the average speed on the road section near the sensor at time  $t$ ,  $Q_t$  is the flow of cars at time  $t$ ,  $\delta_h(t)$  is hour of the day fixed effects and  $\delta_{m(t)}$  is month of the sample fixed effects. I also control for weather characteristics such as wind speed, wind direction or temperature represented by  $W'_t$ . The parameter of interest is  $\alpha$ : the elasticity of nitrogen dioxide concentration to speed.

## 2.4.2 Results

The results of estimation (2.6) are represented in table 2.5. The first column represents the naive regression with no time fixed effects. The elasticity would be biased if we consider that cars are less polluting with time. To this matter, I add month of the sample fixed effects to capture the time trend. The estimates are in column (2) and show that the order of magnitude and the significance of the results remain unchanged. Since speed is correlated with the hour of the day and emissions - conditional on the average speed - can vary across hours (for example because of heating, activities, trucks on the road), one might be tempted to add hour fixed effect. The estimate is represented in column (3). On the ring road, the magnitude of the estimate increases and the result remains significant at the 1% level. However, the elasticity of  $NO_2$  with respect to speed using the monitor on the upperbanks becomes negative. Last, I add day of the week fixed effects to account for differences across the days of the week. The estimates are in column (4). The significance and sign do not change compared to the specification of column (3). My preferred specification is the one with month of sample and hour fixed effects (estimation of column (4)) since I make use of this elasticity to compute the average pollution cost across all days. On the ring roads, a decrease of speed by 1% increases air pollution by 0.35%. However, the impact is smaller on local roads, with an elasticity of 0.08%. The difference in the elasticities

<sup>23</sup>By plotting the average speed and pollutant concentrations, I find a decreasing relationship (Figure 2.23). This negative correlation is already observed in other contexts (Pandian et al., 2009)

stems from the architecture of these two roads and the type of automobiles circulating on these roads. Indeed, the ring road is a freeway that does not have any traffic lights or pedestrian crosswalks. Hence, in the absence of congestion, the flow of cars would be uninterrupted and a decrease in the average speed is automatically attributed to an increase in congestion. On the contrary, automobiles driving on the upper banks are forced to stop due to the presence of traffic lights, regardless of the presence of congestion.

**Imputation exercise.** In all specifications the impact of the flow of cars on  $NO_2$  emissions is negligible.<sup>24</sup> This said, I only use the elasticity of  $NO_2$  to average speed to compute the impact of the GP closure on  $NO_2$  concentrations. In order to do so, I extrapolate the elasticities found above to the context of the closure of the GP expressway. Recall that the GP shutdown caused a decrease in the average speed of 16.5% on the ring road and 17.5% on local roads during the day. Considering that the impact is linear and using the elasticities described above, I find an increase of 5.8% in nitrogen dioxide concentrations near the periphery and an increase of 1.5% near the upper banks.<sup>25</sup> This increase in  $NO_2$  comes on top of already high exposures, especially near the periphery (see Table 2.10).<sup>26</sup>

**Other negative externalities.** The increase in traffic does not only impact  $NO_2$  emissions. It also alters the level of noise pollution and other types of pollution. Due to data availability, I am unable to evaluate the general impact of an increase in congestion on negative externalities. In order to have a sense of the magnitude of this effect, I look at the impact of housing prices near the ring road. The motive behind this analysis stems from the principle that all externalities, if anticipated or well-perceived by residents, should be reflected in housing prices. The analysis is described in Appendix 2.7.3 and results suggest that transacted prices decreased by at least 5% within 700-meters of the south ring road. Sullivan (2016) finds that an increase in  $1 \mu g/m^3$  in  $NO_2$  emissions is associated with a decrease in housing values by 0.7%. The average  $NO_2$

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<sup>24</sup>This is due to the fact that car flow is already present in the average speed.

<sup>25</sup>For the ring road:  $-16.5 \times -0.35 = -5.775$ . For local roads:  $-17.5 \times -0.084 = -1.47$

<sup>26</sup>The European Union legislation states that the maximum acceptable level of  $NO_2$  is fixed to 40 microgram per cubic meter (Lorente et al., 2019).

**Table 2.5:** Elasticity of Nitrogen Dioxide with respect to the average speed

	(1)	(2)	(3)	(4)
	<i>NO</i> <sub>2</sub> emissions (in log)			
	<b>Ring Roads</b>			
Speed (in log)	-0.293*** (0.019)	-0.275*** (0.018)	-0.346*** (0.021)	-0.256*** (0.022)
Flow (1000 v/h)	0.043*** (0.003)	0.034*** (0.003)	0.077*** (0.006)	0.073*** (0.006)
Constant	6.053*** (0.100)	5.502*** (0.100)	5.579*** (0.104)	5.214*** (0.108)
Observations	75,51	7,551	7,551	7,551
<i>R</i> <sup>2</sup>	0.249	0.349	0.406	0.417
	<b>Upperbanks</b>			
Speed (in log)	0.062*** (0.023)	0.064*** (0.022)	-0.084*** (0.020)	-0.091*** (0.020)
Flow (1000 v/h)	0.361*** (0.010)	0.367*** (0.010)	0.357*** (0.017)	0.290*** (0.017)
Constant	5.440*** (0.076)	5.181*** (0.079)	5.376*** (0.069)	5.470*** (0.068)
Observations	10,170	10,170	10,170	10,170
<i>R</i> <sup>2</sup>	0.336	0.373	0.536	0.559
Weather Characteristics	Yes	Yes	Yes	Yes
Month of Sample FE	No	Yes	Yes	Yes
Hour FE	No	No	Yes	Yes
Day of the week FE	No	No	No	Yes

\* *p*<.10, \*\* *p*<.05, \*\*\* *p*<.01

*Notes:* This table represents the elasticity of nitrogen dioxide emissions with respect to the average speed of vehicles on nearby roads. The first part of table represents the estimates of equation (2.6) on the ring road and the second part of the table the estimates on the upperbanks. The first column represents the naive regression without any time fixed effects. The second column adds month of the sample fixed effect to the regression. The third one adds hours fixed effects and the last column adds day of the week fixed effects. Since weather conditions are only registered every 3 hours, I only keep the traffic data of those hours in the sample. The flow of cars is normalized to 1000 vehicles per hour.

level registered in 2015 near the ring road was of  $67 \mu\text{g}/\text{m}^3$  which implies that *NO*<sub>2</sub> increased by  $3.8 \mu\text{g}/\text{m}^3$  using 2015 as the reference year. In this sense, the impact on housing prices is much larger than the one reflected in the literature. This result implies that the road closure generated an increase in negative externalities beyond *NO*<sub>2</sub> emissions.

## 2.5 A Model of Route Choice

The total cost of this policy can be reduced to (i) commuters' time losses and (ii) residents' exposure to higher pollution levels. If pollution is fixed in the short-run, reduced-form results on pollution along with an exogenous calibration are sufficient to compute the pollution costs.

On the contrary, computing the cost associated with the time loss is more complex. The reduced-form estimates measure the causal impacts of the GP closure on traffic on substitute roads. However, the non-linear relationship between flow and speed makes it impossible to assess the number of people shifting on substitute roads just by looking at the reduced-form results, which prevents me from computing the costs of the policy.

For this purpose, I build a traffic model inspired by Akbar and Duranton (2017). By distinguishing between inner-city and suburban commuters and residents, the model allows me to speak to the distributional aspects of this policy. Finally, I make use of the model to study counterfactual scenarios.

### 2.5.1 A General Framework

#### Set Up

The model follows the congestion model of Akbar and Duranton (2017), in which roads and route choices are modeled in a stylized model and congestion is endogenous. I extend this framework by adding two types of commuters, where each commuter chooses the fastest route.

In contrast to many of the papers in the transport literature, the model abstracts away from any mode switch, motivated by the public transport analysis in Appendix 2.7.2 suggesting that - at least in the short run - commuters do not rethink their transportation mode following a marginal change in the road supply. This assumption restricts the decision of commuters to their route choice. I also abstract from any job and home reallocation. Last, I abstract from any network effect.<sup>27</sup>

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<sup>27</sup>One potential network effect that is not taken into account here is the decision of other commuters not directly impacted by the policy. For example, commuters initially present on the substitute roads.

**The road system.** Consider a city and its near suburbs composed of different neighborhoods  $j \in J$ , served by several roads  $r \in R$  of direction  $d(r)$ . Each road  $r$  belongs to a road type  $\mu(r) \in \{a,e,f\}$ . Arterial roads (a) are high capacity roads that deliver traffic to and from centers of activity. I denote by  $n_a$  the number of arterial roads in the region considered. Freeways (f) are roads designed for fast moving vehicles to travel longer distances with high speeds (ring roads, highways...). I denote by  $n_f$  the number of freeways. Finally, expressways (e) are roads designed to travel quickly with great comfort and safety by avoiding sharp curves, busy traffic intersections or railway junctions. In this framework, I consider that the region has at most 1 expressway of each direction and each expressway crosses the city.

**Residents.** The region is populated with a continuum of agents of measure 1. Each individual suffers from the presence of cars on the roads through (i) travel time and (ii) air pollution. In fact, (non-commuter) residents suffer from the increase in commuters on nearby roads since it increases pollution. Car-commuters suffer from the increase in the number of travelers on the roads used to commute, since it triggers congestion. They also suffer from an increase of commuters on roads near their residential place. Therefore the marginal cost of additional cars on a set of road  $C$  are reflected in (i) the marginal pollution cost in the residential areas near roads  $r \in C$ , and (ii) the marginal increase in commuting time for car-commuters using any road  $r \in C$ .

**Travel Time.** Consider two types of commuters: (i) Inner city commuters denoted by  $I$ : commuters who live and work inside the limits of the city, and (ii) Suburban commuters denoted by  $O$ : commuters who live in the suburbs and work either in the suburbs or inside the city. The total number of commuters on each road  $r$  is  $N_r = O_r + I_r$ . Each commuter chooses a means of transportation  $m \in \{\text{Car, Public Transportation}\}$ <sup>28</sup>. The travel time of a trip using a set of roads

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<sup>28</sup>The share of  $m$  from residence  $i$  to workplace  $j$  is considered fixed



$C \in R$  can be expressed as:<sup>29</sup>

$$\sum_{r \in C} T_{rt} = \sum_{r \in C} \frac{D_r}{S_{rt}(N_{rt})} \quad (2.7)$$

where  $S_{rt}(N_r)$  is the average speed on route  $r$  at time  $t$  and  $D_r$  is the length in kilometer of road  $r$ .

I borrow the functional form of the average speed from the framework developed by Akbar and Duranton (2017):

$$S_{rt}(N_{rt}) = \bar{S}_r N_{rt}^{-\sigma_\mu(N_{rt})} \quad (2.8)$$

where  $\bar{S}_r$  is the theoretical maximal speed on road  $r$ ,  $N_r$  the number of cars on road  $r$  and  $\sigma_\mu(N_{rt})$  is the elasticity of congestion on a road of type  $\mu$  i.e. the degree to which the average speed on the road is impacted by the number of cars on that given road, with:

$$\sigma_\mu(N_r) \begin{cases} < 1 \text{ if } N_r < N_r^{max} \\ > 1 \text{ if } N_r > N_r^{max} \end{cases}$$

With a low car density, increasing the number of cars on a given road decreases less than proportionally the average speed. However, once the number of cars reaches a certain level, the decrease in the average speed becomes more than proportional, referring to a hyper-congested situation. This result is caused by the traffic demand greatly exceeding the traffic capacity, which cannot be relieved in time.

There are two extreme situations. The first one is when the elasticity of congestion is inelastic. In that case, the average speed on the road remains constant to the change in the car density. This can be observed at night when few cars are on the road. Increasing the demand marginally will not influence the average speed, especially in the absence of traffic lights. The second extreme case is an infinite elasticity of congestion. If the car density remains unchanged, the impact on the average speed will be infinite. This can be reached in the presence of high traffic volume, especially during peak hours.

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<sup>29</sup>The trip can either be done by using single-type roads, or the combination of arterial roads and expressway since both roads are inside the city. In the latter case, the travel time would be the weighted average speed of the trip over the total length of the roads.

**Pollution.** The presence of cars on the road increases air pollution through two channels: (i) the number of cars and (ii) the level of congestion. An increase in the number of cars mechanically generates an increase in emissions. If the increase in traffic is such that it provokes an increase in congestion, the average speed on the road decreases. As such, the average speed on the road is correlated with the level of pollutant emissions. However, the relationship is not linear. If the average speed on a given road is high, decreasing it might be a way to reduce emissions since it would decrease fuel consumption. However, reaching a certain speed level, lowering the average speed would increase the emission levels. This is because of the increased amount of acceleration and braking in stop-start driving, although these could be reduced if traffic flow was smoothed. The transportation and environmental literature well documents this relationship between emissions and average speed (Kean et al., 2003; Lozhkina and Lozhkin, 2016). To this end, the level of pollutant emissions can be expressed as:

$$A_i(\mu(r')) = \begin{cases} S_{r'}(N_{r'})^{-\alpha_{\mu(r')}} & \text{if } S_{r'} < \tilde{S}_{r'} \\ S_{r'}(N_{r'})^{\zeta_{\mu(r')}} & \text{if } S_{r'} > \tilde{S}_{r'} \end{cases} \quad (2.9)$$

$\tilde{S}_{r'}$  is the threshold above which an increase in the average speed increases emissions,  $\alpha_{\mu(r')}$  is the elasticity of pollution with respect to the speed whenever  $S_{r'} < \tilde{S}_{r'}$  and  $\zeta_{\mu(r')}$  the elasticity of pollution with respect to the speed whenever  $S_{r'} > \tilde{S}_{r'}$ .

### Closing a fraction of the expressway

Consider a public reform where a fraction  $x$  of a road  $r$  of type  $e(r)$  is permanently closed to increase the amenities in the vicinity of the closed section. Consequently, car commuters who used to take the expressway ( $N_e^{pre}$ ) need to shift to other alternative roads.

**Inner-city commuters** The closure of a fraction of the expressway forces expressway commuters to alter their itinerary. Inner-city commuters are forced to substitute the closed segment of the expressway with substitute arterial roads.<sup>30</sup> Let  $A$  be the set of arterial roads serving as

<sup>30</sup>Arterial roads are the only roads inside the city apart from the expressway.

substitutes to the closed expressway. The average speed on substitutes arterial roads  $r \in A$  after the closure is:

$$S_{rt}^{post}(N_{rt}) = \bar{S}_r(N_{rt}^{post})^{-\sigma_{\mu(r)t}(N_{rt}^{post})} \quad (2.10)$$

where  $N_r^{post} = \bar{N}_r^{pre} + \frac{I_e^{pre}}{n_{r \in A}}$ ,  $\bar{N}_r^{pre}$  is the fixed number of commuters initially on road  $r$  independently of the expressway shutdown,  $I_e^{pre}$  is the number of inner-city commuters who used to take the closed expressway and  $n_{r \in A}$  the number of arterial roads serving as substitutes roads. Here, the congestion elasticity on substitutes arterial roads is  $\sigma_{\mu}(r)$  and depends on the technical characteristics of arterial roads, and the number of cars on the road.<sup>31</sup>

**Suburban Commuters** Once a fraction of the expressway is closed to car circulation, suburban commuters are left with two choices: (i) take one of the alternative arterial roads inside the city ( $r \in A$ ) once they get to the closed section, and (ii) abandon the expressway to the profit of a freeway at the periphery that can serve as a substitute:  $r' \in F$  with  $F$  the set of substitute freeways. A freeway is considered as a direct substitute if: (i) it is of almost the same length of the entire expressway, (ii) it shares an entrance and exit with the expressway and (iii) it has the same flow direction. If in the pre-shutdown period, using the mixed itinerary of expressway and local roads is faster than using an alternative freeway:  $T_{r \in A} + T_{e, non-closed} \leq T_{r \in F}$ , a fraction  $\beta$  of the ex-expressway suburban commuters will reroute to the freeway and a fraction  $1 - \beta$  will circumvent the closed section until travel times on both itineraries are equalized. The number of suburban commuters choosing to reroute is defined by the following post-shutdown equilibrium equation:<sup>32</sup>

$$\underbrace{(1-x)\bar{S}_e(\bar{N}_e + N_e - \beta O_e)^{-\sigma_e}}_{\text{Speed on the non-pedestrianized stretch}} + \underbrace{x\bar{S}_r(\bar{N}_r + (1-\beta)\frac{O_e}{n_a} + \frac{I_e}{n_a})^{-\sigma_a}}_{\text{Speed on arterial roads with diverted inner-city and suburban commuters}} = \underbrace{\bar{S}_{r'}(\bar{N}_{r'} + \beta\frac{O_e}{n_f})^{-\sigma_f}}_{\text{Speed on the freeway with diverted suburban commuters}} \quad (2.11)$$

In that case, the freeway congestion elasticity does not only depend on the number of cars on that road but also on the congestion elasticity of local roads as well as the initial number

<sup>31</sup>The congestion elasticity can be expressed as follow:  $\frac{\partial S_{rt}}{\partial N_{rt}} \frac{N_{rt}}{S_{rt}} = \sigma_r(N_{rt})$

<sup>32</sup>The equation holds for any  $t$ , therefore I remove  $t$  for convenience.

of people on these roads. Hence, for every  $r' \in F$  the congestion elasticity can be written as:

$$\frac{\partial S_r^t}{\partial N_r^t} \frac{N_r^t}{S_r^t} = \sigma_f(\sigma_a, \sigma_e, N_r, N_{r'}).$$

The pattern of commuter sorting therefore depends on several parameters like the number of alternative substitute roads, the relative technical performance of roads and the initial conditions on each road, which are themselves conditioned by the city's architecture.

## 2.5.2 Model Calibration: The Case of Paris

I consider the case of Paris with 1 expressway (GP) of an eastern flow direction and of length normalized to 1 and one freeway of the same flow direction and of length 0.8, which represents the south outer ring road. The expressway was used by both inner-city commuters and suburban commuters to get from the south west of Paris to the south east. The lack of traffic lights and the fluidity of traffic make the expressway a convenient route to cross the city even for suburban commuters. In 2016, 25% of the expressway is pedestrianized at its center. Hence, all riverbank users are forced to alter their paths. In this set-up, there are 2 substitute arterial roads to the closed section and 1 substitute freeway to the entire expressway. Inner-city commuters will circumvent the closed section either by using the upper banks or the *Boulevard Saint Germain*. Suburban commuters, can either shift on the arterial roads previously mentioned or abandon the riverbank to the profit of the ring road.

### Parameter Estimation

There are three parameters to be estimated. The first one is  $\sigma$ , the elasticity of congestion. The second one is  $\beta$ , the fraction of suburban commuters switching on the ring road. Last, there is  $\alpha$ , the elasticity of pollution with respect to the average speed on the road.

**Estimating  $\sigma$ .** To estimate the congestion elasticities, I run the following regression for each treated road separately in the pre-shutdown period:

$$\ln(S_{it}) = \alpha - \sigma_t \ln(N_{it}) + \gamma_t + \gamma_i + \epsilon_{it} \quad (2.12)$$

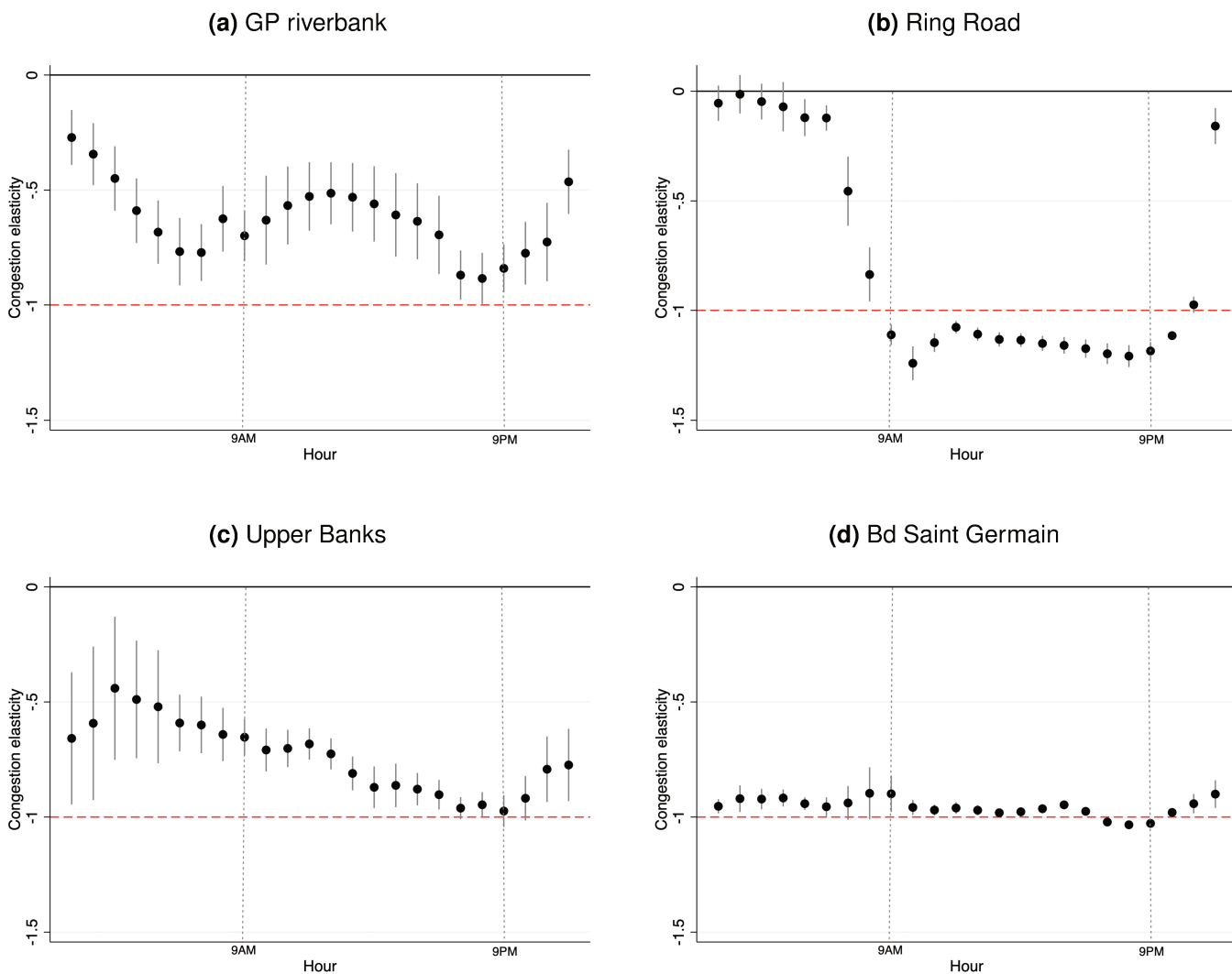
where  $S_{it}$  is the average speed on road section  $i$  at time  $t$ ,  $\sigma_t$  the elasticity of congestion (parameter of interest),  $N_{it}$  is the density of cars on road section  $i$  at time  $t$ ,  $\gamma_t$  and  $\gamma_i$  are day of the sample and road section fixed effects respectively. Figure 2.6 shows the estimation of the elasticity of congestion for every road, by the hour of the day. The GP expressway presents an elasticity of congestion with little variability between the hours of the day. The elasticity of congestion is the closest to 0 during night hours, due to low traffic. No hypercongestion situation is noted here. However, the elasticity of congestion approaches 1 during evening hours.

The ring road presents an elasticity of congestion near 0 during night hours. However, for every hour during daytime, the ring road is hypercongested meaning that every extra vehicle on the road causes a decrease in the average speed that is more than proportional. While the upper bank shows an elasticity of congestion that decreases by the hour during the day reaching 1 at 9pm, the *Boulevard Saint Germain* presents almost no variability between the hours.<sup>33</sup>

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<sup>33</sup>The roads inside the city have non-zero elasticities of congestion during night hours since they are equipped with several traffic lights and pedestrian crosswalks, which causes a decrease in the average speed on the road independently of the number of cars passing by.

**Figure 2.6:** Congestion Elasticities by hour of the day



Notes: I plot the estimates of equation (2.12) by road and hour of the day. The estimates are represented with the black dot. The vertical lines represent the 95% confidence intervals.

