Displacing Congestion: Evidence from Paris*

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Abstract

This paper shows that traffic-calming policies may have adverse spatial spillovers 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 the road closure generated a net increase in population-weighted NO2 concentrations. 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 substantial pollution burden due to the increasing relationship between pollutant concentrations and traffic congestion. Overall, I estimate that most 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 negative effects could have been mitigated.

Keywords: Congestion, Air Pollution, Public Transportation, Route Choice
JEL Classification: R41, R42, Q53, Q54

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I 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). 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, offering an immediate and cost-effective solution while enhancing urban amenities.

While the immediate benefits of car-free areas are crystal clear, the associated costs are intricate and fiercely debated given their uneven distribution. Economically, according to "the fundamental law of road congestion," drivers are expected to adjust their road demand based on the available road supply (Downs, 1962; Duranton & Turner, 2011). From a policy standpoint, one could argue that unless the deep-rooted dependence on private motorized transportation within cities is addressed, traffic-calming policies may shift congestion and pollution to alternative areas. Estimating the externalities of traffic-calming policies becomes key for promoting sustainability and equity in urban development.

This paper explores the role of spatial spillovers in the context of road closures. Despite extensive research on the impacts of traffic-calming policies within the targeted areas, the quantification of the displaced effects remains unexplored. To fill this gap, 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. 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 traffic conditions of substitute roads.[1] The biggest challenges when evaluating a disruption 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 other city alterations. To overcome these challenges, this paper uses a difference-in-difference strategy, leveraging the unique flow direction of the GP. Exploiting this distinctive feature, the direction of roads serves as a natural selection for defining treatment and control groups: roads aligned with the GP's flow are likely directly affected by the closure, accommodating a portion of displaced GP users. In contrast, the impact on westward lanes, without alternative expressways within the city, might be indirect through a general 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. Moreover, each eastward substitute road is paired with a westward counterpart sharing similar architectural features, such as steel and strip type, presence or absence of traffic lights, and outward/inward exit lanes. These distinct characteristics allow for an evaluation of the GP closure by comparing its effect on the eastward roads to its effect on the westward roads within 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

[1] 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 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. 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^{st} 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.[2]

I first look at the impact of the GP closure on the two main outcomes: flow of cars and 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 density of cars on nearby road segments, controlling for weather characteristics and the flow of cars. I multiply this elasticity by the impact on the density of cars to impute the effect on NO_2 concentrations, both near the upper banks and near the ring roads. With an elasticity of pollution to density of 0.25% on the ring roads and 0.12% on local roads, I show that the

[2]The speed limit on local roads was lowered to 30km/h citywide in 2022.

concentrations of nitrogen dioxide increased near the ring road and near local roads with a net increase in population-weighted exposure to pollutant emissions. However, increased NO_2 concentrations are only one facet of the consequences stemming from increased traffic. Concurrent increases in noise pollution and other particulate pollutants may also manifest. 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, taking into account the capitalization of all amenities in housing valuations. The findings reveal a 5% decrease in housing prices within the 700-meter radius of the periphery.

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. Therefore, deducing the number of drivers opting for each alternative road solely from the reduced-form results is unattainable. Yet, quantifying the additional cars on each road is crucial for conducting a cost analysis. To address this, the second section of my paper introduces a straightforward model of the shortest route with endogenous congestion, drawing on Akbar & Duranton (2017)'s framework, to quantify the policy's costs. 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 cost while lower-income residents bear 70% of the pollution cost, 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 makes three main contributions. First, it adds to the literature on the effects of traffic-calming policies, which has been studied in numerous works. On the demand-side, road pricing is the textbook policy to deal with traffic externalities (Pigou, 2017) documented in several studies (Börjesson *et al.*, 2012; Gibson & Carnovale, 2015; Herzog, 2021). However, with little social acceptance[3], many cities have instead used supply-side policies, such as restricting the days or hours in which car users can drive on congested roads (de Grange & Troncoso, 2011; Gallego *et al.*, 2013; Kornhauser & Fehlig, 2003), restricting access to the most polluting vehicles (Malina & Scheffler, 2015; Tassinari, 2022; Wolff, 2014) or expanding urban rail-transit (Adler & van Ommeren, 2016; Gonzalez-Navarro & Turner, 2018; Gu *et al.*, 2021). Other