**Estimating  $\beta$ .**  $\beta$  is the fraction of suburban commuters who abandon the expressway to the profit of the south ring road after the GP closure. In the pre-shutdown period, the number of cars using the GP expressway can be expressed as:

$$N_e = \underbrace{I_e}_{\text{Inner-city commuters using the expressway}} + \underbrace{\beta O_e}_{\text{Suburban commuters switching to the ring road}} + \underbrace{(1 - \beta) O_e}_{\text{Suburban commuters switching to local routes}}$$

which are the inner-city commuters, the suburban commuters who will later reroute to the ring road and the suburban commuters who will choose to shift to arterial roads. One of the assumptions of the model consists in saying that car-commuters choose the fastest route. Table 2.7 shows that before the GP closure, suburban commuters could cross Paris using either the expressway or the south outer ring road for almost the same journey time. Conversely, the mixed itinerary of expressway and local roads results in a longer travel time than the south outer ring road, regardless of the time of the day. Therefore, it is reasonable to consider that once the GP expressway is closed, all suburban commuters shift on the south outer ring road instead ( $\beta = 1$ ). Since inner-city commuters use the GP to get from one point to another both inside the city, they are most likely going to shift to local arterial roads: upper banks and *Boulevard Saint Germain*.

**Estimating  $\alpha$ .** Since I only have data on nitrogen dioxide emissions at the daily level, I restrict this elasticity to  $NO_2$  emissions. The elasticity of  $NO_2$  emissions to the average speed is estimated in section 2.4. I find an elasticity of -0.08% on local roads and -0.34% on the ring road.

### Model Predictions.

Since only suburban commuters can shift on the freeway, every car abandoning the non-pedestrianized stretch of the expressway is a suburban commuter:  $N_{e,non-closed}^{pre} - N_{e,non-closed}^{post} = \beta O_e$ , with  $\beta = 1$ . Using the speed formula expressed in equation (2.8), I recover the speed impact by using (i)  $N_{e,non-closed}^{pre} - N_{e,non-closed}^{post}$  as the number of suburban commuters, and (ii) the difference between the number of cars on the pedestrianized stretch before its shutdown and the number of suburban commuters:  $N_{e,closed}^{pre} - O_e$  as the number of inner-city commuters who will shift to local roads. Using the estimated congestion elasticities, I recover the speed impact from the model  $\gamma_{model}$  displayed in figure 2.28.<sup>34</sup>

<sup>34</sup>From table 2.6, I recover the average car density  $O_e$  and  $N_{e,non-closed}^{pre} - N_{e,non-closed}^{post}$ .  $O_e$  is the number of suburban commuters shifting to the ring road. I multiply this number by 2.4 since the GP has on average 2.4 lanes in order to have the number of cars on the entire road. I then divide the latter number by 3.3, since the ring road has 3.3 lanes on average and commuters will spread on all lanes. For inner-city commuters, I first multiply  $N_{e,non-closed}^{pre} - N_{e,non-closed}^{post}$  by 2 since the closed GP has 2 lanes. I then divide the latter number by 6 since inner-city commuters will shift to 2 local roads, each of them having 3 lanes.

Results show that the speed impacts recovered from the model are closed to and lie in the confidence interval of the reduced-form estimates, suggesting that the model predicts accurately the impacts of the policy. Furthermore, the results predicted from the model suggest that there was no significant mode switch away from car use. Indeed, if some commuters had dropped their car due to the increased level of congestion, the results generated from the model would have been larger than the ones obtained with the reduced-form.<sup>35</sup>

### 2.5.3 Cost Analysis

In this section, I first quantify the costs of the 3.3-kilometer closure in Paris. Then, I compute the costs of several counterfactual scenarios.

#### The costs of the 2016 GP closure

The pedestrianized section of the GP riverbank received 1.5 million visitors in 18 months, which the Mayor refers to as a "popular infatuation".<sup>36</sup> This high number of visitors reflects the highly-valued amenities derived from this closed section. However, the absence of additional data such as consumption, commercial rents, or the impossibility of determining whether these visitors are residents or tourists complicates the quantification of the benefits.

To this matter, I focus on the quantification of the costs of this road closure, reduced to the time loss and the increased pollution. This number can be therefore used by policy-makers to assess whether this type of policy makes sense according to the amenities that are anticipated. The description of the cost computation is described in Appendix 2.7.4.

**Pollution costs.** The GP closure is responsible for an increase in pollutant emissions near substitute roads. Exposure to worsen air quality has adverse effects on human health.<sup>37</sup> Mink (2022) quantifies the health costs associated with an increase in  $NO_2$  emissions in French urban

<sup>35</sup>In the model, I make the assumption that individuals can only change their behavior at the intensive margin. Hence, I assume that every individual on the riverbank was displaced on another substitute road.

<sup>36</sup><https://www.lepoint.fr/societe/berges-de-seine-rive-droite-la-mairie-de-paris-affiche-son-succes-19-23.php#11>

<sup>37</sup>In 2016, air pollution was estimated to play a part in 7.6% of worldwide deaths (WHO, 2017).



areas. The rise in pollution near the local roads accounts for an annual cost of 950k €. The cost associated with the increase in pollution near the ring road is seven times higher, representing an annual cost of 7.2M €. The difference in costs stems from (i) the difference in the impact on pollution and (ii) the difference in the number of people impacted by the increase in emissions. One limitation of this analysis is that I assume that the area of residence corresponds to the location of exposure to pollution. However, individuals could also be exposed to air pollution at their work location, during their leisure time and also while commuting. In addition, if they also spend some time on the closed section of the GP, they might be exposed to better air quality. In this paper, I abstract from these effects.

**Travel time costs.** Two categories of commuters are suffering from an increase in travel time after the GP closure. First, the direct losers of this policy are the ex-GP commuters. Suburban commuters initially using the riverbank shift on the south ring road, which experienced a decrease in the average speed. 6,500 commuters per day lose 4 minutes, representing a value of 1.5M € to the economy. Inner-city commuters circumvent the closed stretch with local roads, contributing to the decrease of the average speed on these roads. Hence, 20,700 commuters lose 13 minutes, associated with a cost of 15.4M €. <sup>38</sup> Second, indirect losers are drivers initially on the substitute roads and now bearing the cost of extra users. The 40,700 drivers initially on local roads lose 2.6 minutes, which corresponds to an annual cost of 6.05M € and the 60,790 drivers initially on the south outer ring road lose 4 minutes, representing a cost of 14M €. The total time cost generated by the GP closure amounts to 37M €.

**Benefits expected to exceed the costs.** With a total annual cost of 44M €, I can compute the amount that each visitor should spend on the pedestrianized GP such that it compensates for the costs of the policy. Knowing that 1.5M people visited the closed GP in 18 months, I consider that the GP received 1M visitors in a year. This means that each visitor should spend at least 44 €.

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<sup>38</sup>Subtracting from the flow of cars on the pedestrianized stretch the number of cars shifting on the ring road, we get that 1,594 individuals per hour shifted on local roads (cf. table 2.6).

**Distributional impacts.** While the benefits of pedestrianizing the riverbank are concentrated in the heart of the city, the costs are more spread out and impact two main groups of people: (i) Parisians and (ii) suburbaners. The center of Paris is populated mostly by high-income residents. On the contrary, the peripheral area is inhabited by low-income residents (Figure 2.27).

Being closer to the GP, residents living in Paris are more likely to benefit from the pedestrianization of the riverbank. Yet, they are not immune to the costs associated with this policy. Some inner-city car-commuters face an increase in travel time, and residents living near the local substitute roads (Bd Saint Germain and the upper banks) suffer from a deterioration in air quality.

Provided that all cars on the local roads are inner-city commuters while 5% of the commuters on the ring roads are Parisians (Aur, 2016), the total time costs incurred by high-income residents is of 22.15M€, which represents 60% of the time costs.<sup>39</sup> Regarding the pollution cost, all residents near the local roads are considered high-income residents. They bear the 950k€ cost of extra emissions generated by the additional traffic on each road, which represents 10% of the pollution cost. All residents living near the periphery - on both sides - suffer from higher levels of air pollution representing an annual cost of 7.2M€, 90% of the pollution cost.

The high level of cost incurred by low-income residents mainly comes from the pollution they have to bear near the periphery. This is caused by 25% of ex- GP commuters who now use the south ring road and still cause 90% of the pollution costs. Therefore, one way of avoiding these large costs is to close the riverbank such as suburban commuters choose to use local routes instead of the south ring road. The shift of suburban commuters to the ring road happens at 2.6-kilometers of GP closure.<sup>40</sup> Below 2.6-kilometers of pedestrianization, suburban commuters prefer to shift to local roads as it would deliver a lower travel time.

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<sup>39</sup>I suppose that the time cost is constant and not proportional to income. However, one can consider that higher-income commuters have a higher cost time cost which would increase the gap between the time costs of higher-income and lower-income commuters.

<sup>40</sup>Computations are found in Appendix 2.7.4.

### 2.5.4 Counterfactual Scenarios

Recall that there are three main variables that define the number of road substitutes to a closed road. The first variable is the flow direction. To be considered as an alternative road, it has to be of the same flow direction to allow commuters to get to the same destination. The second variable is the entrance point of the closed road segment. Substitute roads should be reachable before or at the start of the closed segment. The third variable is the length of the closed segment. Direct substitute roads need to be of similar length. In this section, I make use of the theoretical framework to generate counterfactual situations. In each situation, the number of alternative roads and the number of commuters on each road deviates from the current situation.

**Optimal closure under no mode switch.** Here, I consider a counterfactual situation where the closed road segment varies. The starting point of the segment pedestrianized is fixed and the length of the road closed varies. Four cases can be identified in figure 2.29. Computation details can be found in Appendix 2.7.5.

The first one is when the closed segment is less than 2.6-kilometers. I have shown that below 2.6-kilometers, suburban commuters switch to local roads along with inner-city commuters. However, if the segment closed is below 3.3- kilometers, *Boulevard Saint Germain* does not belong to the set of substitute arterial roads since it only shares one exit with the GP, after 3.3-kilometers of closure. Since the GP is the fastest route, commuters use it as much as they are able to. Hence, every commuter on the GP goes on the upper banks. In that case, the time cost is a linear function of the closed segment and the larger the closed segment the higher the time cost. The consequences are concentrated in the center of the city and residents near the ring roads are left untouched. Low-income commuters are only impacted through the time loss of ex-GP suburban commuters.

The second case refers to the situation where the closed segment is between 2.6 and 3.3 kilometers. At 2.6-kilometers, suburban commuters choose the ring road instead of local roads and inner-city commuters choose the upper banks. This decreases the time cost for inner-city commuters and increases the time cost for suburban commuters. The time cost keeps on

increasing until it reaches 3.3-kilometers. However, the pollution cost increases drastically as the highly dense area of the south of Paris now suffers from increased pollution.

The third case represents the current situation. *Boulevard Saint Germain* is now a plausible substitute along with the upper banks. Therefore, adding another local road as an alternative, decreases the travel time for inner-city commuters. The pollution cost at the center increases linearly since more municipalities are impacted, while it is left unchanged near the ring road.

Last, above 3.3-kilometers, the upperbanks remain a local substitute road on the whole pedestrianized stretch since it is reachable anywhere from the GP. However, since the *Boulevard Saint Germain* only has one entrance and exit, it can only serve as a substitute for 3.5-kilometers. After that, all inner-city commuters shift back on the upperbanks.

One can notice in figure 2.29 that closing 1.8-kilometers instead of 3.3 would avoid the entire pollution cost borne by low-income people while keeping the time cost unchanged. Therefore, 1.8-kilometers corresponds to the larger distance that can be pedestrianized without impacting low-income residents that were not using the GP. This counterfactual scenario is interesting from a theoretical point of view. The set of alternatives is divided by three but the distribution of commuters remains the same, and yet the pollution costs are drastically mitigated.

**Minimal mode switch for zero net pollution costs.** One of this policy's goals was to shift away from private motorization. Although the model shows no room for traffic evaporation, one might wonder how many commuters need to drop their car so that the causal impact on traffic (and therefore on pollution) becomes null. There are two potential scenarios. The first one consists of having all commuters on local roads to avoid displacing externalities to the periphery. In this case, I compute the average speed needed in order for suburban commuters to stay on local roads. Computation details can be found in Appendix 2.7.5. An average speed of at least 35km/h is needed for suburban commuters to choose this itinerary instead of the periphery. However, even at night where congestion is absent, the average speed is almost three times lower due to the road's performance. Therefore, the scenario of having everyone on local roads must be dropped.

This brings me to the second possible scenario: suburban commuters on the ring road and inner-city commuters on local roads, which corresponds to the current situation. In that case, the number of commuters that should drop their car in order to return to the initial level of commuters on each road corresponds to the number of additional commuters on each road. This means that 10.5% of commuters on the south ring road at 51% of commuters on the local substitute roads. In that case, pollution costs drops to 0 and time costs only account for the time loss of ex-GP users since the average speed on each substitute road is unchanged. This scenario is interesting from a policy point of view. In fact, by offering credible alternatives to car, the city might be able to generate zero marginal costs and still create positive amenities in the city.

**Potential impacts of a wider car-free area.** I turn to a counterfactual situation where commuting by car is banned in the center of the city.<sup>41</sup> This situation is already planned to take place by 2030, following the 2015 COP21 agreements. It has sparked some debates in the region with the opponents raising the point that suburban commuters might be penalized. If this situation takes place, the upper banks no longer belong to the set of substitute roads since they are located in the car-free zone. *Boulevard Saint Germain* becomes the only route on which commuters can switch to. Density of cars increases by 34%, decreasing speed by 33.7% on that road. This leads to a time cost of 60.5M€ and a pollution cost of 7M€. Since pollution increased on one local road, a lower number of inner-city residents are impacted by the nearby increase of pollution while the same number of individuals are impacted by the increase in pollution near the periphery. This leads to a slight decrease in the pollution cost since most of the pollution cost is borne by suburbans. However, the time cost increases substantially. Here, I consider that the number of car-commuters is constant. In reality, the number of car-commuters might decrease by 2030 following the pedestrianization of the center, especially among inner-city commuters who can easily refer to alternative means to car transportation.

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<sup>41</sup>The center of the city is considered to be represented by the following *arrondissements*: 1,2,3 and 4.

## 2.6 Policy recommendation

It is quite challenging to find an environmental policy that is at the same time environmentally effective, economically efficient and equitable. To fight increasing inequality and improve the political acceptability of decarbonization, these distributive effects need to be addressed. Otherwise, a political backlash is likely to appear (Boyer et al., 2020). Of course, adverse distributional effects do not call for non-action since it would make everyone worse off. In this sense, the trade-off between environment and equity is absent. The question that arises concerns the design of environmental policies in order to minimize the inequality gap.

This study provides evidence of sizable costs caused by a road supply reduction in a city. Due to the non-linear impacts of car flow on pollution and congestion, policymakers should pay attention to the characteristics of the roads on which traffic is likely to be shifted: the initial level of traffic, the initial level of pollution, the composition of the population living nearby and the number of credible alternatives in place. In fact, even if car usage were to decrease in the short run, a road closure might still generate consequent costs in commuting time and air pollution if traffic is displaced to (more) congested roads. Conversely, the overall impacts on pollution and congestion can be mitigated if (i) traffic is displaced to less congested roads and (ii) a large enough fraction of commuters drop their car.

In the case of Paris, since traffic was displaced to more congested roads, I show significant costs in terms of pollution and time loss. Although the costs are spread in different areas of the city, low-income households are more impacted by higher exposure to air pollution. Indeed, almost 90% of the pollution cost is borne by residents living near the periphery of the city, who might not use private cars to commute but still pay the price of the policy. Also, it is worth noting that many of them live outside of the local jurisdiction responsible for this closure. This brings into question the political economy behind this type of policy. In fact, the Mayor of the city caters each policy to the needs of local constituents, feeding socio-economic and political sorting. On the one hand, she may be right if we consider that suburban commuters should not have crossed Paris in the first place, generating negative externalities in a city for which they do not pay local

taxes. On the other hand, higher levels of decision-making might be tempted to sacrifice the city, as proven by then *plan autoroutier de Pompidou*: plan conceived in the mid-1960s with the aim of providing Paris with a fine network of freeways and "fluidified" roads inside the ring road in order to link Paris to its suburbs.<sup>42</sup>

Regarding the case of Paris, an eastern itinerary was removed for car commuters. The alternative in terms of public transportation is the train line linking the west and the east of the region (RER-A).<sup>43</sup> However, it is the most used urban train in Europe, which makes it extremely saturated during peak hours. Reducing a road lane of the same direction is therefore unlikely to provoke a shift of some commuters on public transportation. The alternative in terms of roads is restricted to local roads or the ring road. However, with an initial high number of cars on the ring road and low-income households living nearby, large consequences could not have been avoided in the absence of credible alternatives.

As such, one way of mitigating the costs of this policy would be to implement policies in favor of a mode switch along with the closure. In fact, I show that if 50% of inner city-commuters and 10% of suburban commuters had dropped their car, congestion and pollution would not have increased on substitute roads. For instance, why not implement the *Grand Paris Express* project before reducing the road supply in the city?<sup>44</sup> Of course, both projects have different time spans. The *Grand Paris Express* project takes almost a decade to be put in place while the closure of a road can be done in a day.

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<sup>42</sup>The primary interest of the plan was to link Paris to the suburbs by means of entirely roadway links, thus freeing the city from traffic congestion. Most of the planned infrastructures were finally abandoned following the 1973 oil crisis and the arrival of Valéry Giscard d'Estaing to the power. The only concrete achievement of this plan remains the Georges-Pompidou expressway, built on the banks of the Seine river in 1966.

<sup>43</sup>The RER A is the main transport line in Paris' region that links the west and east of the city.

<sup>44</sup>Today, the metro and RER form a hub-and-spoke network with Paris at its center. The Grand Paris Express is meant to complete this system with the construction of four new metro lines around the capital (15, 16, 17 and 18) by 2028, serving the inner and outer suburbs. One of the direct benefits is the relief of some public transport lines that would otherwise be saturated.

## 2.7 Appendix

### 2.7.1 Chronology of the *Georges Pompidou* riverbank closure decision

In December 2015, the Paris Council shared the thoughts of a plan concerning the pedestrianization of some riverbanks. The shutdown of 3.3 kilometers of the Georges Pompidou riverbank from the Tuileries to the Henry IV tunnel was first declared the 26<sup>th</sup> of September 2016 through deliberation. The October 18<sup>th</sup>, 2016 decree formalized the creation of a pedestrian area; however, it was contested due to the displacement of pollution and noise generated by this decision. On February 21<sup>st</sup> 2018, the administrative tribunal of Paris canceled the Paris Council's September 26, 2016 deliberation, and the town hall's 18<sup>th</sup> of October 2016 decree creating a public walk on the location of this riverbank. However, on the 6<sup>th</sup> of March 2018, a decree was created forbidding vehicle circulation on a segment of the riverbank for reasons related to site protection and enhancement for touristic and aesthetic purposes. Many associations and individuals asked for the annulment of this decree at the administrative tribunal of Paris. Their voices were heard and on October 22<sup>nd</sup>, 2018 the annulment was confirmed due to doubts concerning the environmental consequences of this project. Lastly, on June 21<sup>st</sup> 2019, the Paris Council confirmed the 6<sup>th</sup> of March 2018 decree while rejecting all the related annulment appeals.

### 2.7.2 Public Transportation

This section explores whether some people have shifted onto public transportation and, more precisely, on the line A of the rail network that cuts across the Paris region from the west to the east with several stations in the suburbs and Paris.<sup>45</sup>

**Population Census.** Intuitively, individuals commuting by car from the west to the east and vice versa are the people potentially impacted by the GP closure. If the GP closure increased the commuting cost such that the cost of using public transportation becomes lower, one might

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<sup>45</sup>The RER is the suburban train network in the Paris region. The RER-A (or A-line) links the west and the east of the region, while the RER-B (or B-line) links the north and the south. Figure 2.19 represents these two lines in the Paris region.



expect a modal shift away from car-based transportation. Since the line A of the rail network cuts across the Paris region the same way the GP riverbank does (west-east), it would be the most credible alternative. Hence, we should expect an increase in its use after September 1<sup>st</sup>, 2016.

Since the riverbank itinerary was an eastward road used to cross Paris, I focus on commuters that can substitute their GP car travel itinerary with public transportation. As mentioned above, the A-line crosses the region the same way the GP did. Hence, it can be considered as a car-substitute for individuals impacted by the policy. Conversely, the B-line of the network would be only indirectly impacted by the GP shutdown since individuals who were commuting by car through the GP itinerary are unlikely to have shifted to a train linking the north and south of the region.

First, using the population census of 2015 and 2017 I compute the share of people commuting by public transportation for each dyad composed of the home place and work place. Figure 2.18 shows that the share of people commuting with public transportation from west to east or east to west is high, whether individuals live near a station of RER A or not. Nonetheless, individuals who commute from west to east or vice versa and who live in a municipality through which the line A passes tend to use slightly more public transportation<sup>46</sup>. Conversely, the remaining dyads<sup>47</sup> have a low share of public transportation usage, regardless of the presence of a train station of RER A in the home municipality. We can note in each case that the difference between the share of public transport commuters in 2015 and 2017 is negligible, if not zero. These results suggest that (i) the individuals potentially touched by the GP closure were already using intensely the public transport system, and (ii) at first sight, there is no suggestive evidence that the riverbank shutdown provoked an increase in the use of public transportation.

I evaluate the causal effect of the GP closure on the share of public transportation commuters in a difference-in-difference design. I use the dyads in which the home municipality hosts an A-line station as the treatment group and the dyads in which the home municipality hosts a B-line station as the control group. The result of this difference-in-difference estimation is represented in column (1) of table 2.11. To go further, I restrict the treated group to the east-west and west-

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<sup>46</sup>However, the difference is not statistically significant.

<sup>47</sup>All travels excluding west-east and east-west

east travels and the control group to the north-south and south-north travels.<sup>48</sup> This allows me to capture the effect on commuters crossing Paris in the same direction as the ones who were commuting through the GP riverbank itinerary prior to 2016. The result is shown in column (2). The dynamic impacts are shown in graph 2.20.

**Tap Validations.** One might argue that the share of people commuting by public transport in the years before and after the riverbank shutdown are not comparable since Paris has been subject to many urban alterations the past decade as mentioned in the introduction. To address this issue, I last turn to an alternative dataset on the number of pass validations of the A-line and B-line at the daily level. This would allow me to compare the number of pass validations on both train lines right around the cutoff (see figure 2.21), where both train lines should be comparable.

I therefore estimate another version of equation (2.5) using the data from March 2016 to end of January 2017, where  $Y_{it}$  now represents the number of weekly entries of station  $i$  at time  $t$ . The graphical results are shown in figure 2.22 and suggest again the absence of significant change in the use of the A-line right after the GP closure.

All of the above suggest that, at least in the short run, the policy did not trigger a mode shift.

### 2.7.3 Housing Prices

Results so far suggest that the GP closure increased traffic and nitrogen dioxide emissions on substitute roads. This section explores whether, on top of experiencing an increase in congestion and nitrogen dioxide emissions, substitute roads also encountered other negative externalities. Chay and Greenstone (2005) show that the elasticity of housing prices to pollution ranges between -0.20 and -0.35. Hence, in the worst case, prices would have decreased by 1.96% near the ring road. I evaluate the impact on the housing prices near the ring road and assess whether

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<sup>48</sup>I consider all the municipalities of the following departments as *west*: 92, 78, 95 and the municipalities of the following departments as *east*: 93, 94, 77, 93. As for the *north* municipalities, I select the ones in the departments 93, 95 and the municipalities of the *south* are the ones of the department 91. Note, that I do not include the municipalities of Paris in the home place (to avoid having people who commute inside Paris), but I do include them in the workplace since many jobs can be located inside the city.

the magnitude is larger than the one expected from a single increase in nitrogen dioxide.

**Empirical Strategy** I make use of housing transactions data to evaluate the impact on transacted prices of apartments close to the south part of the ring road. As mentioned, the ring roads delimit the city of Paris. The *Boulevard des Maréchaux* (Boulevards of the Marshals) are a collection of thoroughfares that encircle the city of Paris just inside its city limits. The ring road and the *Boulevard des Maréchaux* are 350 to 400-meters apart.<sup>49</sup> This provides a setup where the air near the *Boulevard des Maréchaux* is less likely to be contaminated with the increase of pollution on the ring roads. I use this separation to compare houses close to similar amenities (close to the limits of the city, close to a major road) with one particular difference: the ring road experienced an increase in traffic and pollution while the other road is left untouched. Therefore, I compare before and after the policy, transacted prices of houses outside of Paris near the south ring road with transacted prices of houses inside Paris near The Boulevards of the Marshals (see figure 2.24). I vary the bandwidth selected bearing in mind that houses closer to the ring roads should be more impacted than houses further away. I estimate the following hedonic regression:

$$\ln(HV_{it}) = \beta \ln(BA_i) + \theta Rooms_i + \sum_{k=-2, k \neq -1}^{+2} \gamma_k Treated_i * Year_{k(t)} + \delta_{m(t)} + \delta_{n(i)} + \epsilon_{it} \quad (2.13)$$

where  $HV_{it}$  is the price of transaction  $i$  at date  $t$ .  $BA_i$  is the built sare which represents the surface in squared meters of transaction  $i$ ,  $Rooms_i$  represents the number of rooms that apartment  $i$  possesses.  $Treated_i$  is a dummy variable that takes the value 1 if transaction  $i$  is located outside the limits of the city and 0 otherwise.  $Year_{k(t)}$  is the year relative to the GP shutdown of date  $t$  and  $\delta_{m(t)}$  and  $\delta_{n(i)}$  are respectively month of the sample and neighborhood fixed effects.

**Results** Figure 2.25 represents the plots of the leads-and-lags regression of equation (2.13). The impact is negative and statistically significant in 2017. The magnitude of the impact is higher the smaller the bandwidth. However, the impact of 2018 reached 0 and becomes non-statistically significant. This is explained by the announcement made in February 2018 regarding

<sup>49</sup>In between, I find almost no housing transactions since it is occupied by public social housings.

the implementation of new metro lines in the south of Paris.<sup>50</sup>

### 2.7.4 Calculating the 2016 GP Closure Costs in Euro Value

The 2016 GP closure displaced congestion and pollution to other substitute roads. However, since the impacts on traffic and pollution are non-linear the overall impact might change. To measure the costs of this policy, I quantify the impacts of an increase in pollutant emissions and an increase in travel time among the treated population.

#### Pollution Cost

To measure the change in pollution, the ideal data set would have all types of pollution (local particles, global pollution, noise pollution etc.), at the road level at a granular time window. In reality, pollution data is much more limited. Instead, I can look at the source of nitrogen dioxide emissions  $NO_2$  at an hourly level near the east of the ring road and the upper banks. Provided that the relationship between average speed on the road and  $NO_2$  emissions is well estimated, I find a causal impact on  $NO_2$  emissions of +5.8% on the south ring road and +1.5% on the upper banks. This represents an increase of roughly  $1\mu g/m^3$  near local roads and an increase of  $3.8\mu g/m^3$  near the ring roads compared to the levels of 2015 (cf table2.10). I can do some back-of-the-envelope calculations to estimate the magnitude of this change in emissions. Mink (2022) finds that an increase in  $1\mu g/m^3$  of  $NO_2$  emissions is associated with 15.08€ per day per postcode for big cities in France.<sup>51</sup> I use the estimates from Mink (2022) to quantify the cost of  $1\mu g/m^3$  health cost expenditure in France. However, these estimates are estimated using a sample the size of 1/97 of the total French population with 6,048 postcodes.<sup>52</sup> Hence, the total cost per postcode per day must be multiplied by 97 in order to have a sense of the true impact. The increase in pollution on local roads affect 5 municipalities. However not all residents of these 5 municipalities are impacted. The increase in pollution near the ring roads affect 10

<sup>50</sup><https://www.societedugrandparis.fr/gpe/actualite/la-nouvelle-feuille-de-route-du-grand-paris-express>

<sup>51</sup>In Mink (2022), healthcare costs caused by exposure to moderate levels of air pollution in France are quantified using an instrumental variable approach where wind speed is an instrument for air pollution.

<sup>52</sup>The study is conducted on a representative sample of the administrative data on healthcare reimbursements from French National System of Health Data.

municipalities. To this matter, I consider that only half of these residents suffer from the increase of pollution on these local roads. The healthcare costs associated with the increase of pollution for the 260 working days of the year near the upperbanks correspond to  $15.08 \times 97 \times \frac{5}{2} \times 260 \times 1 = 950,794$ , and near the ring roads of  $15.08 \times 97 \times \frac{10}{2} \times 260 \times 3.75 = 7,226,034$ .

### Time Loss

In order to compute the time loss for commuters due to the decrease in the average speed, I first predict what would have been the average speed on each road in the treated roads had the policy not taken place (cf. table 2.13). Two categories of commuters are suffering from an increase in travel time. First, direct losers are diverted commuters. The difference in travel time consists of the difference between the travel time using the GP expressway and the travel time using the diverted itinerary. Second, indirect losers are commuters initially on substitute roads. Adding additional users on the road decreases the average speed on that road and hence increases their travel time. The difference in travel time consists of the difference between the travel time on the treated road had the policy not taken place and the actual travel time during the post-shutdown period. Ex-riverbank users would use the entire expressway for a travel time of 24.4 minutes. If they substitute the expressway with the south outer ring road, they lose 4 minutes. If they circumvent the closed section with local roads they lose 13 minutes. Commuters initially on the local roads suffer from an increase of 2.6 minutes in their commuting time. Commuters initially on the ring road experience an increase of 4 minutes on the 10.4-kilometer ring road. In order to quantify in Euro Value the costs of time losses, I use the value of time proposed by the French government and used for cost/benefit analysis.<sup>53</sup> An hour in the Ile-de-France region is valued at 13.4. A minute costs 0.22. To this matter, I compute the daily cost of an increase in the travel journey for each category of commuter. Numbers are shown in table 2.14.

<sup>53</sup><https://www.ecologie.gouv.fr/sites/default/files/V.3.pdf>

### Maximum distance closed that keeps suburban commuters on local roads

I can compute the maximum length that would keep suburban commuters on local roads. In order to do so, I equalize the average travel time when suburban commuters stay on local roads to the average travel time when suburban commuters shift on the ring road. If all commuters shift on local roads, the extra car density becomes 47, which accounts for 62% of the pre-shutdown density. Using the congestion elasticity of local roads, I find that speed decreases by 54%, which brings it back to an average speed of 6.4km/h. This gives:

$$\begin{aligned}(1 - x)S_e + xS_a &\leq S_f \\ x(S_e - S_a) &\geq S_f - S_e \\ x(6.4 - 30) &\geq 25 - 30 \\ x &\leq 0.2\end{aligned}$$

The maximum fraction of road that can be pedestrianized without provoking the shift of suburban commuters on the ring road is 0.2. This represents 2.6-kilometers of the GP riverbank.

### 2.7.5 Calculating the Costs of Counterfactual Situations in Euro Value

#### 2.7.6 Car-ban in the center of Paris

In order to compute the costs of counterfactual situations, I first need to predict what would have been the traffic and pollution situation in each hypothetical situation. Regarding the traffic situation, I use the elasticity of congestion estimated and the predicted number of commuters who shifts on each substitute road to compute the predicted average speed. Regarding the pollution situation, I use the elasticity of  $NO_2$  emissions with respect to the average speed and the impact on speed predicted from the model to predict the change in  $NO_2$  emissions. The counterfactual situation where the center of Paris is closed to car circulation removed the upperbank from the choice set of substitute roads. Therefore, all inner-city commuters refer on the *boulevard*

*saint germain*. The 6,500 suburban commuters are untouched by the policy since they switch to the south ring road, losing 4 minutes. Similarly, the 60,790 individuals initially on the south ring road are not differently impacted, with a time loss of 4 minutes as well. However, inner-city commuters are impacted. Density of cars increases by 34% on the *boulevard saint germain*, decreasing speed by 33.7% on that road. This leads to a time loss of 28.5 minutes for diverted commuters and 10.3 minutes for commuters initially on the boulevard. The time cost in this is the following:

$$260 \times 0.22(6,500 \times 4 + 60,790 \times 4 + 20,700 \times 28.5 + 19,400 \times 10.3) = 60.5M$$

As for the pollution cost, residents living near the south ring road suffer from the same pollution cost since the traffic situation on that road remains unchanged. On the contrary, a smaller fraction of people are now impacted by an increase of pollution in the center since the number of roads impacted by a decrease in the average speed decreased. However, the magnitude of the impact on the average speed (and therefore on pollution) is higher. In this case, only 2 municipalities are impacted by a deterioration in air quality. The pollution cost is:

$$15.08 \times 97 \times \frac{2}{2} \times 260 \times 0.09 \times 63 \times 34\% = 733,176$$

### **Changing the length of the road closure**

There are four different stages. The first one is when the length of the closed segment is between 0 and 2.6-kilometers. Below 2.6-kilometers, suburban commuters shift on local roads. However, in that case, the upperbank is the only substitute road available. The second stage corresponds to a length of 2.6 to 3.3-kilometers of road closure. In that case, suburban commuters shift to the ring road and inner-city commuters stay on the upperbanks. The third stage corresponds to the actual situation of a 3.3-kilometer closure. Here, the *boulevard saint germain* becomes a local substitute road. Inner-city commuters shift on both local roads and suburban commuters divert to the ring road. Last, above 3.3-kilometers, the upperbanks stay a local substitute road on the whole length since it is reachable anywhere from the GP. However, since the *boulevard*

*saint germain* only has one entrance and exit, it can only serve as a substitute for 3.5-kilometers. After that, all inner-city commuters shift back on the upperbanks.

### Minimum mode switch needed for zero net pollution costs

If we take the scenario where all commuters shift on local roads to avoid displacing externalities to the periphery, one can compute the average speed needed so that suburban commuters choose local roads instead of the ring road. In that case, commuting time using the ring road should be higher than travel time using expressway and local roads. The minimal average speed needed would be:

$$\begin{aligned} \frac{D_{e,non-closed}}{S_{e,non-closed}} + \frac{D_{local}}{S_{local}} &< \frac{D_{ringroad}}{S_{ringroad}} \\ \frac{9.7}{30} + \frac{3.3}{S^*} &< \frac{10.4}{25} \\ S^* &> 35.4 \end{aligned}$$



## 2.7.7 Appendix Tables

Table 2.6: Traffic by road

	<b>Pre-shutdown</b>			<b>Post-shutdown</b>		
	Density	Speed	Flow	Density	Speed	Flow
<i>Panel A: Non-pedestrianized stretch of the riverbank</i>						
Morning	55	30.5	2,300	44.4	25	1,677
Evening	70	26.3	2,369	47.7	23.7	1,875
Dayweek & Daytime	54.5	30	2,239	42.8	25.1	1,741
<i>Panel B: Pedestrianized stretch of the riverbank</i>						
Morning	40.3	44.5	2,068	-	-	-
Evening	60	42.3	2,307	-	-	-
Dayweek & Daytime	46.3	44.6	2,083	-	-	-
<i>Panel C: South outer Ring Road</i>						
Morning	62.4	28.6	4,807	66.6	26	4,563
Evening	84.6	20	4,347	91	16.8	3,994
Dayweek & Daytime	71	25	4,676	75.5	22	4,366
<i>Panel D: Upper Banks</i>						
Morning	63.4	15.07	1,533	80.5	12.7	1,565
Evening	76.7	15.3	1,770	103	12.1	1,787
Dayweek & Daytime	69.3	14.8	1,584	90.4	12.1	1,611
<i>Panel E: Bd Saint Germain</i>						
Morning	85.5	8.9	1,311	120	8.4	1,545
Evening	121.5	9.6	1,816	167	7.9	1,901
Dayweek & Daytime	103	8.7	1,487	142	7.8	1,634
<i>Panel F: Bd Saint Germain &amp; Upper Banks</i>						
Morning	67.3	13.9	1,491	89.1	11.7	1,560
Evening	84.4	14.3	1,779	116	11.1	1,816
Dayweek & Daytime	75.2	13.7	1,566	101	11.2	1,616

*Notes:* The speed is expressed in km/h. All speeds are computed for daytime during weekdays. The average speed on each road is computed using the weighted average of speeds on each arc of road. The flow represents the average number of cars on each arc of road in an hour. the occupancy rate is in percentage, and represents the percentage of the road that is occupied by cars in an hour.

**Table 2.7:** Average travel time in the pre-shutdown period

<b>Itinerary</b>	<b>Time</b>	<b>Travel Time</b>
Expressway	Morning	24 minutes
Expressway	Evening	27 minutes
Expressway + local roads	Morning	33 minutes
Expressway + local roads	Evening	36 minutes
South outer ring road	Morning	22 minutes
South outer ring road	Evening	31 minutes

*Notes:* Notes: The travel time of each itinerary is computed using the data of the pre-shutdown period summarized in table 2.6 by computing  $TravelTime = \frac{Length}{Speed}$ . The first itinerary is the expressway where the non-pedestrianized stretch accounts for 9.7km and the pedestrianized for 3.3km. The second itinerary is the expressway of the non-pedestrianized stretch and the local roads (Bd Saint Germain or Upper banks) instead of the pedestrianized stretch. The last itinerary is the south outer ring road that is of 10.4 km.

**Table 2.8:** Robustness Checks: Occupancy Rate

	(1)	(2)	(3)	(4)	(5)
	<b>Occupancy rate (in log)</b>				
	<b>Ring Roads</b>				
Treatment	0.112*** (0.018)	0.117*** (0.018)	0.112*** (0.018)	0.112*** (0.024)	0.112*** (0.018)
Constant	3.146*** (0.005)	3.071*** (0.068)	3.158*** (0.006)	3.146*** (0.006)	3.146*** (0.005)
Observations	765,044	765,044	765,047	765,044	765,044
R <sup>2</sup>	0.569	0.297	0.372	0.569	0.569
	<b>Local Roads</b>				
Treatment	0.339*** (0.080)	0.357*** (0.084)	0.339*** (0.079)	0.339*** (0.089)	0.339*** (0.080)
Constant	2.233*** (0.024)	2.142*** (0.091)	2.247*** (0.015)	2.233*** (0.027)	2.233*** (0.024)
Observations	1729726	1729726	1729733	1729726	1729726
R <sup>2</sup>	0.579	0.250	0.482	0.579	0.579
Arc FE	Yes	No	Yes	Yes	Yes
Time FE	Yes	Yes	No	Yes	Yes
Additive time FE	No	No	Yes	No	No
Clustering	Arc	Arc	Arc	Between Entries	Arc
Trimmed data	No	No	No	No	Yes

\* p<.10, \*\* p<.05, \*\*\* p<.01

*Notes:* The outcome is the log of occupancy rate. Column (1) represents the main estimation during daytime. Columns (2) to (5) represent the different robustness checks performed to validate the results. In column (2), I include the dummy variable Treated instead of arc fixed effects. In column (3), the fixed effects are decomposed into year, month of the year, day of the week and hour of the day referred to as *additive time FE*. In column (4) clusters are composed of arcs between two entries. Column (5) adds up a restriction to the data: the data are winsorized at the 1% level.

**Table 2.9:** Robustness Checks: Flow

	(1)	(2)	(3)	(4)	(5)
<b>Flow of cars (in log)</b>					
<b>Ring Roads</b>					
Treatment	-0.061*** (0.013)	-0.059*** (0.013)	-0.061*** (0.013)	-0.061*** (0.012)	-0.061*** (0.013)
Constant	8.395*** (0.003)	8.405*** (0.076)	8.389*** (0.002)	8.395*** (0.003)	8.395*** (0.003)
Observations	627,122	627,122	627,127	627,122	627,122
$R^2$	0.855	0.128	0.753	0.855	0.855
<b>Local Roads</b>					
Treatment	0.264*** (0.048)	0.362*** (0.055)	0.257*** (0.048)	0.264*** (0.075)	0.264*** (0.048)
Constant	7.189*** (0.017)	7.196*** (0.079)	7.176*** (0.013)	7.189*** (0.026)	7.189*** (0.017)
Observations	1,461,499	1,461,499	1,461,508	1,461,499	1,461,499
$R^2$	0.750	0.238	0.647	0.750	0.750
Arc FE	Yes	No	Yes	Yes	Yes
Time FE	Yes	Yes	No	Yes	Yes
Additive time FE	No	No	Yes	No	No
Clustering	Arc	Arc	Arc	Between Entries	Arc
Trimmed data	No	No	No	No	Yes

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$

*Notes:* The outcome is the log of the flow of cars in an hour. Column (1) represents the main estimation during daytime. Columns (2) to (5) represent the different robustness checks performed to validate the results. In column (2), I include the dummy variable Treated instead of arc fixed effects. In column (3), the fixed effects are decomposed into year, month of the year, day of the week and hour of the day referred to as *additive time FE*. In column (4) clusters are composed of arcs between two entries. Column (5) adds up a restriction to the data: the data are winsorized at the 1% level.

**Table 2.10:** Yearly levels of NO<sub>2</sub>

Year	Ring Road		Upper Banks	
	Mean	Sd. Dev.	Mean	Sd. Dev.
2013	75.6	47	66.7	31.7
2014	74.7	36.5	62.08	30.5
2015	67	34.8	60.4	30.6
2016	66.2	34.8	59,3	28.7
2017	64.8	34.3	58.6	30.05
2018	67.4	33	59	29.8

*Notes:* This table represents the average and standard deviation of NO<sub>2</sub> emissions two sensors: the one located on the upper banks and the one on the east of the ring road. NO<sub>2</sub> emissions are measure in  $\mu\text{g}/\text{m}^3$ .

**Table 2.11:** Impact on the share of people commuting by public transportation

	(1)	(2)
	Share of public transportation commuters	
Treatment	0.002 (0.002)	-0.001 (0.006)
Constant	0.405*** (0.000)	0.709*** (0.001)
Observations	38,921	3,362
R <sup>2</sup>	0.980	0.959
Dyad FE	Yes	Yes
Year FE	Yes	Yes
Travels	All	West-Est + North-South

\* p<.10, \*\* p<.05, \*\*\* p<.01

*Notes:* Standard errors are in parentheses and clustered at the dyad level. The equation estimated is the following:  $Y_{it} = \lambda_t + \psi_i + \gamma \mathbb{1}_{treated_i=1} \mathbb{1}_{post=1} + \epsilon_{it}$  where  $i$  represents the dyad,  $t$  the year and  $Y_{it}$  the share of public transportation of dyad  $i$  at date  $t$ . The dummy variable *treated* equals to 1 if the line A passes through the home municipality of the dyad and 0 if the line B passes through the home municipality. The dummy variable *post* takes the value 1 the GP riverbank is closed on year  $t$  (year>2015) and 0 otherwise. The first column represents the estimate when all travels are included. The second column restricts the sample to west-east (and east-west) and north-south (and south-north) travels.

**Table 2.12:** Counterfactual - Speed impact predicted by the model

Distance closed	Inner-city	Suburbans	Impact on local roads	Impact on ring road
From 0 to 2.6km	On upperbanks	On upperbanks	-57%	-
From 2.6 to 3.3	On upperbanks	On ring road	-45%	-17%
3.3km	On upperbanks & bd St germain	On ring road	-18%	-17%
>3.3km	On upperbanks & bd St germain(for 3.3km)	On ring road	-18%	-17%

*Notes:* For each length window presented in column 1, I display which road inner-city commuters divert on in column (2), which road suburban commuters divert on in column (3) and their corresponding speed impacts in the remaining two columns.

**Table 2.13:** Speed Predictions

Road	Speed Pre-shutdown	Speed Post-shutdown (predicted)	Actual Speed post-shutdown
South Outer Ring Road	25	25.6	22
Local Roads	13.9	13.16	11.2

*Notes:* For each treated road, the average speed in the pre-shutdown period is taken from the data. The average predicted speed post-shutdown is the speed predicted in the post-shutdown period had the policy not taken place. The actual speed post-shutdown is the average speed observed on each road after the policy implementation. The speed is expressed in km/h. All speeds are computed for daytime during weekdays. The average speed on each road is computed using the weighted average of speeds on each arc of road.

**Table 2.14:** Time Loss in Euro Value

Commuters	Time lost	Daily Cost in €	Yearly Cost in €
Ex-riverbank diverted to the ring road	4	0.88	228.8
Ex-riverbank diverted to local roads	13	2.86	743.6
Commuters on ring road	4	0.88	228.8
Commuters on local roads	2.6	0.57	148.72

*Notes:* I consider that commuters experience an increase in travel time only during weekdays. I multiply the daily cost by 260 days to obtain the yearly cost. Since the expressway is a unique flow direction road, only one way of the commuting trip is impacted. The westward trip of each commuter remains unchanged with no additional cost associated.

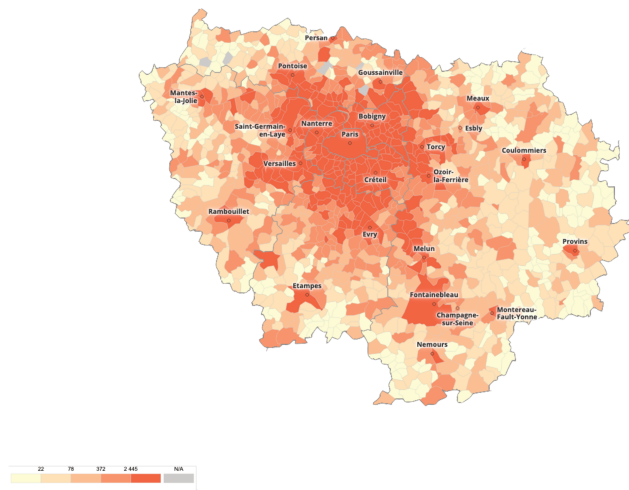
**Table 2.15:** Speed - Counterfactuals Situations

Distance closed	Inner-city	Suburbans	Speed Before	Speed After
0 to 2.6	upper banks	upperbanks	14.8	6.4
2.6 to 3.3	upperbanks	ring road	14.8	8.5
3.3	upper banks and st germain	ring road	13.7	11.3
Above 3.3	upper banks and st germain	ring road	13.7	11.3 on 3.5km 8.5 on the remaining length

*Notes:* The first column indicates the length (in kilometers) of the closed segment of the GP expressway. The second column indicates on which road inner-city commuters divert to. The third column indicates where do suburban commuters shift on. The fourth column indicates the average speed (in km/h) on the diverted road before the GP closure. The last column indicates the predicted speed (in km/h) on the diverted road if commuters shift on it.

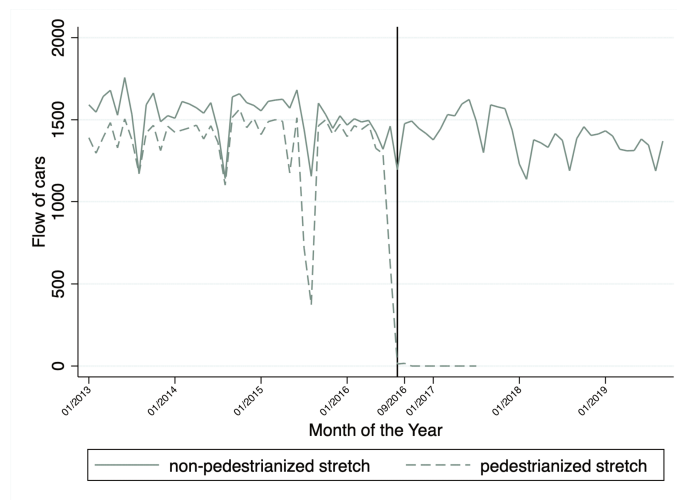
### 2.7.8 Appendix Figures

**Figure 2.7:** Job concentration in 2015



*Notes:* The job concentration is represented on this graph which is the absolute value of the number of jobs taken from the DADS (Déclaration Annuelle de Données Sociales). The brighter the color, the fewer the number of jobs in the region.