[3]By not seeing the potential traffic relief, drivers perceive congestion tolls as an individual welfare loss (Hensher & Button, 2007)

cities, including Paris, have opted for quantity-rationing by gradually reducing their road capacity (Davis, 2008; Hanna *et al.*, 2017). For example, Seoul transformed its main highway into an urban boulevard (Kang & Cervero, 2009) while New York has used *High Occupancy Toll* (HOT) lanes (Poole Jr & Orski, 2000).[4] I add to this literature by using a real-life traffic policy to evaluate the short to medium effects of road closures.

Second, this paper relates to the work evaluating spillovers from driving restrictions. Recognizing the importance of accounting for spillovers becomes paramount when evaluating driving restrictions. Studies that neglect to account for it run the risk of either overestimating or underestimating the true effect of the policy (Neumark & Simpson, 2015). The implementation of driving restrictions during specific hours or days of the week may result in intertemporal spillovers, wherein drivers shift their driving activities to unrestricted hours or days (Davis, 2008; Gu *et al.*, 2017; Kreindler, 2023). The imposition of driving restrictions on specific roads or zones could give rise to spatial spillovers, with drivers opting to travel towards unrestricted areas. Recent studies have quantified spatial spillovers in the context of a low emission zone(Sarmiento *et al.*, 2023; Tassinari, 2022; Wolff, 2014), a congestion charge (Gibson & Carnovale, 2015) or a licensed plate based driving restriction (Davis, 2008; Zhang *et al.*, 2017). I contribute to this literature by quantifying the role of spatial spillovers following a change in the road supply. While existing studies often concentrate on either traffic or pollution displacement individually, my contribution integrates these findings within a framework assessing the consequences of a road closure on both of these externalities. Moreover, my research extends beyond measuring the extent of these spillovers; it delves into their exact locations. I show that the unintended consequences of these policies could result in the shifting of externalities towards lower-income neighborhoods.

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 & 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 & Herman, 1987; Geroliminis & Daganzo, 2008) or for an entire city (Akbar & Duranton, 2017). However, there is a gap in the literature concerning the examination of intermediary effects. In particular, there is a lack of research on how shocks occurring in specific segments actually spill over to impact other segments. To fill this gap, I use the congestion model developed by Akbar & Duranton (2017) and extend it to the case of a road closure. By taking away a route and letting travelers substitute to other routes with different congestion elasticity, I am able to isolate and quantify the first order effect of route substitution.

The reminder of the paper is structured as follows: Section II describes the background and data sources. Section III presents the main empirical analyses on traffic. Section IV documents evidence of pollution increase. Section V sets up a theoretical model of pollution and congestion, employed for the analysis of the GP closure case. This framework serves to quantify the costs associated with the policy and presents various policy counterfactual scenarios. Section VI concludes by providing some policy insights.

[4] 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. 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).

II Context and data

II.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 G.1), consistent with the monocentric model (Chapelle *et al.*, 2020).[5] 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 G.2 (a)) and car use is particularly dominant for suburb-to-suburb journeys (Figure G.2 (b)).

The urge to transform the city into a greener one was at the heart of the 2014 municipal elections, won by Mayor Hidalgo.[6] Her campaign mainly focused on environmental and urban strategies that reversed previous schemes based on increasing road capacities.[7] 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^{st}, 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 A. Despite the struggles she had to face during her first term, Mayor Hidalgo was re-elected in 2020.

II.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 Paris by implementing electromagnetic loops endowed with sensors in its pavements.[8] 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:

[5] The resident gradient is reversed within Paris: densities are higher on the outskirts of the city, particularly around the ring roads.

[6] 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.

[7] For example, the riverbanks along the Seine river (dashed line of Figure 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.

[8] https://opendata.paris.fr/pages/home/

- 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.[9] Using the flow per lane as well as the occupancy rate, the average speed can be computed with Athol's formula (Hall, 1996):

$$Speed_{it} = \Big(Flow_{it} \times (L + K_i)\Big)/Occupancy_{it} \quad (1)$$

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[10].

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

$$N_{it} = \frac{Flow_{it}}{Speed_{it}} \quad (2)$$

$$N_{it} \approx \frac{Occupancy_{it}}{L + K_i} \quad (3)$$

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.

[9]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.

[10]Since the sensor occupies the entire road section, the length of each road section is equal to the length of the sensor.

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 (NO2, PM10, PM2,5 and O3). 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[11] provides data on the daily number of people entering each 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).

II.3 The Georges Pompidou riverbank

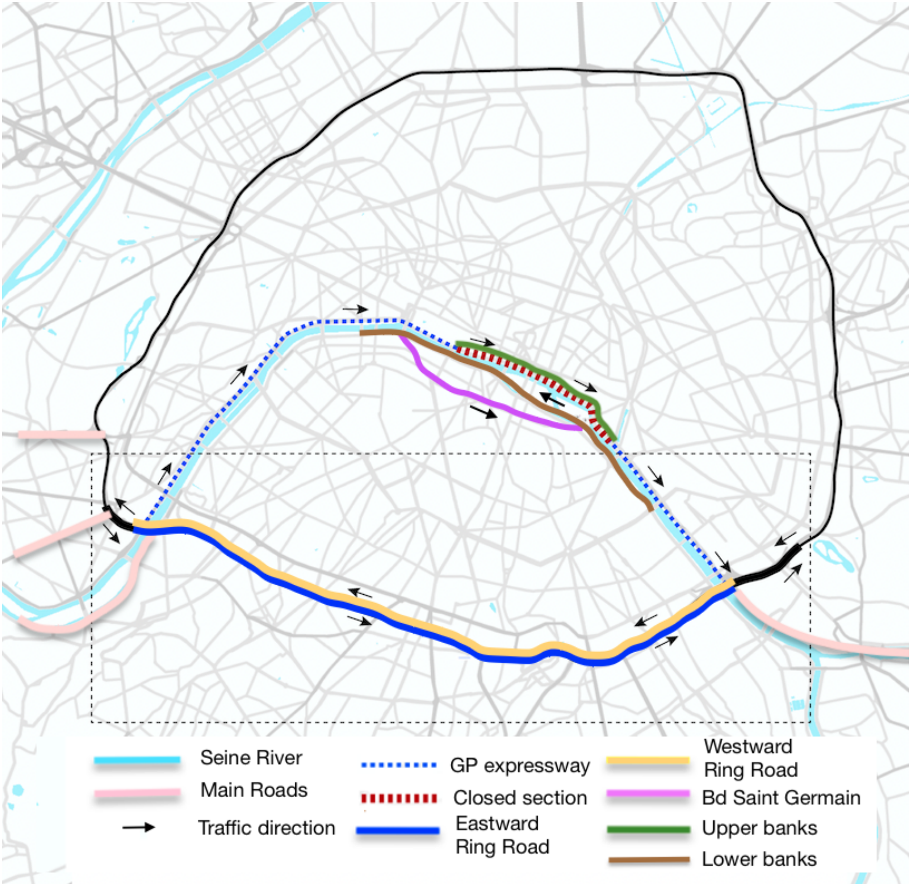
The *Georges Pompidou* riverbank is 13 kilometers long and crosses Paris from southwest to southeast (see Figure 1) with a unique flow direction (eastward).

Figure G.3 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 G.3 (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^{st} 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 G.4). 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 G.5). The non-pedestrianized stretch of the riverbank presents a lower flow average 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.

[11] *Île-de-France Mobilités* is the Organizing Authority for sustainable mobility in Ile-de-France.

Figure 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.

II.4 The local roads

The closed section of the riverbank presents two clear substitutes 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 E.1, 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 G.5). 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.

II.5 The ring roads

Three main bypasses encircle Paris (Figure G.6) 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*.[12] 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-Elysées, and account for 2.5% of Paris' total linear roadway. Moreover, they take up to 40% of Paris' road traffic (Apur, 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 E.1, 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.

III Impact on Traffic

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

III.1 Empirical Strategy

III.1.1 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^{st} 2016, substitute roads with the same flow direction as 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

[12] The Boulevard Périphérique is composed of one outer ring road an one inner ring road.