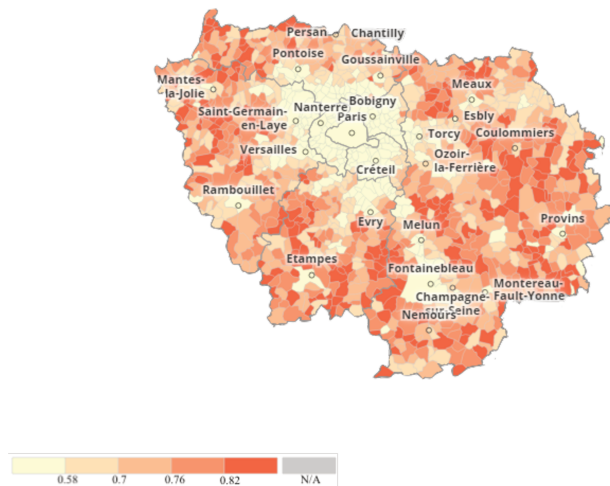
**Figure 2.10:** Flow on the pedestrianized stretch



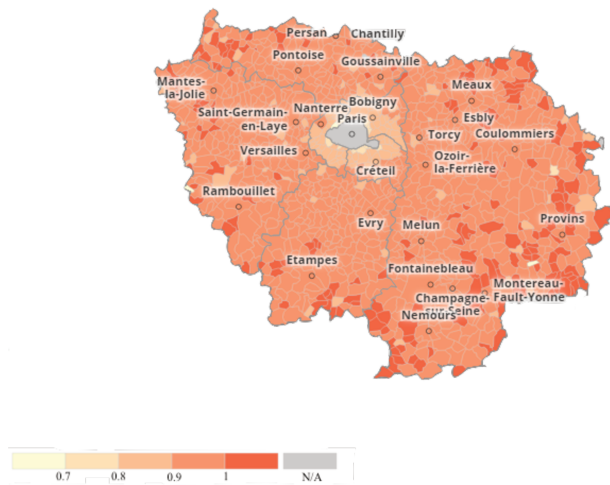
*Notes:* The sample is restricted to the 7 road sections that are pedestrianized as of 2016. The outcome is the flow of cars averaged on the pre-shutdown and post-shutdown period.

**Figure 2.8:** Fraction of people commuting by car in Ile-de-France (2015)

**(a)** All journeys



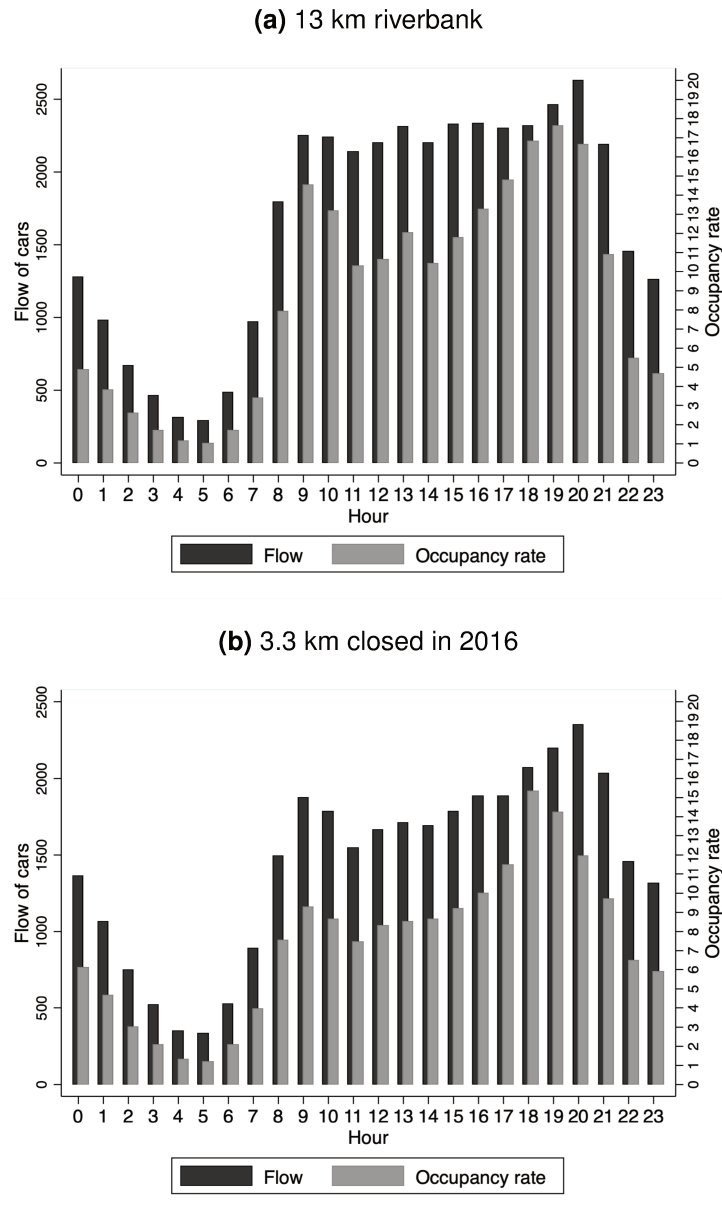
**(b)** Suburb-to-suburb journeys



*Notes:* These graphs represent the fraction of individuals commuting by car in Ile-de-France. The data is taken from INSEE - "Recensement 2015". A low fraction of car commuters is represented by a brighter color.

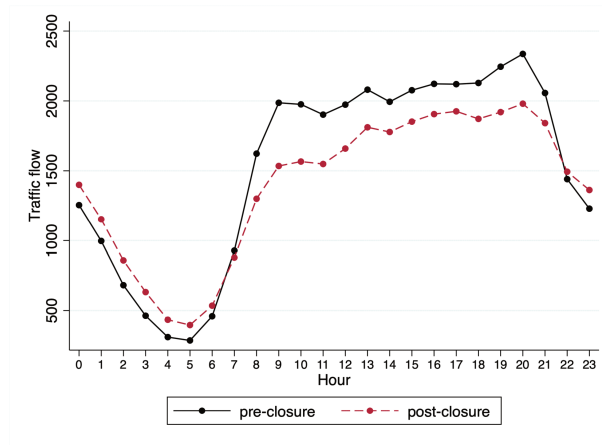


**Figure 2.9:** Descriptive statistics of the riverbank - 2015



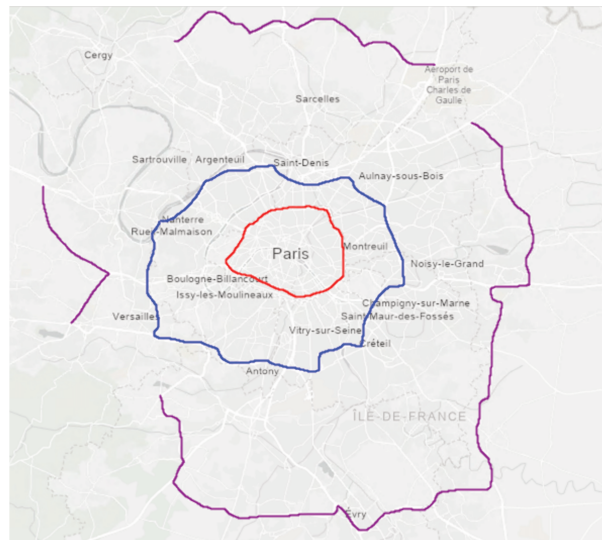
Notes: Data come from the open data source of the city hall. The sample in Figure 2.9 (a) is composed of the 33 road sections that compose the GP riverbank inside the city. The sample in Figure 2.9 (b) is composed of 7 road sections that represent the part of the GP riverbank to be pedestrianized.

**Figure 2.11:** Flow difference of the non-pedestrianized stretch, before and after the 2016 shut-down

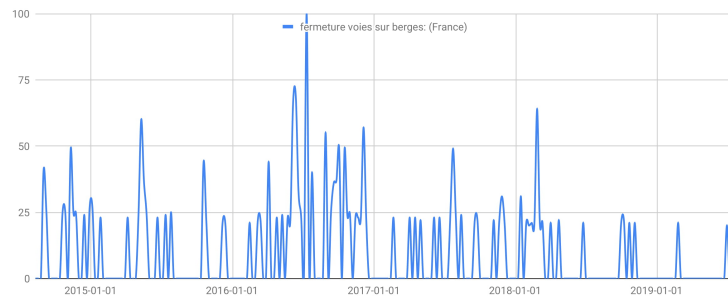


Notes: The sample excludes the 7 road sections that are pedestrianized as of 2016. The outcome is the flow of cars averaged in the pre-shutdown and post-shutdown period.

**Figure 2.12:** The three bypasses encircling Paris



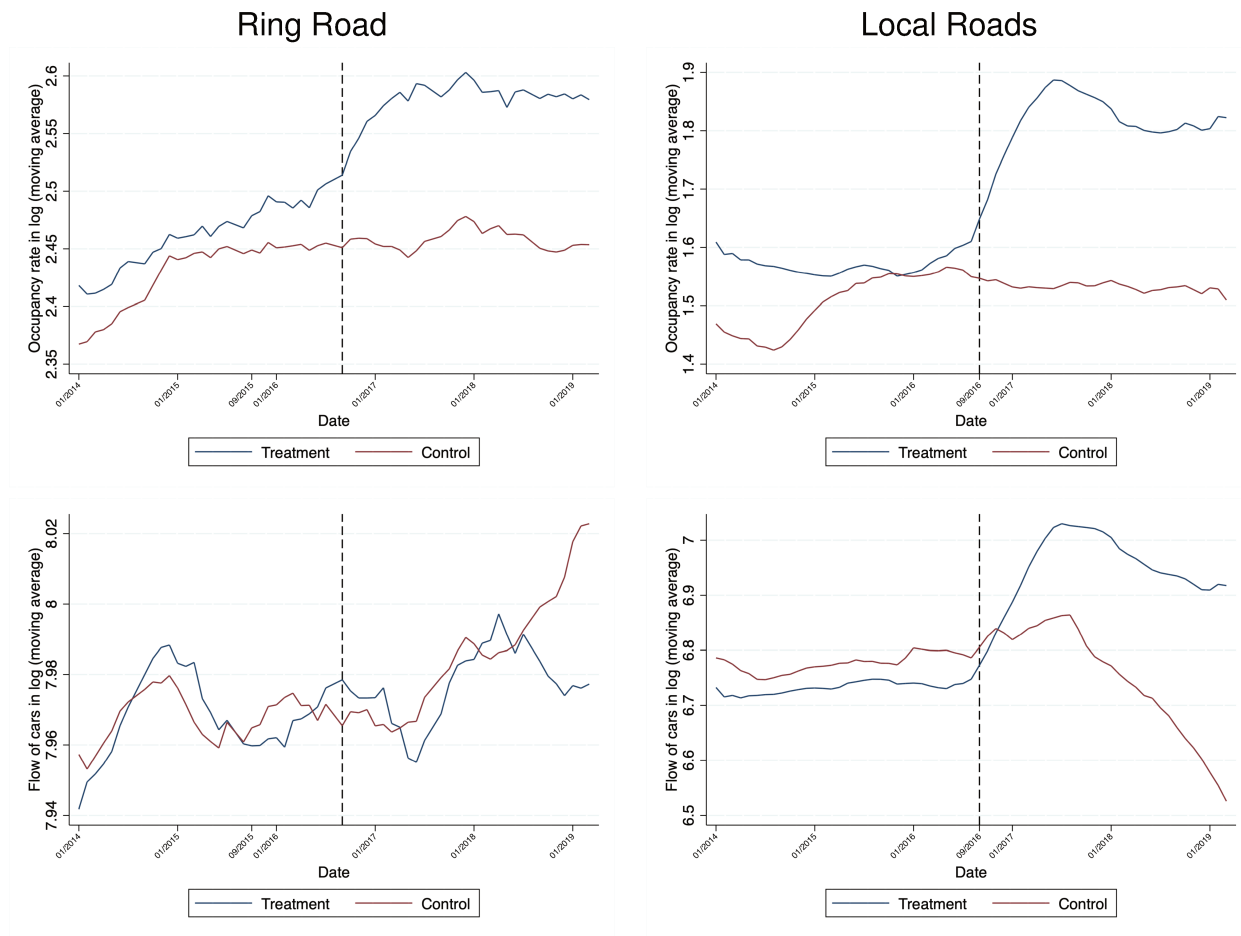
Notes: The red bypass represents the ring roads called *Boulevard Périphérique*. The second bypass (blue) is the A86 highway. The third and incomplete one (purple) represents the *Francilienne*.



**Figure 2.13:** Google trend

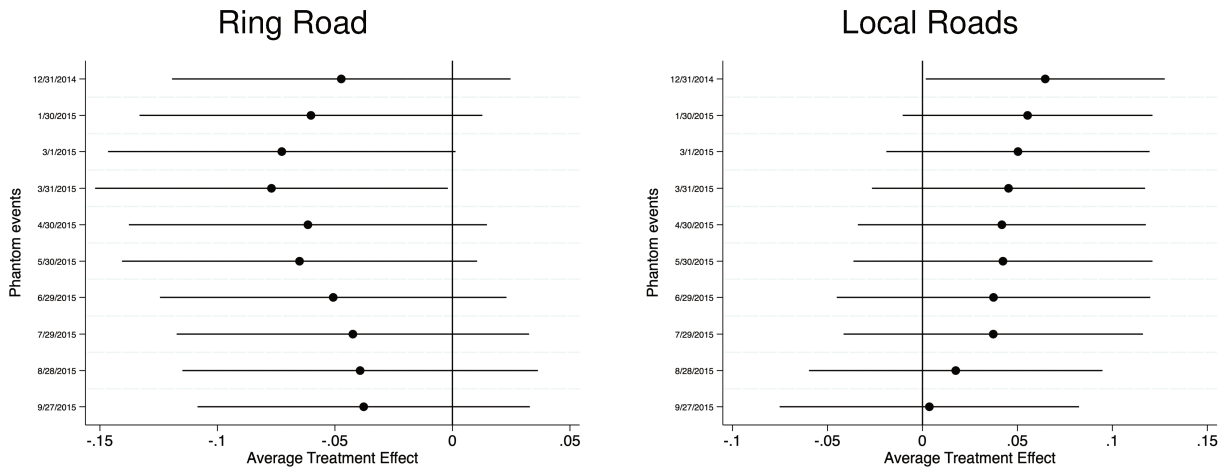
This graph represents the *Google trend* of the number of times that people in France googled "Fermeture des voies sur berges", which literally means "Riverbanks closure".

Figure 2.14: Common Trends



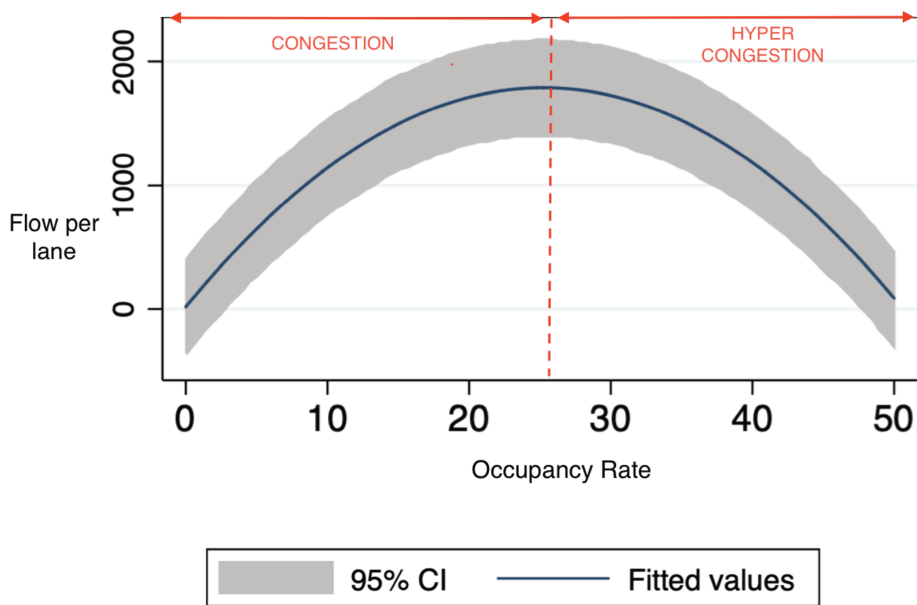
Notes: These graphs represent the common trend assumptions of the difference-in-difference research design. The first row is the common trends on the occupancy rate. The second row is the common trends on the flow of cars. The average occupancy rate is calculated with a moving average of a window of (11 1 0): the window includes the current month as well as the previous 11 months in order to smooth the noise over the year.

Figure 2.15: Placebo Tests



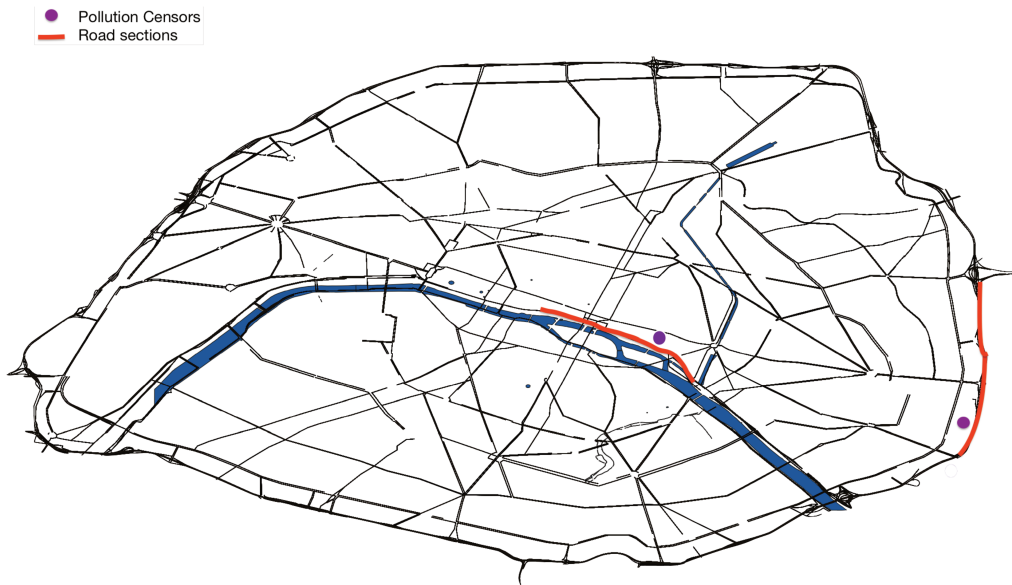
Notes: I use data from January 1, 2013 to September 1, 2016. Starting from January 1, 2015 I create every 30 days a phantom event and run regression (2.4) during the day and for weekdays with the average speed as the outcome variable. These graphs plot the estimates and 95% confidence intervals of this regression.

Figure 2.16: Fundamental Diagram



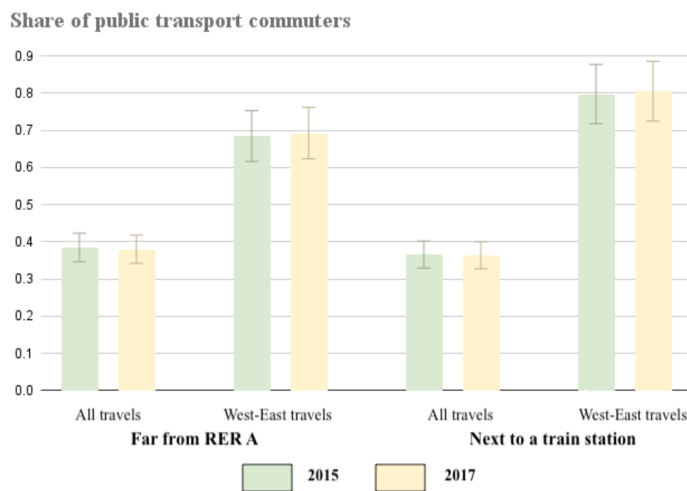
Notes: I estimate the concave relationship between Flow per lane and occupancy rate of one arc of road. The ascendant part of the graph is what we define as the *congested* part, while the descendant part is the *hyper-congested* one.

**Figure 2.17:** Pollution monitors and road sections selected



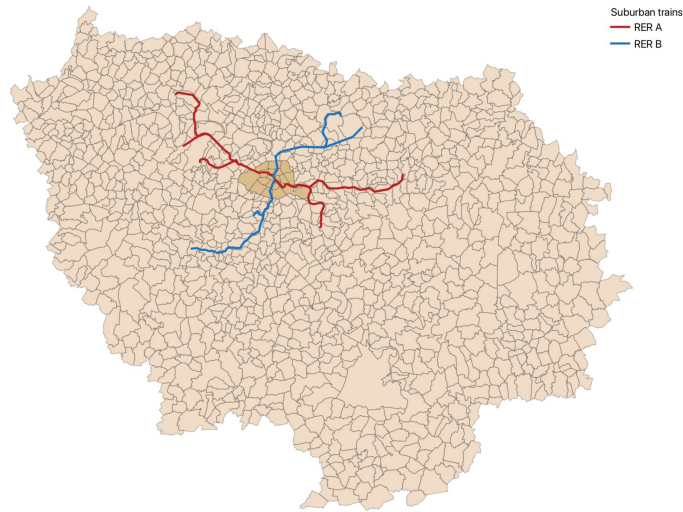
*Notes:* This map represents the two monitors I use for my analysis. One is located in the center near the upper east and one on the east of the ring road. The line in red represents the arcs of road selected near each monitor.

**Figure 2.18:** Share of public transport commuters in 2015 and 2017



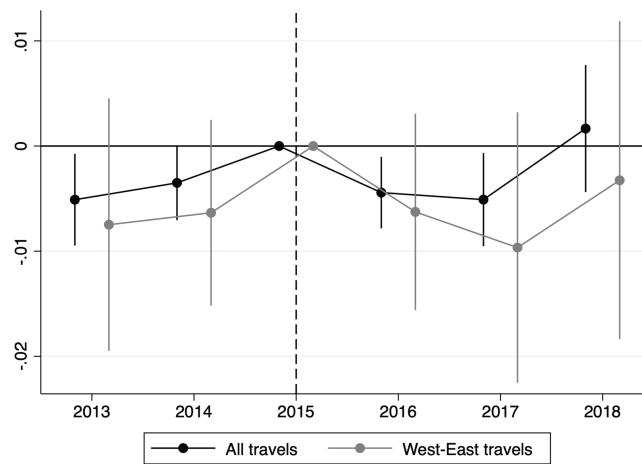
*Notes:* This chart compares the share of people commuting in public transportation in 2015 and 2017. The outcome is the mean of the share of public transportation usage in the dyads considered. The first part of the chart considers the dyads whose home municipalities do not have a station of the RER A: "Far from RER A". The last part of the chart considers the dyads whose home municipalities have a station of the RER A: "Next to a train station". For each part, I distinguish between the west-east travels and all travels excluding the west-east ones.

**Figure 2.19:** Public Transportation - RER A and RER B



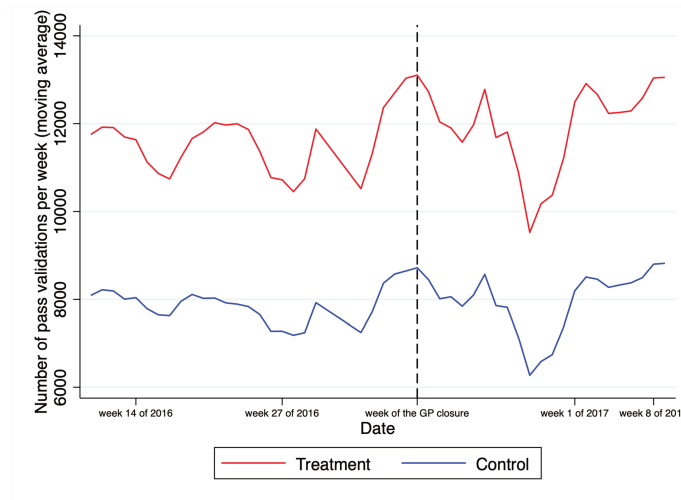
*Notes:* This figure represents the two train lines used in the analysis. The A-line is represented by the red line. The B-line by the blue line.

**Figure 2.20:** Share of public transportation



*Notes:* This graph represents the estimates of equation:

$$Y_{it} = \lambda_t + \psi_i + \sum_{k=2013}^{2018} \beta_k \mathbb{1}_{treated_i=1} \mathbb{1}_{t=k} + \epsilon_{it}$$
 where  $i$  represents the dyad,  $k$  the year and  $Y_{it}$  the share of public transportation of dyad  $i$  at date  $t$ . The dummy variable  $treated$  equals to 1 if the line A passes through the home municipality of the dyad and 0 if the line B passes through the home municipality. 2015 is the reference year and all the impacts are normalized to 2015. The black line represents the estimates when all travels are included. The gray line represents the estimates when the sample is restricted to west-east (and east-west) and north-south (and south-north) travels.