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.[13]

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.[14]

III.1.2 Specifications

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

$$Y_{it} = \alpha + \gamma \mathbb{1}_{treated_i=1} \mathbb{1}_{post=1} + \lambda_t + \psi_i + \epsilon_{it} \tag{4}$$

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. ψ_i and λ_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 γ. 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.

$$Y_{it} = \alpha + \sum_{k=-3}^{+2} \beta_k \mathbb{1}_{treated_i=1} \mathbb{1}_{T(t)=k} + \lambda_t + \psi_i + \epsilon_{it} \tag{5}$$

where $T(t)$ represents the relative year compared to the year the GP riverbank was pedestrianized.[15] β_k represents the incremental impact of the policy on year k, compared to the reference year. All coefficient are normalized relative to year -1.

III.1.3 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 would have evolved similarly. The trends of treatment and control groups are represented in figure G.8, where the occupancy rates and flow of cars are represented by a yearly moving average. Control and treated units present, at least visually, parallel

[13] The average length of a local road segment is of 0.14 kilometers.
[14] The average length of a ring road segment is of 0.45 kilometers.
[15] A year includes the period from the 1^{st} of September to the 31^{st} of July of the following year, since August is omitted.

trends before 2016. In addition to graphical support, I test for the significance of the pre-treatment estimates. Figure 3 display the estimates of equation (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 G.8) 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 B 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.[16] In addition, the model developed in section V 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 G.7 provides evidence of a potential anticipatory effect showing that people googled this event at the end of 2015. However, Figure 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

[16]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.

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^{st}, 2013 to August 31^{st}, 2016. I then perform a difference-in-difference with phantom events (every 30 days starting January 1, 2015 until September 29, 2015). Figure G.9 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.

III.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 II. 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 (4) and (5) to evaluate the average impact of the riverbank shutdown on the traffic situation of (i) local roads and (ii) the south ring roads.

III.2.1 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 1 gather the estimates of equation (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). 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.

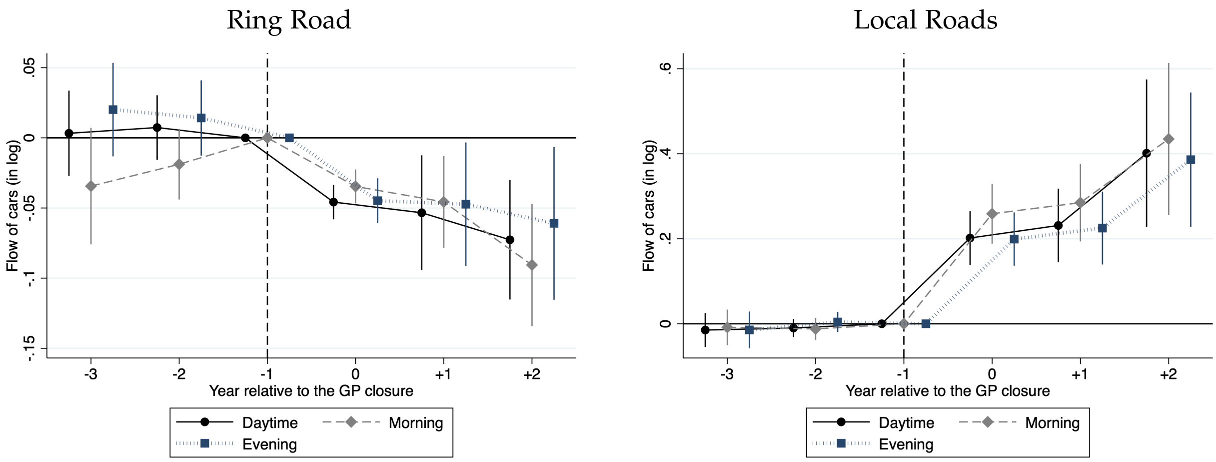
Table 1: Impact on the flow of cars

	(1)	(2)	(3)
		Flow (in log)	
	Morning	Evening	Daytime
		Ring Roads	
Treatment	-0.061***	-0.081***	-0.061***
	(0.013)	(0.020)	(0.013)
Constant	8.387***	8.366***	8.395***
	(0.003)	(0.005)	(0.003)
Observations	14,4155	97,405	627,122
R^2	0.895	0.863	0.855
		Local Roads	
Treatment	0.331***	0.212***	0.264***
	(0.050)	(0.051)	(0.048)
Constant	7.125***	7.331***	7.189***
	(0.017)	(0.017)	(0.017)
Observations	335,934	227,045	1,461,499
R^2	0.797	0.712	0.750
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 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: Impact on the flow of cars



Notes: These graphs plot the estimates and 95% confidence intervals from equation (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.

III.2.2 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 G.3 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). Figure 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.

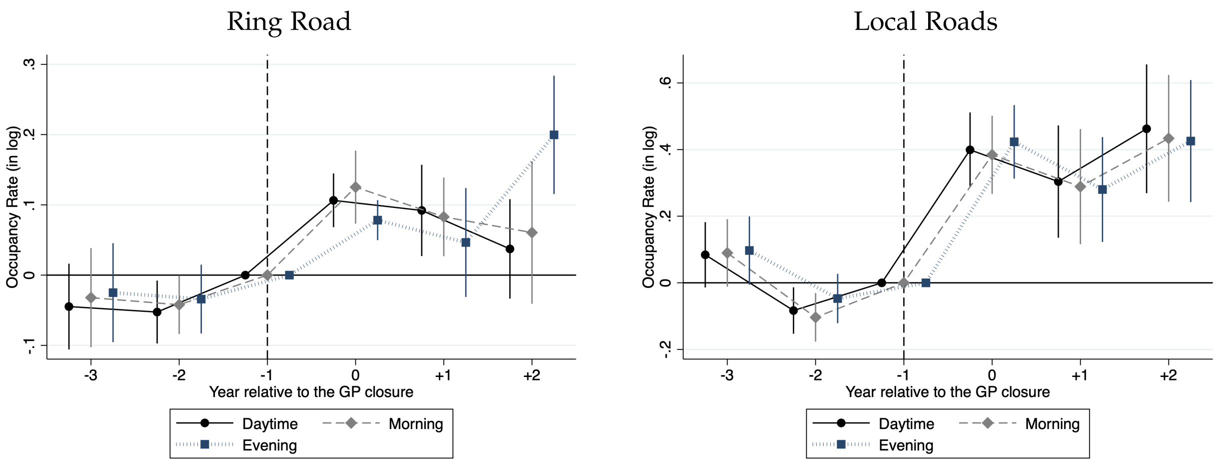
Table 2: Impact on the occupancy rate

	(1)	(2)	(3)
	Occupancy rate (in log)		
	Morning	Evening	Daytime
		Ring Roads	
Treatment	0.094***	0.142***	0.112***
	(0.017)	(0.026)	(0.018)
Constant	3.141***	3.264***	3.146***
	(0.004)	(0.007)	(0.005)
Observations	176,038	118,781	765,044
R^2	0.676	0.566	0.569
		Local Roads	
Treatment	0.321***	0.328***	0.339***
	(0.078)	(0.083)	(0.080)
Constant	2.158***	2.365***	2.233***
	(0.024)	(0.025)	(0.024)
Observations	397,931	268,689	1,729,726
R^2	0.613	0.580	0.579
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 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 3: Impact on the occupancy rate



Notes: These graphs plot the estimates and 95% confidence intervals from equation (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).

III.2.3 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 (4) and drop the arc fixed effects (Column (2) of Tables E.3 and E.4). 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 E.3 and E.4 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 E.3 and E.4. The estimates and standard errors do not vary, which indicates that outliers do not drive the results.

III.2.4 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 & 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.[17] 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.[18] If the road's occupancy rates are close to the threshold prior to 2016, I expect the impact to be significant and positive. Table 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 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.

[17]See Figure G.10 for an example.

[18]The outcome here is based on the estimated variable $Occupancy^*$. This might cause some measurement errors. However, as shown in Table 3, the coefficients are quite precisely estimated.