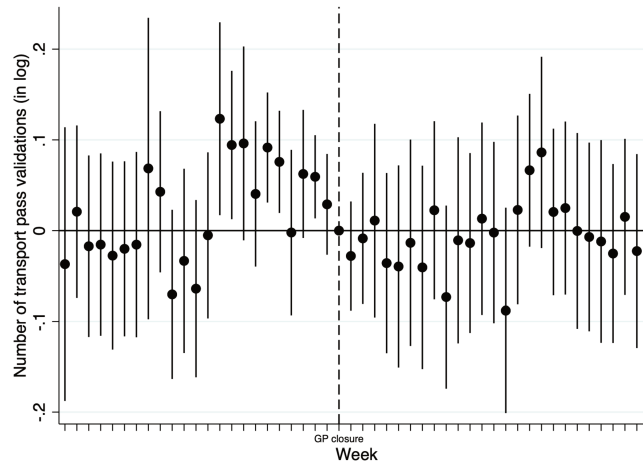
**Figure 2.21:** Weekly number of validations - RER A and RER B

*Notes:* I plot the moving average of the number of weekly validations between March 1, 2016 and February 2, 2017, excluding the days between July 23, 2016 and August 21, 2016 as the RER A was going through renovation works. The moving average is computed with a window of (0 1 3), which includes the current week and the three next weeks. The vertical dashed black line represents week 35 of 2016, the before the riverbank shutdown.

I therefore estimate another version of equation (2.5) using the data from March 2016 to end of January 2017, where  $Y_{it}$  now represents the number of weekly entries of station  $i$  at time  $t$ . The graphical results are shown in figure 2.22 and suggest again the absence of significant change in the use of the A-line right after the GP closure.

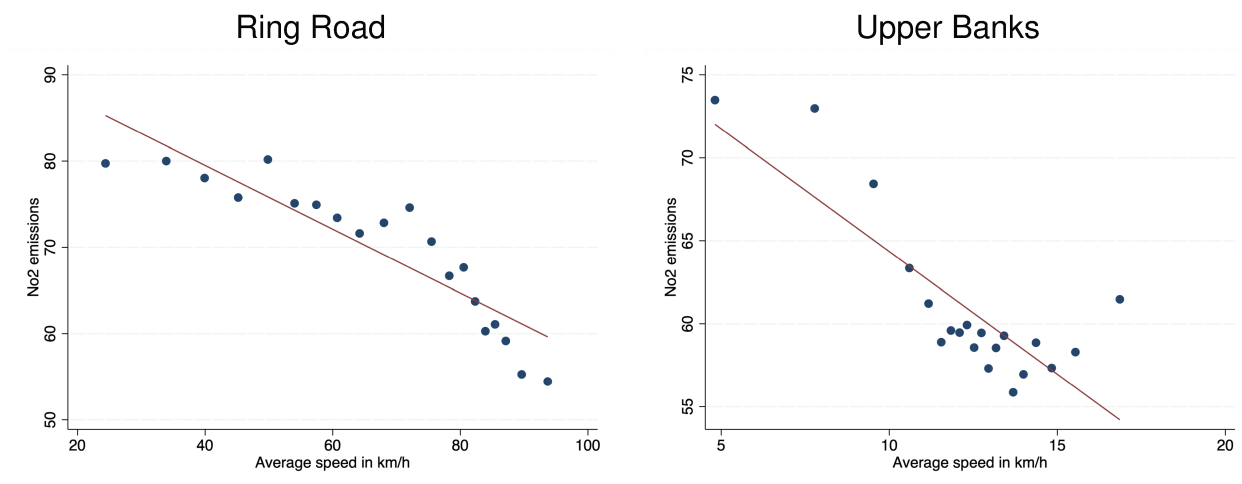


**Figure 2.22: Impact on the RER A**



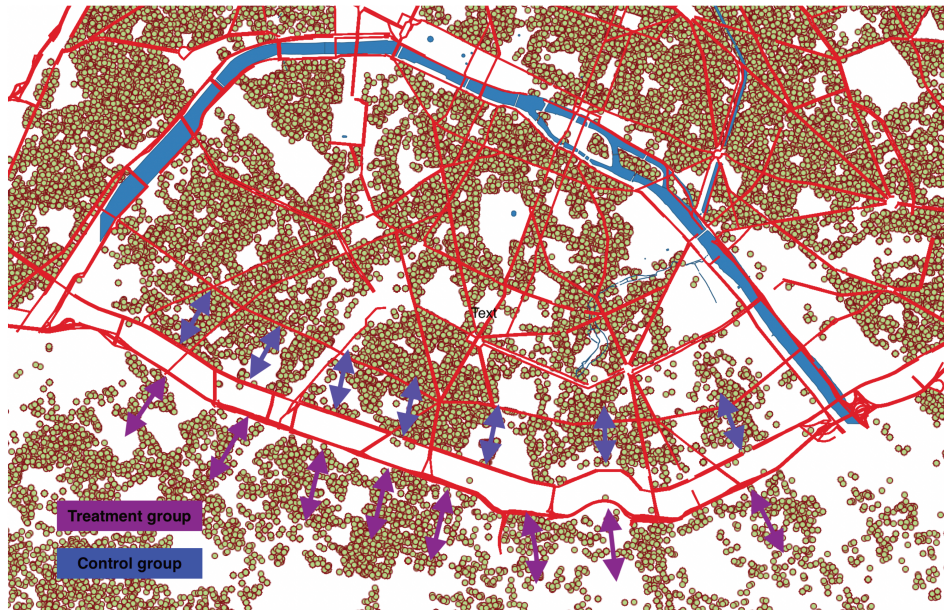
Notes: In this graph, I plot the estimates of equation (2.5).  $\lambda_t$  and  $\psi_i$  are year and station fixed effects, respectively. The indicator variable  $\mathbb{1}_{post=1}$  equals 1 if the reform has been adopted (after September 1, 2016) and 0 otherwise. The dummy  $\mathbb{1}_{treated_i=1}$  takes the value 1 if station  $i$  is on RER A and 0 if it is on RER B. The sample includes the weeks between March 1, 2016 and February 2, 2017, excluding the days between July 23, 2016 and August 21, 2016 as the RER A was going through renovation works. The vertical dashed black line represents week 35 of 2016, the before the riverbank shutdown.

**Figure 2.23: Link between  $NO_2$  emissions and average speed**



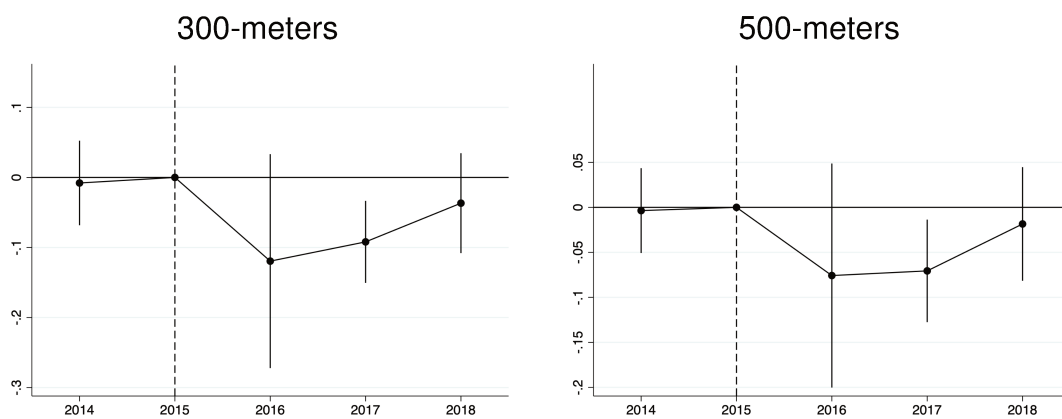
Notes: These graphs plot the relationship between average speed on the road near the pollution censor and  $NO_2$  emissions.

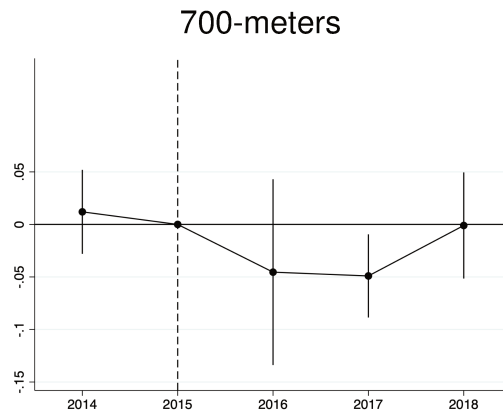
**Figure 2.24:** Treatment and control groups for housing prices



*Notes:* This graph represents all housing transactions from 2014 to 2018. There are two roads encircling the city. The first one is the "Boulevard des maréchaux" which is a boulevard inside the limits of the city. The second road is the ring road, which delimits the city of Paris. Transactions outside the limits of the city and close enough to the ring roads are impacted by the increase of negative externalities on the ring road and are considered as treated. Transactions near the "boulevard des maréchaux" are located at a distance of 350 to 400-meters from the ring roads and are therefore less likely to be impacted by the increase in negative externalities on the ring road. They are consist of the control group.

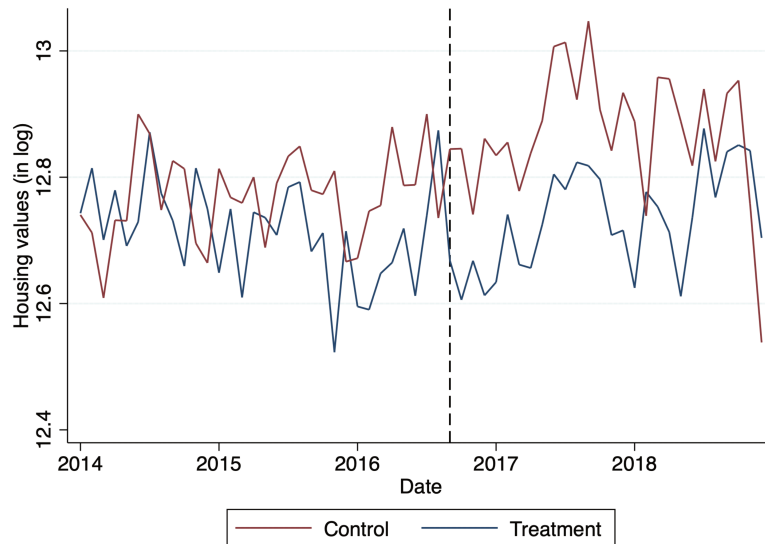
**Figure 2.25:** Impact on housing prices





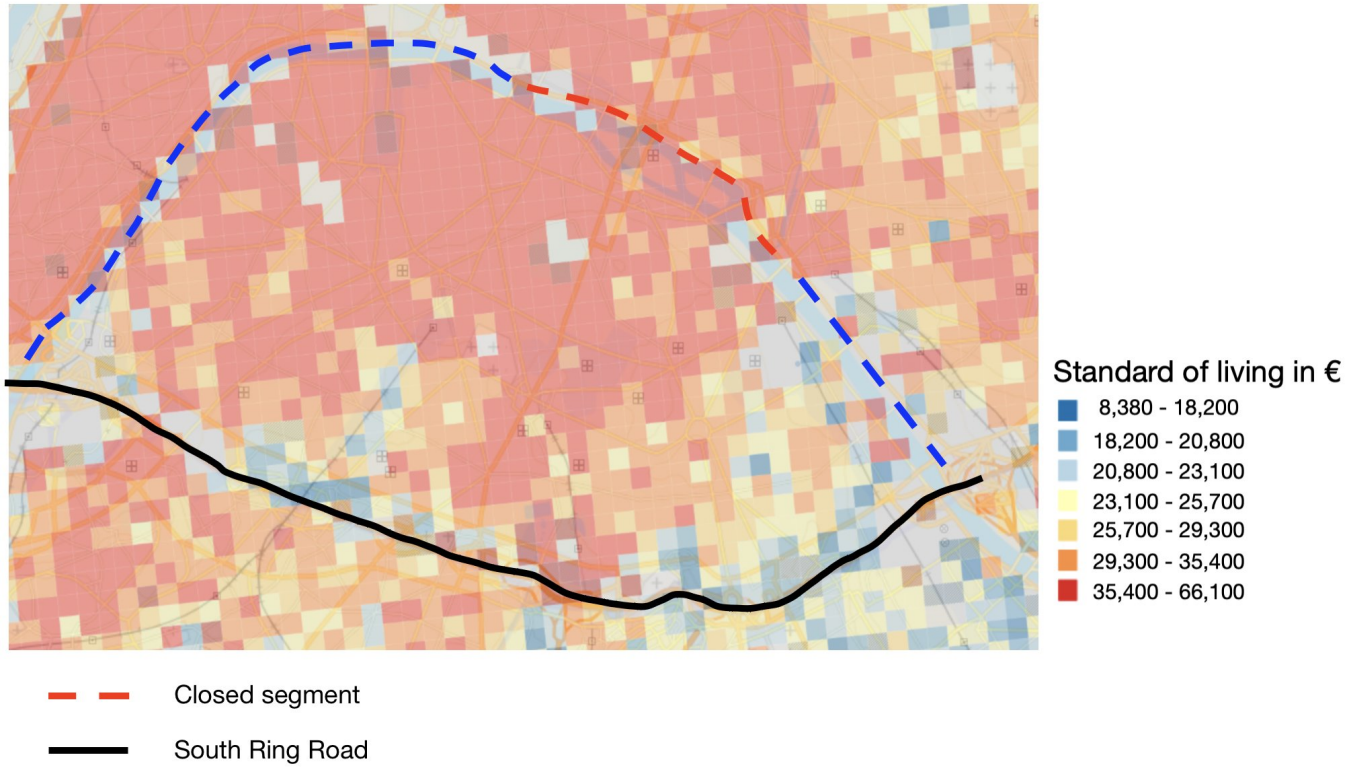
Notes: The outcome is the log of the transacted price. The reference year is 2015, a year before the GP shutdown. The regression is run on apartments only. Townhouses are removed from the sample. The sample consisting of transactions within 300-meters of the major road is composed of 5,769 observations. The sample consisting of transactions within 500-meters of the major road is composed of 11,119 observations and within 700-meters of 11,950 observations.

Figure 2.26: Common Trend Assumption - Housing Transactions



Notes: This graph plots the common trend of the transacted price in log for treatment and control groups within 700-meters of the main road. The treated group is composed of the transactions within 700-meters of the south outer ring road. The control group is composed of transaction within 700-meters of the *Boulevard des maréchaux*. Both groups are represented in figure 2.24.

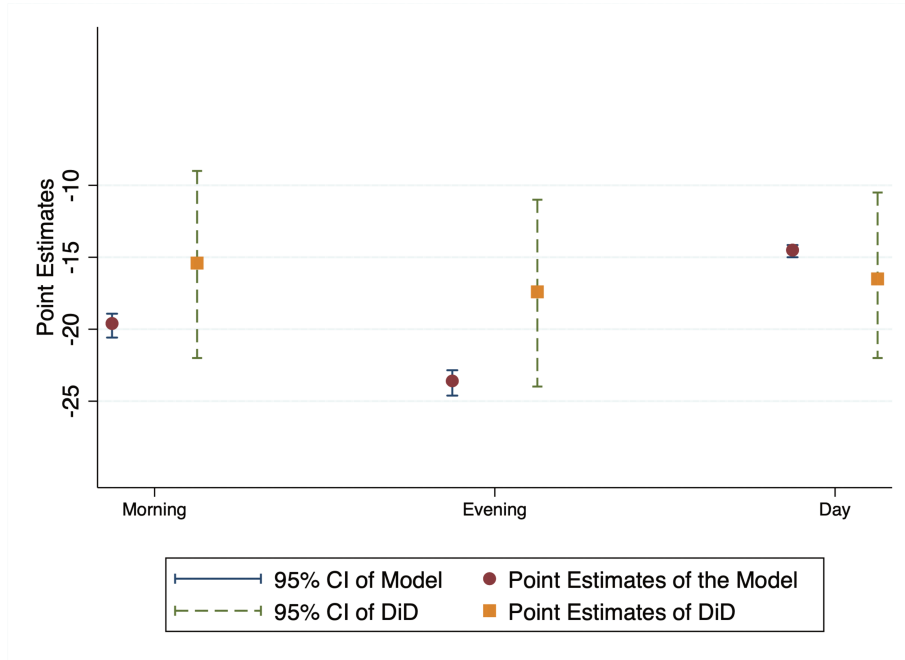
**Figure 2.27:** Standard of living across the Paris region



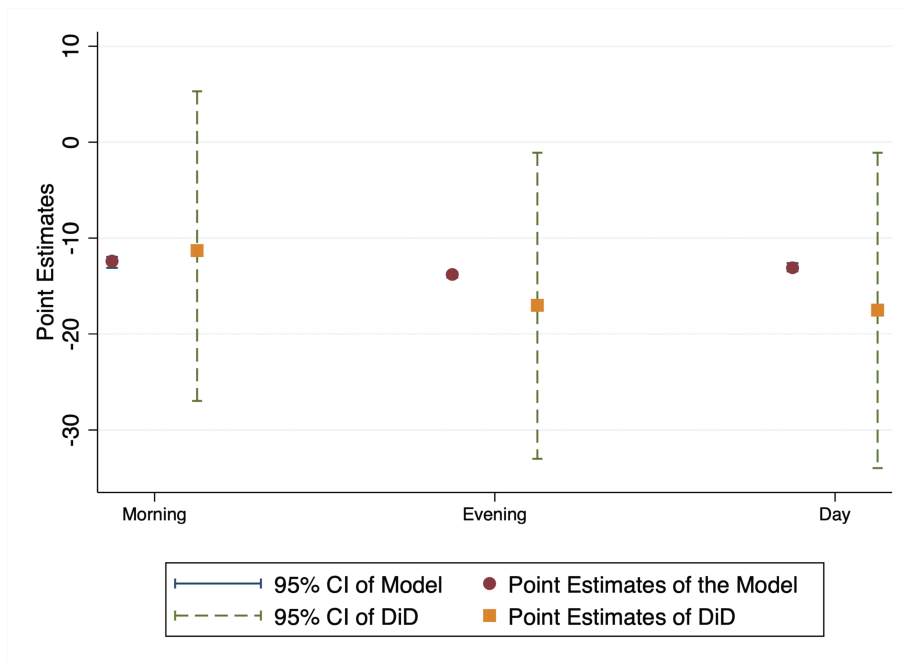
*Notes:* This map represents the spatial distribution of income near the treated roads. Red squares represent richer areas while blue squares represent poorer areas.

**Figure 2.28: Model Estimates Versus DiD Estimates**

**(a) Ring Road**



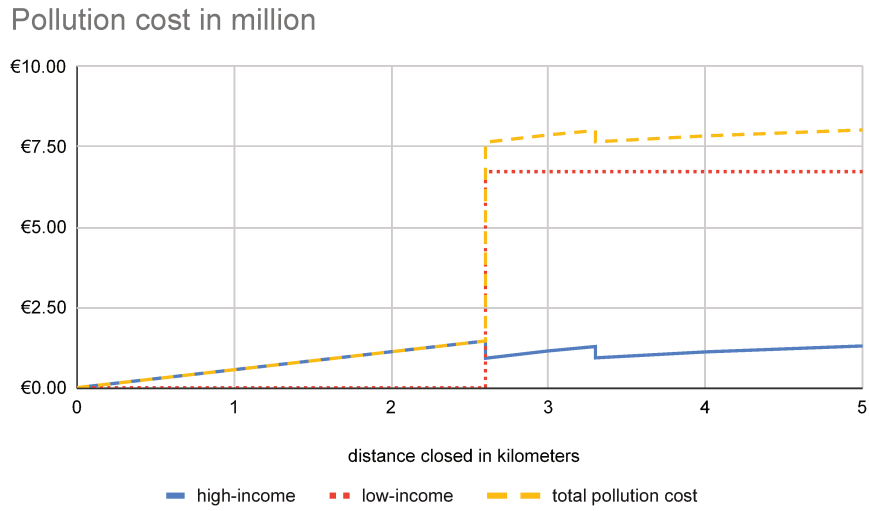
**(b) Local Road**



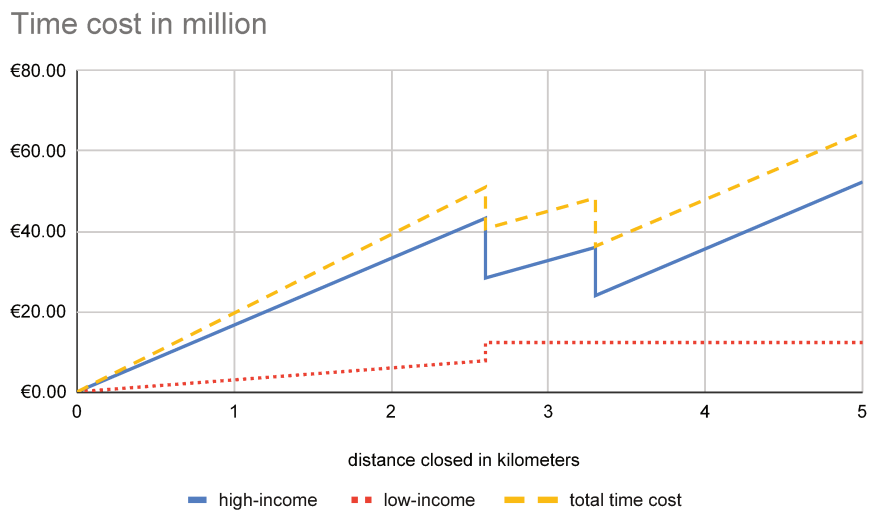
*Notes:* These graphs show the difference in point estimates between the impact of the GP closure on the average speed computed using the model, and the one computed using the difference-in-difference strategy. The model estimates are computed using the congestion elasticity  $\sigma$  of each time period.

**Figure 2.29: Costs in counterfactual situations**

**(a) Time Cost**



**(b) Pollution Cost**



Notes: These graphs represents the costs of the policy with respect to the distance of the GP closed. Computations are described in Appendix [2.7.5](#). All costs are computed using the speed impacts from the model's predictions.

## Chapter 3

# Can Politicians Make People Drop Their Cars? Evidence from French Municipalities<sup>1</sup> (with Benoit Schmutz)

### Abstract

Using a sample of French municipalities and detailed information on commuting patterns, we study whether local election results impact car use. We show that the election of a left- instead of right-wing mayor leads to a reduction of 1 p.p. in the growth of the share of car commuters. The effect is larger for within-city commuters (3.4p.p.) which translates into a decrease in the growth of the number of cars per adult (1.4p.p.). However, it does not reflect an increase in the use of public transportation, at least in the short run. Heterogeneity analyses suggest that larger cities are more impacted. In addition, the impacts are stronger for municipalities with lower initial shares of car commuters.

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<sup>1</sup>This research was supported by grants from the Agence Nationale de la Recherche (ANR-11-IDEX-0003-02/Labex ECODEC No. ANR-11-LABEX-0047).

## 3.1 Introduction

The transportation sector is an important contributor to greenhouse gas emissions, and reducing car usage is crucial for mitigating the effects of climate change (European Environmental Agency, 2020; WHO, 2005). Municipalities play an important role in shaping transportation policy and promoting non-polluting transportation alternatives, but the implementation and effectiveness of these policies can depend on the political orientation of the municipality.

Over the past few years, there has been a tendency to associate left-wing mayors with a greater emphasis on environmentally-friendly policies in their agendas than their right-wing counterparts. Mayors can influence commuting behaviors towards more sustainable options through two potential channels: (i) punishing car-commuters, and (ii) rewarding non-car commuters. Punishing car-commuters involves implementing policies that make driving more expensive such as road pricing, increasing parking fees or reducing available parking spaces. Conversely, rewarding non-car commuters involves policies such as subsidizing public transit passes, building bike or bus lanes or having pedestrian-friendly infrastructure. Both approaches have the potential to effectively reduce the share of car commuters in a given municipality, and the most appropriate approach may depend on the specific context of the municipality. The question at hand is whether political elections can influence car usage through one of these channels. In other words, do left-wing mayors use elections as an opportunity to implement policies that either punish car-commuters or reward non-car commuters?

In a municipality, car commuters can be classified into three groups: out-of-the-city commuters, into-the-city commuters, and within-the-city commuters. Policies aimed at reducing car usage may have varying impacts on these groups. For instance, measures such as installing cycling lanes within the city may benefit only within-the-city commuters, while reducing the cost of public transportation may benefit all commuters. This creates a strategic dilemma for mayors, as they may prioritize pleasing residents who are voters and punishing into-the-city commuters who do not have a voice in local elections.