Table 3: Impact on the probability of congestion

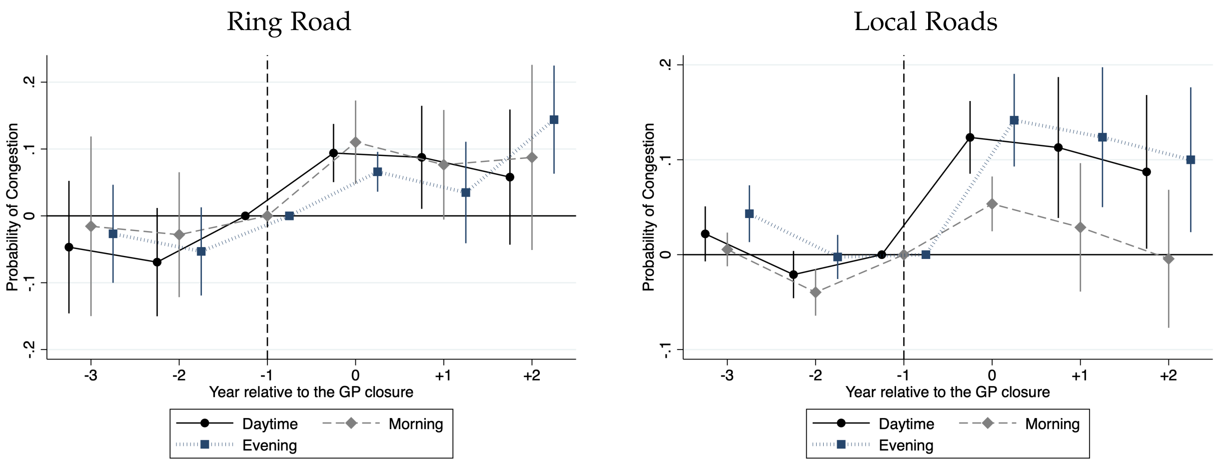
	(1)	(2)	(3)
	Probability of Congestion		
	Morning	Evening	Daytime
		Ring Roads	
Treatment	0.106***	0.107***	0.119***
	(0.032)	(0.018)	(0.022)
Constant	0.359***	0.444***	0.421***
	(0.009)	(0.004)	(0.005)
Observations	120,788	204,004	627,123
Mean DepVar	0.307	0.570	0.557
R^2	0.363	0.366	0.372
		Local Roads	
Treatment	0.033	0.100***	0.101***
	((0.025)	(0.031)	(0.031)
Constant	0.053***	0.075***	0.079***
	(0.010)	(0.011)	(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
Day × *hour* 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 4: Impact on the probability of congestion



Notes: These graphs plot the estimates and 95% confidence intervals from equation (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 4). Namely, a decrease in the average speed is detected on the ring roads

Table 4: Impact on the average speed

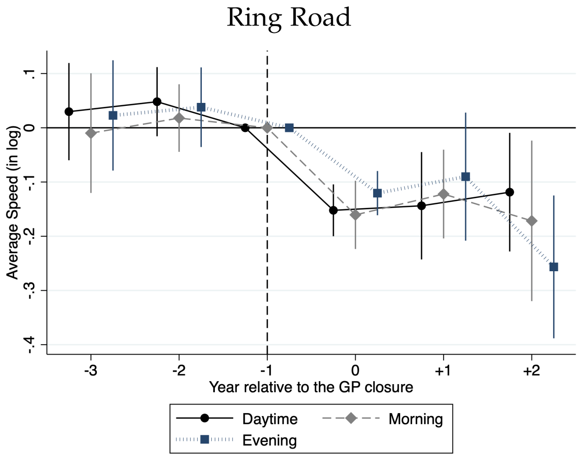
	(1)	(2)	(3)
	Average Speed (in log)		
	Morning	Evening	Daytime
	Ring Roads		
Treatment	-0.154***	-0.175***	-0.165***
	(0.032)	(0.033)	(0.029)
Constant	3.325***	3.220***	3.243***
	(0.009)	(0.008)	(0.007)
Observations	120,788	204,004	627,122
R^2	0.587	0.581	0.586
	Local Roads		
Treatment	-0.113	-0.170**	-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^2	0.698	0.665	0.692
Arc FE	Yes	Yes	Yes
Day × *hour* FE	Yes	Yes	Yes