In this paper, we examine the role of politicians in influencing the share of car commuters



among all commuter types. Specifically, we investigate how the political orientation of a municipality affects the implementation of transportation policies that promote sustainable transportation options, and how these policies in turn impact car usage patterns. Using data from French municipalities on commuting patterns over a decade and municipalities elections, we provide evidence that the political color of a municipality influences the share of car commuters in the municipality.

To identify the effects of elections on local policies, we follow Ferreira and Gyourko (2009) and use a regression discontinuity design analysis (RDD) that exploits quasi-random variations in the political affiliation of the mayor as a consequence of close elections. We focus on one election that occurred in 2014 and restrict the sample to municipalities for which information on the mode of transportation is available every year from 2006 to 2019 in the French census. Our sample is composed of 1,622 municipalities. In our sample, 781 elections were won by the left, and 841 by the right. Thus, our data allow us to investigate the effects of elections on the share of car commuters after the 2014 election.

First, our study reveals that the share of car commuters declines significantly faster (by 1 percentage point) in municipalities with left-wing mayors compared to those with right-wing mayors. When analyzing only within-city commutes, this effect becomes more substantial (3.5 percentage points), which corresponds to a decrease of 5.7% in car usage compared to 2014. We can exclude the possibility that this decrease is due to a significant increase in public transportation usage, which might be explained by the initial low share of public transit users in our sample.

We then study how this decrease in car commuters affects the number of cars per adult. We find a decrease in the number of cars owned by 1.1 p.p. The impact is stronger among out-of-the city commuters (-1.9 p.p.) and within-city commuters (-1.4 p.p.). However, these results are not statistically significant.

Finally, we test whether electing a left-wing mayor in close elections affects the share of car commuters homogeneously across all municipalities. Results suggest that the impacts of electing a left- relative to right wing mayor is stronger (i) in larger cities, (ii) in municipalities with a lower initial share of car commuters and (iii) in municipalities with a higher share of net car migration.

One possible explanation for these findings is that larger cities may have better-established public transit systems that facilitate a shift away from car transportation. Additionally, municipalities with lower initial shares of car commuters might already have alternatives to car transportation put in place. Last, municipalities with a higher share of into-the-city car commuters compared to out-of-the-city car commuters might be more inclined to implement stricter transportation policies to limit the amount of externalities generated by non-residents and borne by residents.

This paper builds on several strands of the literature.

First, this paper contributes to the literature that seeks to understand the link between voting and public policies. In recent years, there have been several studies examining the factors that influence individuals to vote for environmentally friendly policies and candidates. Hoffmann et al. (2022) found that experiencing extreme weather conditions such as temperature anomalies, heat episodes or dry spells makes you more likely to vote for candidates who prioritize environmental policies. This is consistent with the findings of Baccini and Leemann (2021), who observe a positive association between experiencing a flood and pro-climate voting among individuals. A separate body of literature examines the relationship between transportation policies and voting behavior. For example, Hansla et al. (2017) investigate how the implementation of a congestion tax affects public opinion, while Colantone et al. (2022) assess the impact of a ban on polluting cars, implemented in Milan, on the probability of voting for a right-wing political party. In contrast, our study examines how political elections can influence transportation and environmental outcomes.

Second, many papers look at the impact of transportation policies on pollution and car-usage, in different contexts. For example, a large set of papers evaluates the impacts of road pricing on congestion and pollution, such as those conducted by Liu and McDonald (1999); Santos et al. (2008); Tirachini and Hensher (2012); Winston and Langer (2006). Others look at the effectiveness of car bans during certain hours or days (de Grange and Troncoso, 2011; Gallego et al., 2013; Kornhauser and Fehlig, 2003) or at the impacts of urban rail-transit expansions (Adler and van Ommeren, 2016; Gonzalez-Navarro and Turner, 2018; Gu et al., 2021). In our paper, we contribute to this literature by evaluating the aggregate effect of all traffic-calming

policies done in a municipality through left-wing elections.

Finally, our study contributes to the existing literature on "Beggar-thy-neighbor" policies, particularly in the context of green policies. (Liu et al., 2022; Zhong and Pei, 2022). By distinguishing between into-the-city commuters and out-of-the-city commuters, we evaluate whether the election results have spatial spillover effects that could either benefit or harm neighboring areas.

The rest of the paper is organized as follows. Section 3.2 presents the context of French municipal elections and the data used in this study. Section 3.3 details our empirical strategy. In Section 3.4, we present our results and conclude in Section 3.5.

## 3.2 Context and data

We combine several French data sources to investigate whether municipal elections affect car use. We describe here the electoral setting and the data that we use.

### 3.2.1 Municipal elections

Municipalities are the lowest level of French government. They are identified using a statistical identifier that is constant over time, and changes in municipal boundaries are extremely rare. As is the case for most local authorities, mayors cannot use gerrymandering to change the border of municipalities. Municipal elections are held every 6 years to elect the municipal council that will elect the mayor.<sup>2</sup> The elections are based on lists, and voters can pick at most one list. If no list achieves an absolute majority in the first round, a second round is organized. Only lists obtaining more than 10% of the vote in the first round can compete in this second round.

After the elections, the seats in the municipal council are allocated using a majority premium which gives a large absolute majority to the list that obtained the most votes in the final round. The electoral system stipulates that half of the seats are attributed to the list that obtained the most votes. The other half are distributed according to their vote share across all competing

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<sup>2</sup>An exception is the 2007 municipal elections, postponed to 2008 because of the 2007 presidential elections. See Schmutz and Verdugo (2023) for details.

lists, including the list that obtained the most votes. One advantage for our study is that such an electoral system generates a large discontinuity between vote shares and the share of seats in the municipal council. For example, a list just above 50% of votes will get 75% of the seats. As a result, the list that obtained the most votes is guaranteed to govern the municipality, as no post-electoral coalitions among other lists could reach a majority and overturn the results. We exploit this feature in our RDD framework.

We focus on one election that occurred in 2014, because it is the only election for which we can leverage both pre-election and post-election outcomes (see next subsection). We categorize the lists in the final election round as either left- or right-wing using the classifications of French electoral authorities. Most of the time, this assignment is straightforward, as there were no national or local bipartisan coalitions over the period. Since their electoral system is different, we do not keep Paris, Lyon and Marseilles. In addition, we restrict the sample to municipalities for which information on the mode of transportation is available every year from 2006 to 2019. We end up with a sample of 1622 municipalities. According to the French Statistical Institute, 257 of these municipalities could be considered as “rural” in 2017, while 1110 belonged to an urban area.

In our sample, 781 elections were won by the left, and 841 by the right. Municipalities won by the right are slightly more populated, but the difference is not statistically significant. Conversely, the share of high-skilled workers is 2 p.p. higher in right-wing municipalities. We define our running variable as the vote share difference between the main left-wing list at the final round of the election and the main right-wing list at the final round of the elections. If the two main lists are of right-wing parties (resp., left-wing parties), this variable is set to -1 (resp., 1). This corresponds to 144 and 258 elections. However, the median value is very close to zero (-0.01). Close elections are quite frequent: there are 509 elections with a margin of less than 10 p.p., 277 of which were won by the right. The corresponding figures are 279 (153) for 5 p.p. and 133 (75) for 2.5 p.p.

### 3.2.2 Car-based commuting

We assess the effects of elections on commuting patterns using a module of the French census called MODPRO, available on a yearly basis from 2006 to 2019. Since 2004, the French census has taken the form of a survey, conducted every year for a fifth of the population. Therefore, values correspond to a five-year average around the year. For example, the 2006 values correspond to a five-year average between 2004 and 2008. Similarly, the 2019 values correspond to a five-year average between 2017 and 2021. In order to avoid contamination by the COVID-19 crisis, we consider 2017 as the end date.

**Individual-level analysis** — We use the 2014 year to document the role of location on car use. The dataset contains more than 3 million observations. We consider the determinants of a binary variable equal to 1 if the respondent declares the car as her main commuting mode. On average, using sampling weights, this variable is equal to 0.64. We can control for: individual variables (head of household status, gender, age (in five-year categories), occupation (single-digit), diploma (four categories), contract type (9 categories), immigration and citizenship (binary) and job sector (5 categories)), household variables (number of persons, number of active adults, family type (10 categories)) and housing variables: whether the dwelling is a house (binary), home-ownership (binary) and public housing (binary)). We also control for municipality fixed effects, either for the place of residence, or for the place of work.<sup>3</sup>

Table 3.1 shows the explanatory power of the three groups of variables, as well as municipality fixed effects. We see that a large part of individual variations is left unexplained by the covariates. However, we can also note that municipality fixed effects have twice as much explanatory power as individual controls for the municipality of residence, and close to three times more for the municipality of work. Even if housing characteristics are strongly correlated with location, it does not affect much the explanatory power of municipality fixed effects. Overall, these estimates suggest that both residential and workplace location are important determinants of mode choice, which is not fully explained by individual characteristics.

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<sup>3</sup>Municipality of work is documented for all individuals, except for cross-border workers (1% of observations).

**Table 3.1:** Covariates of car use

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
R-Squared	0.06	0.16	0.21	0.07	0.17	0.22	0.10	0.17	0.23	0.12	0.17
Individual	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Household				✓	✓	✓	✓	✓	✓		
Housing							✓	✓	✓		
Residence		✓			✓			✓		✓	
Work			✓			✓			✓		✓

Notes: Depending on the specifications, there are between 2.9 and 3.1 million observations. OLS regressions, weighted by sampling weights. The dependent variable is a dummy equal to one if the respondent declares the car as her main commuting mode.

**Municipal analysis** — We construct a dataset at the municipality level, using sampling weights. In order to better proxy total car use, we construct a measure of commuters which comprises both resident commuters and workers who live outside the municipality. The 2014 cross section is described in Table 3.2. On average, a municipality has almost ten thousand commuters, 20% of them commute within the municipality, while outflows and inflows respectively account for 46% and 35%. Average car use among commuters is 82%, which, considering the discrepancy with the aggregate share of 0.64, shows that larger municipalities are characterized by a lower share. Unsurprisingly, commuters are much more likely to use their car when they work in a different municipality (0.86 for outflows and 0.90 for inflows) than when they work in the same municipality (0.59). However, the reverse pattern is not observed for public transit use, because the average share of within-city commuters who walk to work is equal to 18%, while it is very close to zero for other kinds of commuters. The data also allows us to compute a measure of car penetration, by leveraging information on the number of cars and the number of active adults in the respondent's household. This ratio is very close to one on average, but it exhibits substantial variations across space, as well as depending on the respondent's commuting type.

In order to get a sense of the evolution of car use over the period, we make use of other cross-sections of the MOBPRO data to compute first differences between 2006 and 2017. The results are documented in Table 3.3. The total number of commuters increases by about 3%. Municipalities become more and more dependent on outside municipalities: the share of within-

**Table 3.2:** Descriptive statistics: 2014 cross section

Variable	Mean	Std. Dev.	Min	Max
Number of commuters	9427	20,541	361	353,435
Share of within-city commuters	0.20	0.09	0.02	0.65
Share of out-of-the-city commuters	0.46	0.19	0.03	0.89
Share of into-the-city commuters	0.35	0.16	0.02	0.90
Share of car users	0.82	0.11	0.27	0.98
among within-city commuters	0.59	0.12	0.13	0.90
among out-of-the-city commuters	0.86	0.14	0.21	1
among into-the-city commuters	0.90	0.10	0.27	1
Share of PT users	0.08	0.10	0	0.58
among within-city commuters	0.04	0.07	0	0.41
among out-of-the-city commuters	0.11	0.13	0	0.69
among into-the-city commuters	0.06	0.09	0	0.61
Nb car per active adult	1.01	0.10	0.51	1.26
among within-city commuters	0.97	0.13	0.41	1.44
among out-of-the-city commuters	1.03	0.12	0.42	1.35
among into-the-city commuters	1.01	0.11	0.55	1.39

Source: MOBPRO 2014. Sample of municipalities with information on the 2014 municipal election ( $N = 1622$ ).

city commuters decreases by 3 p.p. Relatedly, the shares of car and PT users increase by 1 p.p., and the number of cars per adult increases by 4 p.p. These changes are not very large on average, but there is substantial variability between municipalities.

### 3.2.3 Politics and car use

Historically, environmental issues do not clearly align with the left/right divide in France. While the first ministry of Environment was created in 1971 under right-wing prime minister Jacques Chaban-Delmas, the first ecologist presidential candidate in 1974, René Dumont, was more of a left-wing figure. The socialist party, which is the central left-wing party was long dominated by a modernist, pro-industry platform. After two decades of internal debates and no electoral success, the ecologist party has mostly been anchored to the left since 1994, and it took active part in Lionel Jospin's government between 1997 and 2002, as well as under socialist president François Hollande between 2012 and 2017. However, until today, there is a tension between the supporters of "political ecology", who argue that environmental issues require systemic changes

**Table 3.3:** Descriptive statistics: evolution 2006-2017

Variable	Mean	Std. Dev.	Min	Max
Number of commuters	355	2511	-9079	44129
Share of within-city commuters	-0.03	0.04	-0.20	0.22
Share of out-of-the-city commuters	0.01	0.05	-0.28	0.26
Share of into-the-city commuters	0.01	0.05	-0.40	0.29
Share of car users	0.01	0.04	-0.17	0.15
Share of PT users	0.01	0.02	-0.32	0.11
Nb car per active adult	0.04	0.05	-0.12	0.25

Source: MOBPRO 2006 and 2017. First difference between 2017 and 2006 values. Sample of municipalities with information on the 2014 municipal election ( $N = 1622$ ).

to capitalism, and more centrist figures, who advocate more incremental improvements.

Since the 1980s, many local transportation policies with a strong environmental component have been implemented by left-wing mayors. For example, the Nantes tramway, which was inaugurated in 1984, had been launched by newly-elected socialist mayor Alain Chénard. The same is true for Paris, which started to bend its transportation policy after the 2001 electoral turnover, when socialist mayor Bertrand Delanoë was elected. In 2014, its successor Anne Hidalgo was elected with an even more environmentally-friendly agenda. In 2020, the ecologist party won the elections in several large municipalities, including Lyon and Bordeaux. However, little is known about the environmental component of local policies in smaller municipalities. Politicians in smaller municipalities generally have less financial power. In addition, they may favor *statu quo* because their electorate is more dependent on car use.

In our dataset, there is little obvious correlation between election results in 2014 and the variables described above. Municipalities where a left-wing mayor was elected are somewhat smaller and less likely to have a high share of within-city commuters. Therefore, in 2017, the use of car is slightly higher (1.4 p.p.), the use of public transit is slightly lower. Furthermore, there seems to be a slight divergence between 2006 and 2017: the share of care users increases more in left-wing municipalities (by 0.4 p.p.), the share of PT users decreases more (by 0.3 p.p.) and the number of cars per active adult increases more (by 0.7 p.p.).



### 3.3 Empirical strategy

To assess the causal effect of municipal elections, an ideal experiment would be to randomly assign a left- or a right-wing mayor to a sample of municipalities. We approximate such an experiment with a regression discontinuity design that compares municipalities in which a left-wing mayor was closely elected with municipalities that closely elected a right-wing mayor. Differences between the two identify the local treatment effect of electing a left- instead of a right-wing mayor after a close election.

#### 3.3.1 The RDD design

Following Lee (2008), our running variable  $X_{it}$  is the vote margin of the left. It is defined as the difference in the share of votes between the better-ranked left-wing list and the better-ranked right-wing list in municipality  $i$  in election year  $t$  in the final round. It is thus positive when the left has won and negative otherwise. With treatment defined as a left victory, the assignment variable  $D_{it}$  is a dummy equal to one when the election was won by the left, and thus  $X_{it} > 0$ , and zero otherwise. Our empirical model is given by:

$$g_{i\tau,t} = \beta_0 + \beta_1 D_{it} + \beta_2 X_{it} + \beta_3 X_{it} D_{it} + \beta_4 X_{it}^2 + \beta_5 X_{it}^2 D_{it} + u_{it} \quad (3.1)$$

where  $g_{i\tau,t} = G_{i\tau}/L_{i\tau} - G_{it}/L_{it}$  measures changes in shares from group  $G$  in municipality  $i$  between election year  $\tau > t$  and year  $t$ , which adjust the size of group  $G$  to the contemporaneous level of the population between elections. Following Cattaneo et al. (2020), we non-parametrically estimate the model using a local linear function with a triangular kernel, and inference is based on their robust-bias correction method. To allow for comparability across outcomes, we use in our main specification an optimal bandwidth and a polynomial of order 2. We also report results using alternative polynomial orders as robustness checks.

### 3.3.2 Validity checks

Whether our RDD estimates capture a causal effect depends on whether municipalities close to each side of the threshold are comparable and had similar characteristics before the elections.<sup>4</sup> To assess this hypothesis, Table 3.5 reports several "placebo" RDD for the evolution of between 2006 and 2011, that test whether the outcome of close elections is associated with past changes in the characteristics of the municipality as measured before the election of interest. Left victory has no significant impact on the growth of the shares of car commuters, the shares of public transit commuters and the number of cars per adult in 2011.

Following McCrary (2008) and Cattaneo et al. (2018), we investigate whether the forcing variable is continuous near the threshold, which is a test for the manipulation of the forcing variable. To check the smoothness of the density of the vote share near the threshold visually, Figure 3.5 reports the outcomes of local linear regression, estimated separately on each side of the cutoff, to test the null hypothesis that the discontinuity at the cutoff is zero. While the share of close victories for the right appears slightly larger, the difference is not statistically significant and we cannot reject the null of no density jump around the threshold ( $p$ -value = 0.227). These results are consistent with earlier evidence from Eggers et al. (2015) and Lippmann (2018) for France and other countries.

Finally, as the causal effects are identified from close elections, an important question to interpret the results is whether close elections occur in municipalities that are systematically different from others. To investigate this issue, Table 3.4 compares the average and standard deviation of various observable predetermined characteristics in municipalities that experienced different margins of victory. Remarkably, close elections occur in municipalities with average characteristics similar to the whole sample, even when considering increasingly close elections.

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<sup>4</sup>Formally, the LATE at  $X = 0$  is identified under the hypothesis of continuity at the cutoff of the conditional expectation of the outcome (Hahn et al., 2001).

**Table 3.4:** Mean predetermined characteristics of municipalities in increasingly close elections

	Car	Public transit	Nb of cars	Population	N
All cities	0.821 (0.11)	0.078 (0.10)	1.01 (0.10)	9,395 (20,484)	1,632
Margin  <15 p.p.	0.818 (0.105)	0.081 (0.09)	1.01 (0.09)	11,657 (24,882)	707
Margin  <5 p.p.	0.815 (0.108)	0.083 (0.10)	1.01 (0.10)	11,461 (28,136)	282
Margin  <2.5 p.p.	0.810 (0.119)	0.088 (0.112)	1.00 (0.110)	11,527 (22,115)	135

Sources: 2014 elections and 2014 mobility census. Notes: The table reports the average values of the share of car commuters, the share of public transit commuters, the number of cars per adult and the population of municipalities in our sample in 2014. The first line reports these averages for the entire sample. Other lines report averages from elections with margins of victory lower than 15%, 5% and 2.5%. the margin of victory is the difference between the share of votes between the list ranked first and the list ranked second in the final round.

## 3.4 Results

In the section, we show how elections influence commuting behaviors. First, we estimate the impact of electing a left-wing mayor compared to a right-wing mayor in close elections on the growth in the share of car commuters, the share of public transit commuters and the number of cars per adult. To make sure that our results are not driven by a change in commuting flows, we estimate the impact of elections on the share of into-the city, within-the-city and out-of-the city commuters. Finally, we ask whether electing a left-wing mayor affect all municipalities homogeneously.

### 3.4.1 Effects on the share of car-commuters

The first part of table 3.5 shows the estimates of the changes in the share of car commuters in municipalities that closely elected a left-wing mayor compared to those who closely elected a right-wing mayor. We begin in Column 1 by assessing whether elections influence the evolution in the share of car commuters and decompose this evolution in columns 2, 3 and 4. While the estimated effects for into-the-city commuters are small and very imprecise, we find a statistically significant negative effect of elections on the change in the share of all car commuters of 0.9 p.p., translating into a decrease of 1% compared to the levels of 2014. The impact is particularly strong for within-city commuters. We find a decrease of 3.5 p.p. in the evolution of the share

of within-city car commuters, inducing a decrease of 5.7% compared to the levels of 2014. We graphically illustrate our results in figure 3.1. Panel A shows that the evolution in the share of total car commuters present a discontinuity at the threshold after the election. This discontinuity is exacerbated in Panel B for within-city commuters. However, we find no evidence of a significant decrease in the share of car commuters after the election among into-the-city commuters (Panel C) and out-of-the-city commuters (Panel D). In Figure 3.6, we show the graphical results using a regression discontinuity design of polynomial 1.

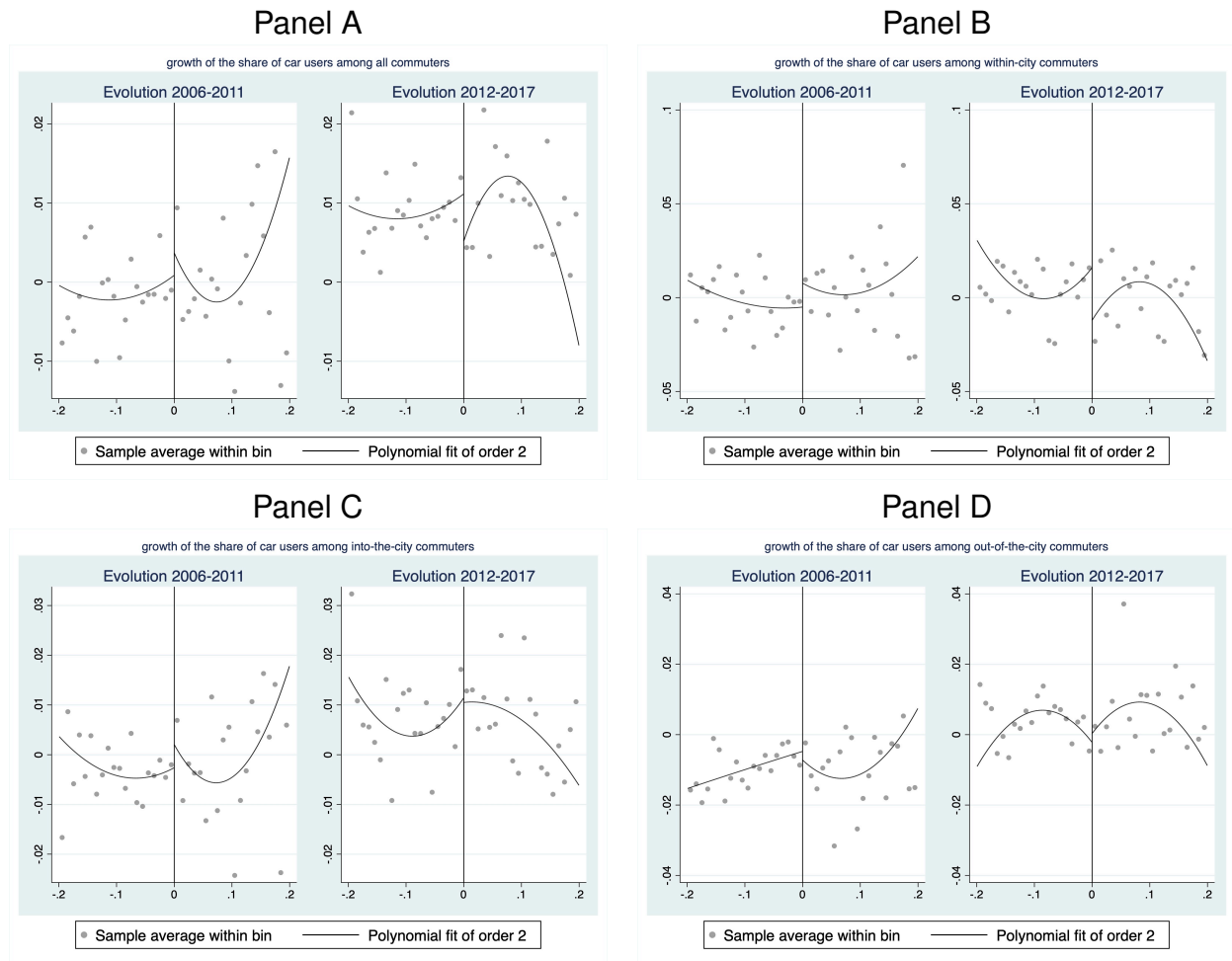
### **3.4.2 Effects on the flows of commuters**

In this section, we examine the potential impact of political elections on changes in the relative share of a particular group within a population. For example, we could consider a scenario where electing a left-wing mayor in a municipality could decrease the share of commuters traveling into the city by causing some workers who oppose left-wing policies to leave. To ensure that our findings are not influenced by changes in the composition of commuting flows but rather by changes in commuting modes, we analyze the effects of elections on commuter flows. Results are illustrated in Figure 3.2. Although it seems like electing a left-wing mayor has a negative impact on the evolution of the share of within-city commuters and a positive effect on the evolution of the share of into-the-city commuters, both estimates are not statistically significant.

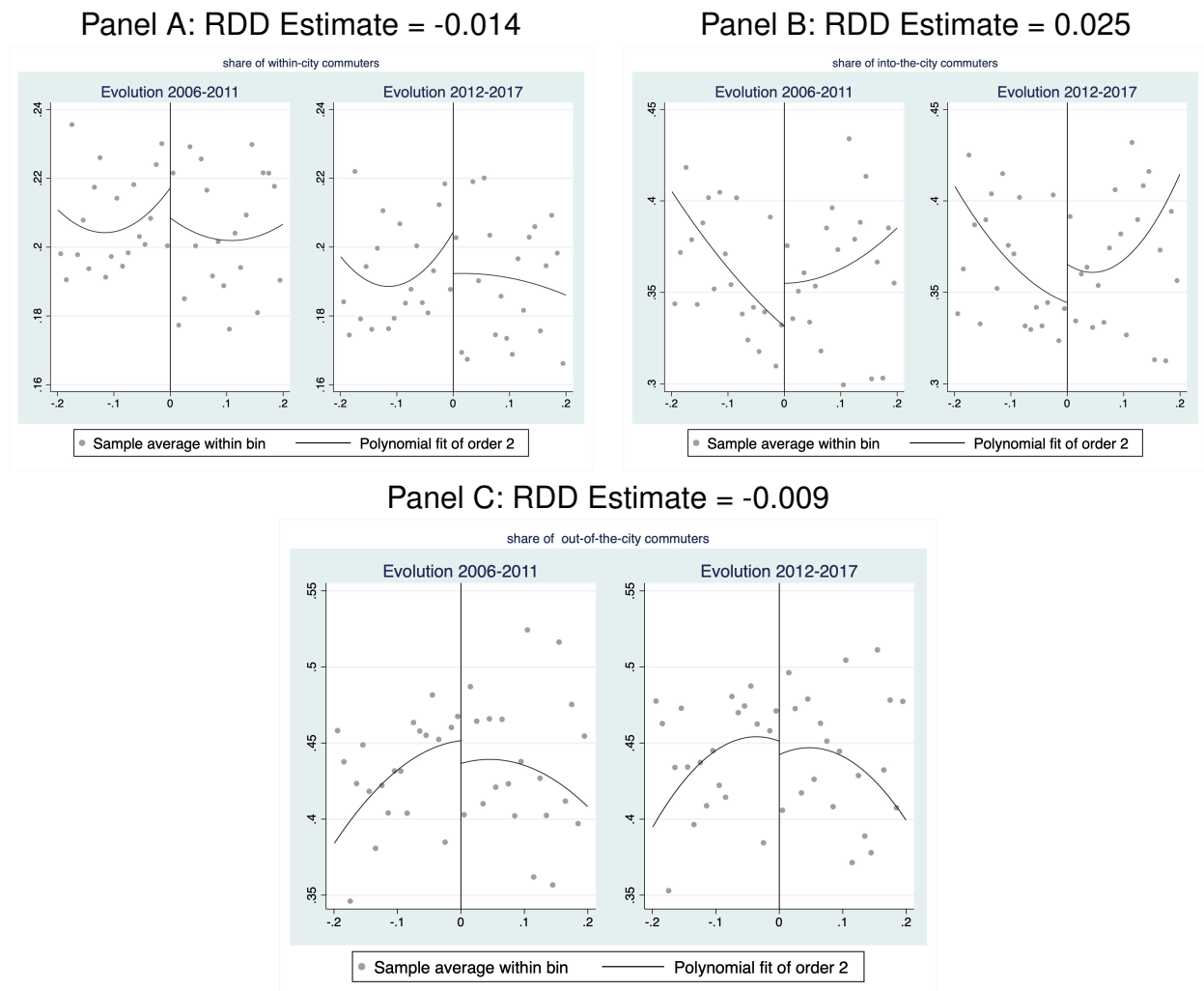
### **3.4.3 Effects on the share of public transit commuters**

Is the decrease in the the share of car commuters compensated (or at least partially) by an increase in the share of public transit users? Here, we estimate the effects of elections on the share of public transit commuters. In the second part of Table 3.5, we show the estimates for all types of commuters. However, our results do not suggest any significant increase in the evolution of the share of public transit commuters. We illustrate our results in Figure 3.3. where there appears to be a discontinuity in the changes in the share of public transit users for within-city and into-the-city commuters (Panels B and C). Nevertheless, these estimates are not statistically

**Figure 3.1: RDD plots - Effects on the share of car commuters**



Sources: 2014 elections and 2011, 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a second-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all commuters within a given municipality. Panel B is restricted to within-city commuters. Panel C is restricted to into-the-city commuters and panel D is restricted to out-of-the city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

**Figure 3.2: RDD plots - Effects on the flows of commuters**

Sources: 2014 elections and 2011, 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a second-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A is restricted to within-city commuters. Panel B is restricted to into-the-city commuters and panel C is restricted to out-of-the city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

significant. One possible explanation for these results is the low initial share of public transit users in the municipalities before the election. This suggests that some municipalities may not have a well-established public transit system in place, which would hinder residents from switching to public transit even after the election of a left-wing mayor. Hence, the decrease in the share of car commuters can be instead explained by other alternatives such as working-from-home or non-polluting means such as walking or cycling.<sup>5</sup> Figure 3.7 reports the graphical evidence of the estimation using a polynomial of degree 1.

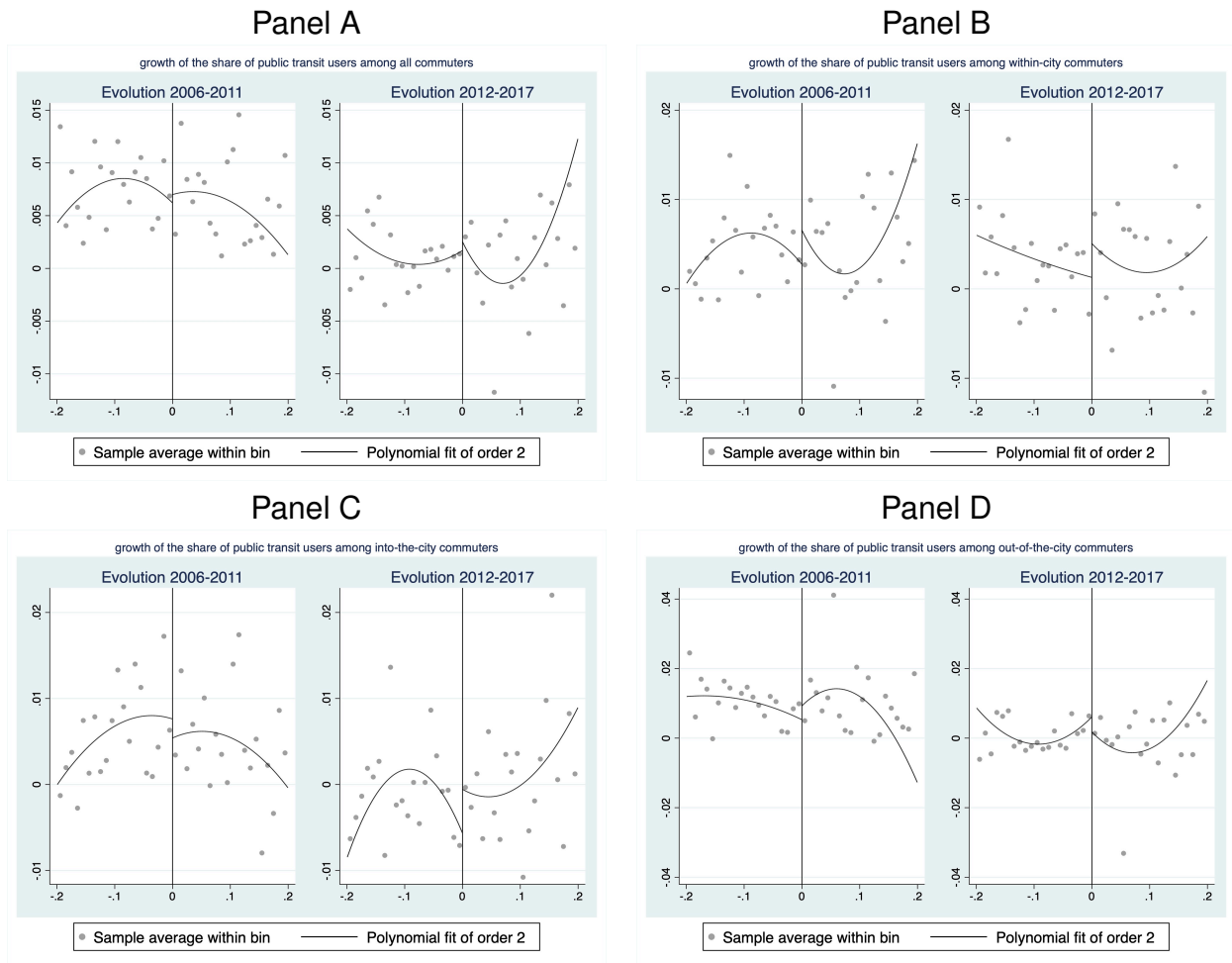
#### 3.4.4 Effects on the number of cars per adult

The findings regarding the decrease in the growth of car commuters imply that a left-wing mayor may be inclined to discourage car usage. Nevertheless, carpooling presents itself as another alternative solution towards achieving the objective of reducing air pollution and greenhouse gas emissions, as it effectively diminishes the number of vehicles on the roads. It should be noted, however, that the use of carpooling may not be reflected in the findings on the share of car commuters, as survey respondents may still report "car" as their mode of commuting, even though they are sharing the ride with others. A possible method to assess the overall impact of elections on car usage is to estimate the impact on the number of cars per adult, although it is possible that this effect may take a longer period to become more noticeable. Part 3 of table 3.5 shows the results on the evolution of the number of cars per adult. The findings reveal a decrease of 1.1 percentage point (1%) in the growth of the number of cars per adult among all commuters, however, this change is not statistically significant. The effect appears to be more pronounced for out-of-the-city commuters. Figure 3.4 shows the graphical results. A discontinuity can be observed after the election for all commuters (Panel A) and out-of-the-city commuters (Panel D). Figure 3.8 illustrates the estimates of the regression using a polynomial of degree one.

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<sup>5</sup>Before 2017, we cannot distinguish in the census data whether an individual commutes using a non-motorized two-wheel or a motorized two-wheel.

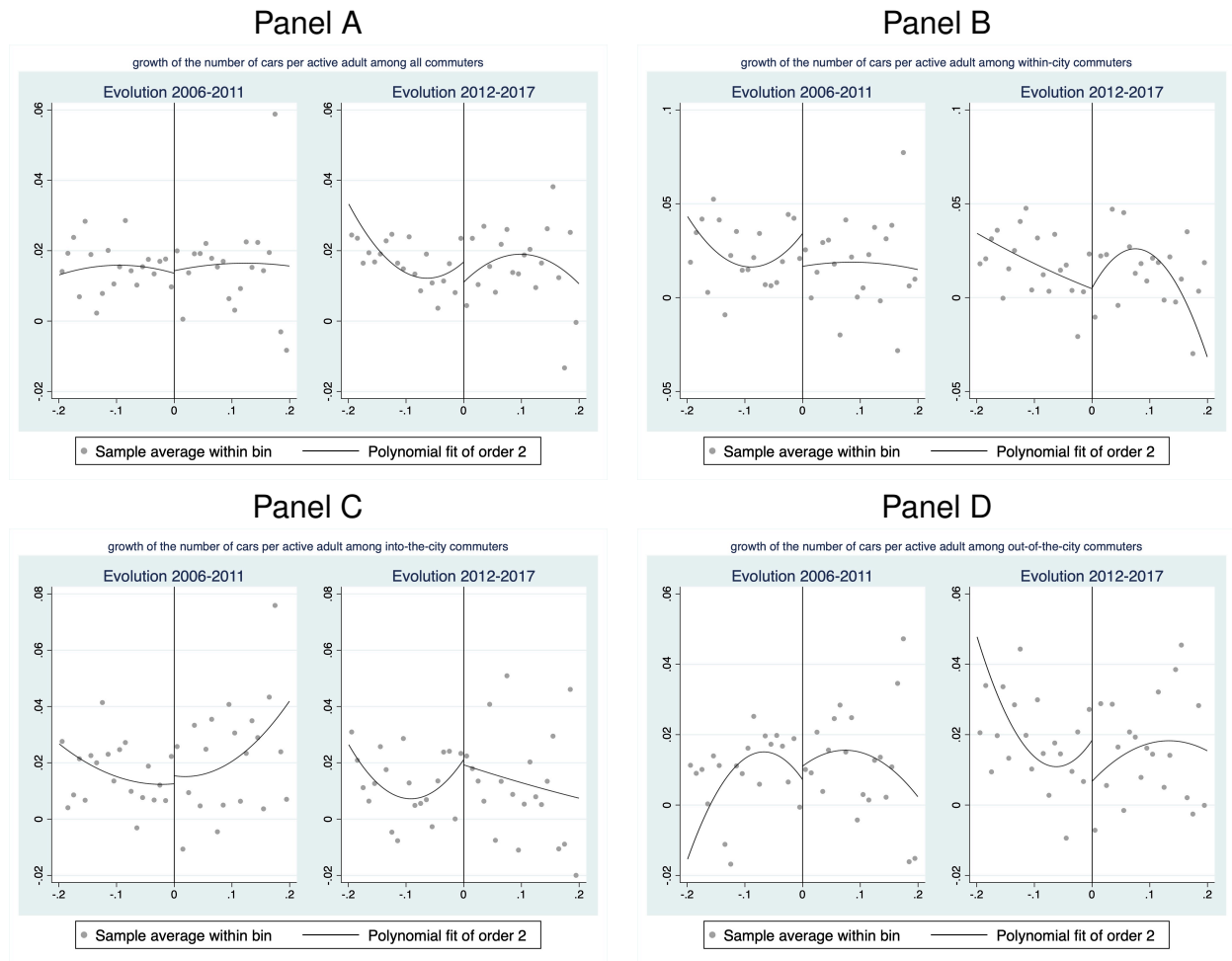
**Figure 3.3:** RDD plots - Effects on the share of public transit commuters



Sources: 2014 elections and 2011, 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a second-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all public transit commuters within a given municipality. Panel B is restricted to within-city public transit commuters. Panel C is restricted to into-the-city public transit commuters and panel D is restricted to out-of-the city public transit commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.



**Figure 3.4:** RDD plots - Effects on the number of cars per adult



Sources: 2014 elections and 2011 and 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a second-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all commuters within a given municipality. Panel B is restricted to within-city commuters. Panel C is restricted to into-the-city commuters and panel D is restricted to out-of-the city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

**Table 3.5:** RDD estimates - The effects of elections

	(1) All	(2) Into-the-city	(3) Out-of-the-city	(4) Within-the-city
<b>1.Car commuters</b>				
Impact of Left Victory on 2011	0.004 (0.006)	0.005 (0.009)	0.001 (0.006)	0.012 (0.013)
Impact of Left Victory on 2017	-0.009* (0.005)	-0.002 (0.007)	0.002 (0.006)	-0.034** (0.015)
<b>2.Public Transit commuters</b>				
Impact of Left Victory on 2011	0.001 (0.003)	-0.002 (0.005)	-0.003 (0.007)	0.005 (0.005)
Impact of Left Victory on 2017	0.002 (0.003)	0.006 (0.004)	-0.001 (0.006)	0.004 (0.005)
<b>3.Number of cars per adult</b>				
Impact of Left Victory on 2011	0.001 (0.007)	0.003 (0.012)	0.005 (0.011)	-0.019 (0.014)
Impact of Left Victory on 2017	-0.011 (0.007)	-0.002 (0.013)	-0.019 (0.012)	-0.014 (0.019)

Sources: 2014 elections and 2011 and 2017 mobility census. Notes: The table shows RDD estimates of the effect of the victory of a left- relative to a right-wing mayor in the municipal election. Estimates are obtained using local linear regressions with a triangular kernel, an optimal bandwidth, and a quadratic polynomial. The first part of the table uses as a dependent variable the changes in the share of car users, the second part of the table the changes in the share of public transit users and the third part the change in the number of cars per adult. Column 1 uses as a dependent variable the change of the share of car commuters among all commuters. This change is decomposed by the inflows, outflows in columns 2 and 3. Column 4 uses as a dependent variable the change of the share of within-city commuters. There are 1,628 observations in 2011 and 1,623 observations in 2017. Robust-bias corrected standard errors are reported in parenthesis. (\*) and (\*\*) and (\*\*\*) denote statistical significance at 10%, 5% and 1% level.

### 3.4.5 Heterogeneity Analysis

In this section, we test whether electing a left-mayor affect the share of car commuters homogeneously across all municipalities.

**Heterogeneity with respect to the size of the municipality** One potential source of heterogeneity is the size of the municipality. While transportation policies impact both small and big cities, the effects can be different based on the size and hence the density of the city. In smaller cities, the transit system may be less developed, which could make it more challenging to transition away from car transportation due to limited alternative options. However, for commuters traveling within smaller cities, it may be more feasible to shift away from cars since the city structure is often more compact, making it more practical to walk or bike between destinations. In larger cities, transportation policies can also have a significant impact as they typically have a wider range of alternatives that can offer more choices to commuters who intend to reduce their reliance on cars. To investigate this issue, we approximate municipalities' size with their median population in 2011 (3,228). Table 3.6 shows the estimates with respect of the size of the municipality. The impact on the evolution of the share of car commuters among all commuters is negative for both city sizes. Unsurprisingly, the impact is twice as large for bigger cities. However, among within-city commuters, the impact is larger in smaller cities. As for the impact on public transit, it appears to be positive for big cities and in general higher than the estimates of smaller cities, although statistically insignificant. Overall these results suggest that electing a left-wing mayor affects more larger cities for inflow and outflow commutes but smaller cities for within-city commutes.

**Heterogeneity by initial car-commuters share** One question that arises is whether the impact of elections differs based on the initial percentage of car commuters in a city. First, some municipalities with a high initial share of car commuters may be hesitant to implement policies that could be seen as punitive towards car users due to concerns about their reputation if they car about running again for office (Besley and Case, 1995). Moreover, the initial share of car

**Table 3.6:** RDD estimates - The effects of elections by municipality size

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	All		Into-the-city		Out-of-the-city		Within-the-city	
<b>1.Car commuters</b>								
Impact of Left Victory on 2011	0.009 (0.008)	-0.005 (0.005)	0.009 (0.015)	-0.002 (0.007)	-0.005 (0.010)	-0.002 (0.006)	0.026 (0.025)	-0.000 (0.012)
Impact of Left Victory on 2017	-0.004 (0.008)	-0.011* (0.006)	0.007 (0.011)	-0.010 (0.006)	0.014 (0.010)	-0.006 (0.007)	-0.052* (0.029)	-0.020 (0.017)
<b>2.Public Transit commuters</b>								
Impact of Left Victory on 2011	-0.002 (0.004)	0.001 (0.004)	-0.009 (0.008)	0.004 (0.005)	0.008 (0.006)	-0.005 (0.006)	0.007 (0.006)	0.003 (0.006)
Impact of Left Victory on 2017	-0.004 (0.004)	0.007 (0.005)	0.007 (0.007)	0.005 (0.005)	-0.017** (0.008)	0.007 (0.007)	0.004 (0.007)	0.006 (0.006)
<b>3.Number of cars per adult</b>								
Impact of Left Victory on 2011	-0.001 (0.012)	-0.005 (0.005)	-0.011 (0.021)	0.008 (0.008)	0.022 (0.024)	-0.016* (0.009)	-0.015 (0.025)	-0.018* (0.011)
Impact of Left Victory on 2017	-0.011 (0.011)	-0.006 (0.006)	0.016 (0.027)	-0.012* (0.007)	-0.035 (0.022)	-0.001 (0.009)	-0.011 (0.035)	0.003 (0.013)

Sources: 2014 elections and 2011 and 2019 mobility census. Notes: The table shows RDD estimates of the effect of the victory of a left- relative to a right-wing mayor in the municipal election. Estimates are obtained using local linear regressions with a triangular kernel, an optimal bandwidth, and a quadratic polynomial. The first part of the table uses as a dependent variable the growth of the share of car users, the second part of the table the growth of the share of public transit users and the third part the growth of the number of cars per adult. Columns 1,3,5 and 7 report the estimates of the model using municipalities below the median. Columns 2,4,6 and 8 report the estimates of the model using municipalities above the median. There are 814 ( 810) observations in 2011 (2017) for below median municipalities and 814 (813) observations in 2011 (2017) for above median municipalities. Robust-bias corrected standard errors are reported in parenthesis. (\*), (\*\*) and (\*\*\*) denote statistical significance at 10%, 5% and 1% level.

commuters might also indicate the presence or absence of a well-established public transit. For example, cities with a lower proportion of car commuters may indicate that there is already a culture of utilizing alternative modes of transportation. In such cases, policies that discourage car usage could potentially reinforce this behavior, leading to more partisan behavior as left-wing mayors are more likely to implement policies that discourage car usage. To this matter, we approximate municipalities' initial attractiveness to car-usage by their median share of car commuters of 2011 (0.85). Table 3.7 presents the estimates for municipalities categorized as having a low or high proportion of car commuters. The initial share of car commuters is a robust predictor of commuting patterns, as evidenced by the 2p.p.reduction in the evolution of the share of car commuters for municipalities below the median, while no impact is observed for municipalities above the median. This trend is even more prominent for within-city commuters, with a decrease of 5 p.p. for below-median municipalities and only 1.7p.p. for those above the median. We also find an increase in the share of public transit users for municipalities below the median, especially among within-city commuters (increase in 2 p.p.).

**Heterogeneity by initial net car migration** Another potential factor contributing to the heterogeneity of political elections' impact on car usage is the ratio of car inflows to car outflows. Municipalities with a higher number of car commuters entering the city compared to the number of car commuters leaving the city might be more inclined to implement stricter transportation policies. This is because the externalities associated with congestion and pollution are primarily generated within the municipality by non-residents and therefore harm its residents. Conversely, when the number of car commuters leaving the municipality is greater than the number entering, policies may be less strict since the externalities are generated outside the municipality. To measure this, we approximate the net car migration by the median of the ratio  $\frac{\text{Into-the-city}}{\text{Out-of-the-city}}$  of car commuters in 2011 (1.04). Table 3.8 shows that the impact on growth of the share of car commuters is larger for municipalities above the median. However, the reverse is observed for within-city commutes.