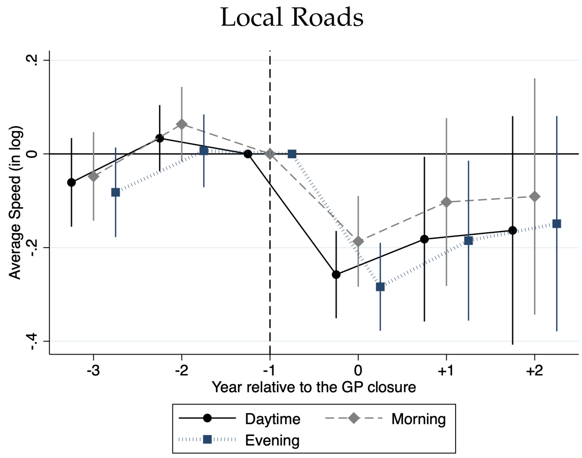
* p<.10, ** p<.05, *** p<.01
standard errors clustered at the arc level

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.

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 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 V.3.

Figure 5: Impact on the average speed





Notes: These graphs plot the estimates and 95% confidence intervals from equation (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).

IV Beyond Traffic: Pollution and Housing Prices

The closure of the GP expressway caused an increase in congestion on substitute roads as seen in section III.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 an increase in the occupancy rate on the concentration of nitrogen dioxide on the same road: particles that primarily gets in the air from the burning of fuel.[19]

IV.1 Empirical Strategy

Ideally, my aim would be to examine how the closure of the riverbank affects pollutant emission levels. This would involve comparing pollution monitors situated near the ring roads with another set located near unaffected roads, both before and after September 1st, 2016. However, the dispersion of emissions in the local area means that spillover effects would occur, complicating my ability to directly compare air quality near the treated roads to that near the untreated roads using 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 occupancy rate on nearby roads in the pre-shutdown period. Using this elasticity, I impute the impact on nitrogen dioxide using the result on occupancy rate shown in section III.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 G.11).[20] I restrict the sample to the pre-shutdown period and I estimate the following equation by assuming a log linear relationship between emissions and occupancy rate:[21]

$$ln(NO_{2t}) = \alpha ln(OccupancyRate_t) + \theta Q_t + \zeta W_t' + \delta_{h(t)} + \delta_{m(t)} + \epsilon_t \quad (6)$$

where NO_{2t} is the nitrogen dioxide concentration at time t, $OccupancyRate_t$ is the average occupancy rate 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 α: the elasticity of nitrogen dioxide concentration to the occupancy rate.

IV.2 Results

The results of estimation (6) are represented in table 5. The baseline regression includes month of the sample fixed effects to account for the fact that cars might be less polluting with time. Since occupancy rate is

[19] 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 NO2.

[20] 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.

[21] By plotting the average occupancy rate and pollutant concentrations, I find an increasing relationship (Figure G.17). This negative correlation is already observed in other contexts (Pandian *et al.*, 2009)

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), I also include hour fixed effects. The estimates are represented in column (1). In column (2), I add the flow of cars as an explanatory variable since occupancy rate and flow of cars are linked by the fundamental diagram of transportation.

On the ring roads, an increase of car density by 1% increases NO_2 concentration by 0.25%. However, the impact is smaller on local roads, with an elasticity of 0.12%. The difference in the elasticities 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. Moreover, vehicles traveling on the ring road are often more polluting, as it tends to serve lower-income commuters residing at the outskirts of the city. Furthermore, heavy trucks are permitted to use the ring roads, whereas they are prohibited from using local roads within the city limits.

Imputation exercise. In all specifications the impact of the flow of cars on NO_2 emissions is negligible.[22] This said, I only use the elasticity of NO_2 to occupancy rate 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. Using equation (6), for each road, I predict the level of No2 concentrations before $N\hat{O}2|_{OccRate=OccRate_{pre}}$ and after $N\hat{O}2|_{OccRate=OccRate_{post}}$ the GP closure using the occupancy rate value predicted from equation 4. The estimates are represented in table **??**.