**Table 3.7:** RDD estimates - The effects of elections by initial share of car commuters

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	All		Into-the-city		Out-of-the-city		Within-the-city	
<b>1.Car commuters</b>								
Impact of Left Victory on 2011	-0.001 (0.007)	0.000 (0.007)	0.008 (0.015)	-0.001 (0.010)	0.002 (0.012)	-0.006 (0.008)	-0.005 (0.013)	0.023 (0.023)
Impact of Left Victory on 2017	-0.019** (0.008)	0.003 (0.007)	-0.004 (0.011)	0.002 (0.010)	-0.015 (0.012)	0.014* (0.008)	-0.050** (0.021)	-0.017 (0.024)
<b>2.Public Transit commuters</b>								
Impact of Left Victory on 2011	0.004 (0.005)	0.002 (0.003)	0.003 (0.007)	-0.002 (0.007)	-0.011 (0.012)	0.007 (0.006)	0.020** (0.009)	-0.002 (0.005)
Impact of Left Victory on 2017	0.007 (0.006)	-0.001 (0.004)	0.002 (0.006)	0.009 (0.006)	0.013 (0.012)	-0.010 (0.007)	0.006 (0.008)	0.003 (0.006)
<b>3.Number of cars per adult</b>								
Impact of Left Victory on 2011	-0.004 (0.009)	-0.000 (0.011)	-0.005 (0.018)	-0.000 (0.020)	-0.004 (0.013)	0.005 (0.019)	-0.015 (0.013)	-0.026 (0.023)
Impact of Left Victory on 2017	-0.007 (0.009)	-0.018* (0.011)	0.007 (0.021)	-0.013 (0.023)	-0.013 (0.015)	-0.022 (0.018)	-0.022 (0.020)	0.007 (0.029)

Sources: 2014 elections and 2011 and 2019 mobility census. Notes: The table shows RDD estimates of the effect of the victory of a left- relative to a right-wing mayor in the municipal election. Estimates are obtained using local linear regressions with a triangular kernel, an optimal bandwidth, and a quadratic polynomial. The first part of the table uses as a dependent variable the growth of the share of car users, the second part of the table the growth of the share of public transit users and the third part the growth of the number of cars per adult. Columns 1,3,5 and 7 report the estimates of the model using municipalities below the median. Columns 2,4,6 and 8 report the estimates of the model using municipalities above the median. There are 814 ( 814) observations in 2011 (2017) for below median municipalities and 814 (809) observations in 2011 (2017) for above median municipalities. Robust-bias corrected standard errors are reported in parenthesis. (\*), (\*\*) and (\*\*\*) denote statistical significance at 10%, 5% and 1% level.

**Table 3.8:** RDD estimates - The effects of elections by net car migration

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	All		Into-the-city		Out-of-the-city		Within-the-city	
<b>1.Car commuters</b>								
Impact of Left Victory on 2011	-0.003 (0.008)	0.005 (0.007)	-0.005 (0.013)	0.015 (0.015)	-0.008 (0.009)	0.007 (0.012)	0.024 (0.024)	0.006 (0.016)
Impact of Left Victory on 2017	0.002 (0.007)	-0.020** (0.009)	0.001 (0.012)	-0.014* (0.008)	0.019** (0.009)	-0.019 (0.012)	-0.052** (0.023)	-0.021 (0.020)
<b>2.Public Transit commuters</b>								
Impact of Left Victory on 2011	-0.000 (0.004)	0.005 (0.004)	-0.003 (0.009)	-0.001 (0.006)	0.008 (0.005)	-0.009 (0.012)	-0.002 (0.006)	0.019** (0.009)
Impact of Left Victory on 2017	-0.001 (0.004)	0.011* (0.006)	0.007 (0.006)	0.011* (0.006)	-0.013* (0.007)	0.017 (0.014)	0.004 (0.006)	0.005 (0.008)
<b>3.Number of cars per adult</b>								
Impact of Left Victory on 2011	-0.006 (0.012)	0.003 (0.009)	0.002 (0.018)	0.004 (0.018)	0.011 (0.021)	-0.005 (0.013)	-0.042* (0.023)	-0.018 (0.016)
Impact of Left Victory on 2017	-0.015 (0.010)	-0.011 (0.009)	-0.017 (0.025)	0.005 (0.010)	-0.005 (0.016)	-0.025* (0.015)	0.009 (0.035)	-0.014 (0.017)

Sources: 2014 elections and 2011 and 2019 mobility census. Notes: The table shows RDD estimates of the effect of the victory of a left- relative to a right-wing mayor in the municipal election. Estimates are obtained using local linear regressions with a triangular kernel, an optimal bandwidth, and a quadratic polynomial. The first part of the table uses as a dependent variable the growth of the share of car users, the second part of the table the growth of the share of public transit users and the third part the growth of the number of cars per adult. Columns 1,3,5 and 7 report the estimates of the model using municipalities below the median. Columns 2,4,6 and 8 report the estimates of the model using municipalities above the median. There are 814 ( 814) observations in 2011 (2017) for below median municipalities and 814 (809) observations in 2011 (2017) for above median municipalities. Robust-bias corrected standard errors are reported in parenthesis. (\*), (\*\*) and (\*\*\*) denote statistical significance at 10%, 5% and 1% level.

## 3.5 Conclusion

This study sheds light on how municipal elections in France impact the share of car commuters. Our findings suggest that electing a left-wing mayor compared to a right-wing mayor decreases the growth in the share of car commuters. This impact is generally more pronounced for within-the-city commuters. One possible explanation for this result is that left-wing municipalities may be more likely to implement traffic-calming policies aimed at alleviating local air pollution and climate change.

Interestingly, we do not find any significant evidence suggesting that the decrease in car usage among car commuters is compensated by an increase in the usage of public transit. This may indicate that some factors hinder the adoption of public transit in the municipalities of our sample, such as poor service quality or limited coverage.

Moreover, our results suggest that the size of the municipality, the initial share of car com-

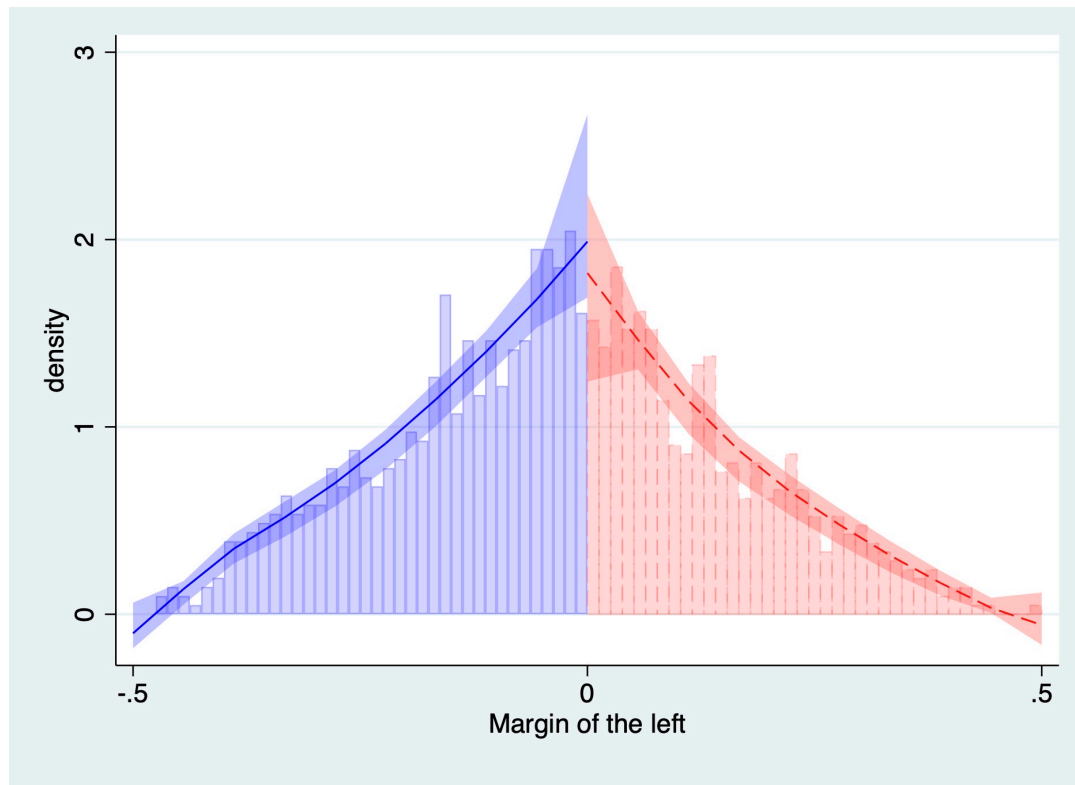
muters, and net car migration are strong predictors of the impacts of electoral outcomes on car usage. In particular, larger cities may have a better infrastructure in place to support alternative transportation modes, while municipalities with a lower initial share of car commuters may already have alternative options in place. Finally, municipalities with a higher proportion of into-the-city car commuters may be more likely to implement stricter transportation policies to limit the externalities generated by non-residents and borne by residents.



## 3.6 Appendix

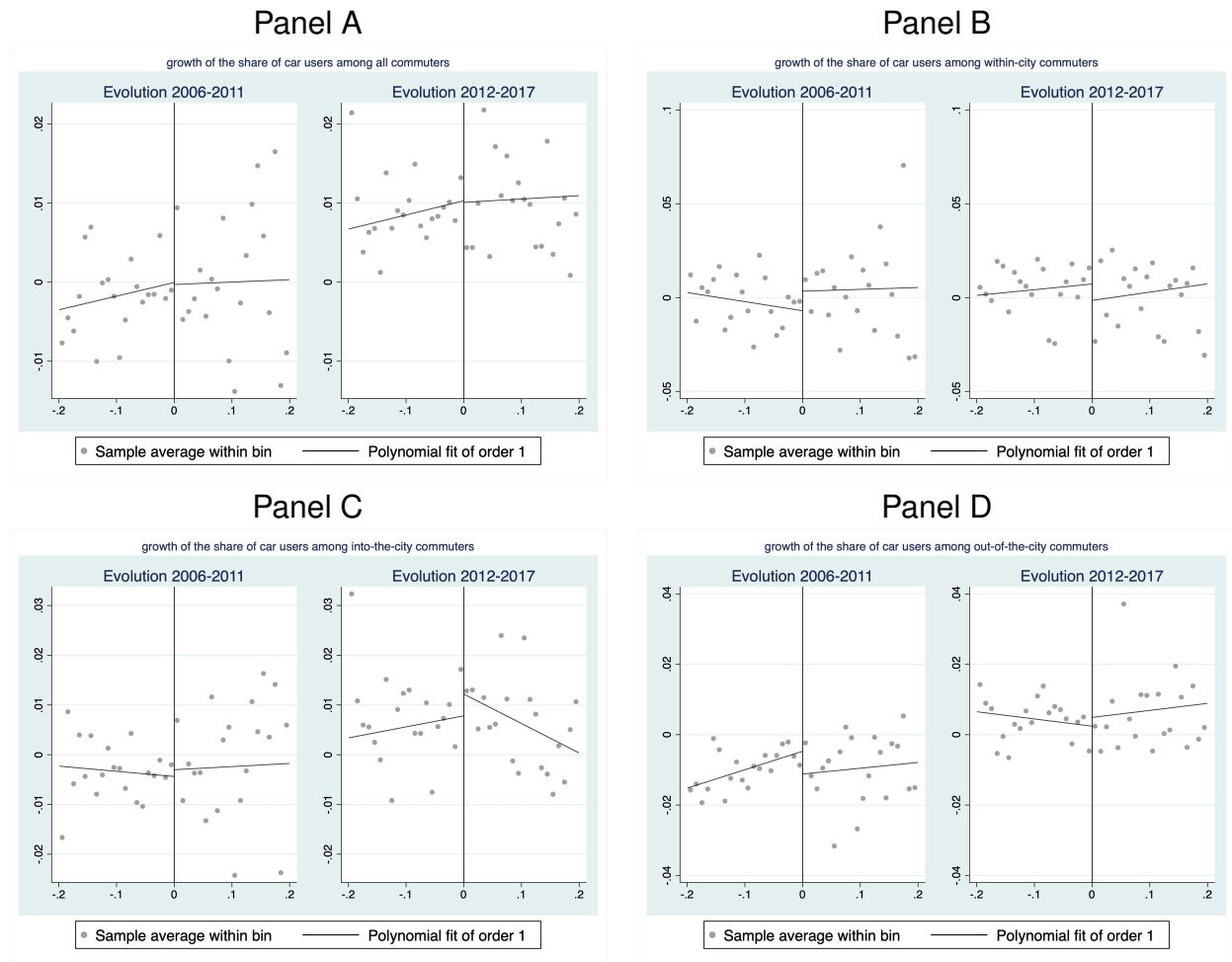
### 3.6.1 Additional Tables and Figures

**Figure 3.5:** Discontinuity in the forcing variable - Kernel plot



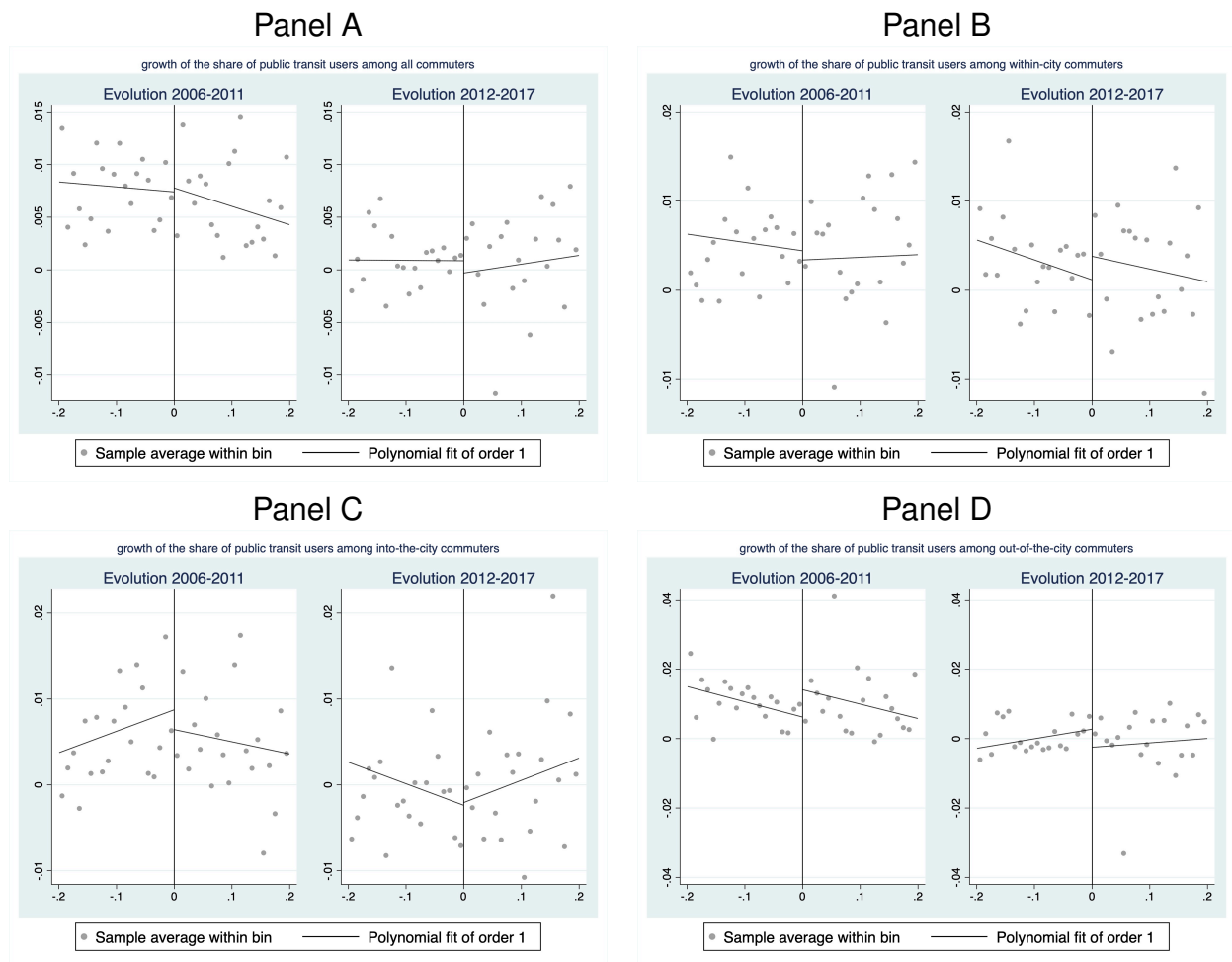
Sources: 2014 elections and 2014 mobility census. Notes: The figure plots weighted kernel density estimates.

**Figure 3.6:** RDD Estimates - Evolution of the share of car commuters

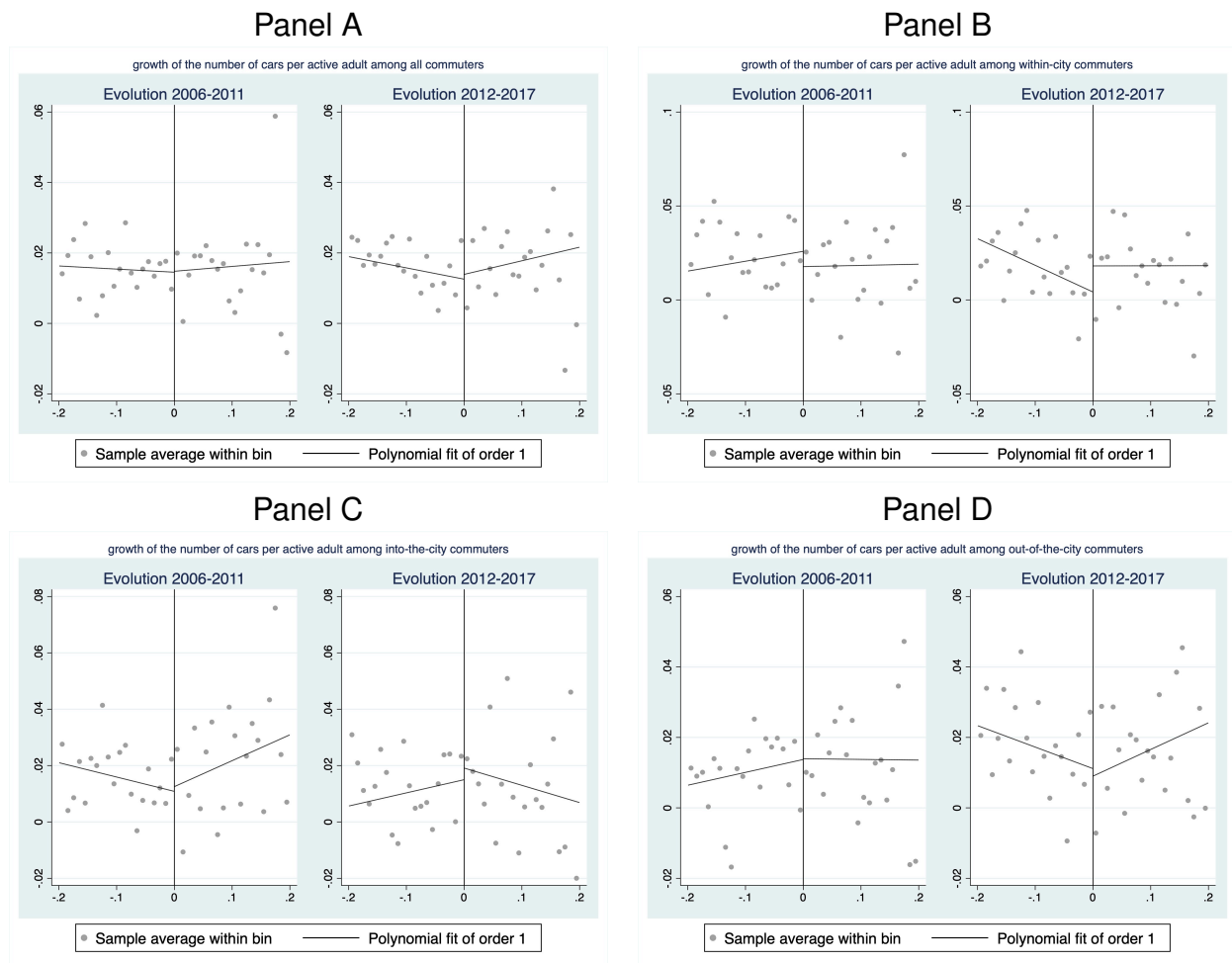


Sources: 2014 elections and 2011 and 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a first-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all commuters within a given municipality. Panel B is restricted to within-city commuters. Panel C is restricted to into-the-city commuters and panel D is restricted to out-of-the city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

**Figure 3.7: RDD Estimates - Evolution of the share of public transit commuters**



Sources: 2014 elections and 2011 and 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a first-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all commuters within a given municipality. Panel B is restricted to within-city commuters. Panel C is restricted to into-the-city commuters and panel D is restricted to out-of-the city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

**Figure 3.8:** RDD Estimates - Evolution of the share of the number of cars per adult

Sources: 2014 elections and 2011 and 2017 mobility census. Notes: the graphs report quantile-spaced bins that capture averages from the same number of observations for each treatment group (Calonico et al., 2015). The lines represent a first-order polynomial. The vertical lines capture the discontinuity point at zero. Panel A includes all commuters within a given municipality. Panel B is restricted to within-city commuters. Panel C is restricted to into-the-city commuters and panel D is restricted to out-of-the-city commuters. For visual clarity, we restrict the range of the forcing variable between -20 and 20 percentage points.

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**Titre :** Essais en Économie Urbaine et Environnementale

**Mots clés :** Congestion; Pollution; Politiques Publiques Locales

**Résumé :** Cette thèse vise à comprendre les impacts des politiques de transport dans les villes d'aujourd'hui.

Les deux premiers chapitres étudient les impacts des politiques de réduction de voiries sur la congestion et la pollution. Le chapitre 1, en collaboration avec Dominique Bureau, analyse comment la prise en compte du changement climatique justifie le réajustement des voies express urbaines tel qu'il a été entrepris dans diverses métropoles. En développant un modèle théorique, nous montrons que dans certains cas, une réduction marginale de l'offre routière peut augmenter le coût du bien-être social. L'idée d'un ajustement radical est donc au cœur du modèle.

Le chapitre 2 évalue les différents impacts des politiques de fermeture de routes, en se concentrant sur une fermeture majeure qui a eu lieu à Paris en 2016 : la "Voie Georges Pompidou". En s'appuyant sur une stratégie de différence en différence, je montre que la fermeture a déplacé la congestion sur deux ensembles de routes : les routes locales et le périphérique. Ce déplacement de la congestion a entraîné une augmentation significative des concentrations de NO<sub>2</sub>. D'après mes estimations, jusqu'à

90% des coûts de pollution ont été supportés par les résidents à faible revenu qui vivaient autour du périphérique, loin des nouvelles aménités créées par la fermeture et en dehors de la juridiction responsable de la décision de la piétonisation de la voie "Georges pompidou".

Le chapitre 3, en collaboration avec Benoît Schmutz, examine le rôle des politiciens dans l'influence de la part des navetteurs en voiture. Plus précisément, nous étudions comment l'orientation politique d'une municipalité affecte la mise en œuvre de politiques de transport qui favorisent les options de transport durable, et comment ces politiques influencent à leur tour les schémas d'utilisation de la voiture. En utilisant une analyse de discontinuité de la régression (RDD) qui exploite les variations quasi-aléatoires de l'affiliation politique du maire à la suite d'élections rapprochées, nous montrons que la couleur politique d'une municipalité influence la part des navetteurs en voiture dans la municipalité. En particulier, l'élection d'un maire de gauche par rapport à un maire de droite diminue la proportion de navetteurs en voiture. Cet effet est d'autant plus important si nous ne prenons en compte que les navetteurs intra-muros.

**Title :** Essays in Urban and Environmental Economics

**Keywords :** Congestion; Pollution; Local Public Policies

**Abstract :** This dissertation aims to understand the impacts of transportation policies in today's cities.

The first two chapters examine the impacts of road reduction policies on congestion and pollution. Chapter 1, in collaboration with Dominique Bureau, analyzes how the consideration of climate change justifies the readjustment of urban expressways as it has been undertaken in various metropolises by developing a theoretical model. We show that in some cases a marginal reduction in road supply can increase the social welfare cost. The idea of a radical adjustment is thus central to the model.

Chapter 2 assesses the different impacts of road closure policies, focusing on a major closure that took place in Paris in 2016 : the "Voie Georges Pompidou". Using a difference-in-difference strategy, I show that the closure shifted congestion onto two sets of roads : local roads and the ring road. This shift in congestion resulted in a significant increase in NO<sub>2</sub> concentrations. I estimate that up to 90% of the pollution costs

were borne by low-income residents who lived around the ring road, far from the new amenities created by the closure and outside the jurisdiction responsible for the decision to pedestrianize the "Georges pompidou" road.

Chapter 3, in collaboration with Benoît Schmutz, examines the role of politicians in influencing the share of car commuters. Specifically, we study how the political orientation of a municipality affects the implementation of transportation policies that promote sustainable transportation options, and how these policies in turn influence patterns of car use. Using a regression discontinuity analysis (RDD) that exploits quasi-random variation in mayoral party affiliation following close elections, we show that the political color of a municipality influences the share of car commuters in the municipality. In particular, the election of a left-wing mayor relative to a right-wing mayor decreases the share of car commuters. This effect is stronger if we only consider within-city commuters.