By computing the difference of NO_2 concentrations before and after the GP closure, one might notice that the overall impact is slightly negative leading us to think that the GP closure decreased the overall level of pollution in the city (cf. figure **??**). However, the number of people impacted by an increase in pollution near the treated roads overcompensate the number of people benefiting from a decrease in pollution near the closed-GP (cf figure G.20).This increase in NO_2 comes on top of already high exposures, especially near the periphery (see Table E.5).[23] I therefore compute the exposure of ambient air pollution:

$$C_t = \frac{\sum_j C_{j,t} P_j}{\sum_j P_j} \tag{7}$$

with C_t the population-weighted concentrations at time t, $C_{j,k}$ concentrations at location j at time t and P_j the population near location j.

The situation is now reversed, where the net population-weighted concentrations is positive (cf figure G.21). Therefore, after the GP closure, more people are exposed to higher pollution.

[22] The flow of cars is already captured by the level of occupancy rate

[23] 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 5: Elasticity of Nitrogen Dioxide with respect to the occupancy rate of vehicles

	(1)	(2)
	NO_2 concentrations (in log)	
	Ring Roads	
Occupancy Rate (in log)	0.249***	0.255***
	(0.016)	(0.016)
Flow (1000 v/h)		0.012**
		(0.005)
Constant	3.777***	3.681***
	(0.071)	(0.085)
Observations	9,406	9,386
R^2	0.514	0.514
	Local Roads	
Occupancy Rate (in log)	0.133***	0.124***
	(0.008)	(0.009)
Flow (1000 v/h)		0.053***
		(0.015)
Constant	5.027***	4.973***
	(0.034)	(0.037)
Observations	12,472	12,472
R^2	0.516	0.516
Weather Characteristics	Yes	Yes
Month of Sample FE	Yes	Yes
Hour FE	Yes	Yes

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

Notes: This table represents the elasticity of nitrogen dioxide emissions with respect to the occupancy rate of vehicles on nearby roads. The first part of table represents the estimates of equation (6) on the ring road and the second part of the table the estimates on the local roads. The first column represents the regression without controlling for the flow of cars. The second column adds the flow of cars as an explanatory variable.

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 C 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 level registered in 2015 near the ring road was of 67 $\mu g/m^3$ which implies that NO_2 increased by $3.8 \mu g/m^3$ 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 NO2 emissions.

V 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 & 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.

V.1 A General Framework

V.1.1 Set Up

The model follows the congestion model of Akbar & 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 B 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.[24]

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.

[24] 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.

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 $m \in$ {Car, Public Transportation}[25]. The travel time of a trip using a set of roads $C \in R$ can be expressed as:[26]

$$\sum_{r \in C} T_{rt} = \sum_{r \in C} \frac{D_r}{S_{rt}(N_{rt})} \tag{8}$$

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 & Duranton (2017):

$$S_{rt}(N_{rt}) = \overline{S_r} N_{rt}^{-\sigma_\mu(N_{rt})} \tag{9}$$

where $\overline{S_r}$ 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 μ i.e. the degree to which the average speed on the road is impacted by the number of cars on that given road, with:

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

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.

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

[25] The share of m from residence i to workplace j is considered fixed

[26] 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.

average speed (Kean *et al.*, 2003; Lozhkina & Lozhkin, 2016). To this end, the level of pollutant emissions can be expressed as:

$$A_i(\mu(r')) = \begin{cases} S_{r'}(N_{r'})^{-\alpha_{\mu(r')}} \; if \; S_{r'} < \tilde{S_{r'}} \\ S_{r'}(N_{r'})^{\zeta_{\mu(r')}} \; if \; S_{r'} > \tilde{S_{r'}} \end{cases} \tag{10}$$

$\tilde{S_{r'}}$ 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 $S_{r'} > \tilde{S_{r'}}$.

V.1.2 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.[27] Let A be the set of arterial roads serving as substitutes to the closed expressway. The average speed on substitutes arterial roads $r \in A$ after the closure is:

$$S_{rt}^{post}(N_{rt}) = \overline{S_r}(N_{rt}^{post})^{-\sigma_{\mu(r)t}(N_{rt}^{post})} \tag{11}$$

where $N_r^{post} = \overline{N_r^{pre}} + \frac{I_e^{pre}}{n_{r\in A}}$, $\overline{N_r^{pre}}$ 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.[28]

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 β 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

[27] Arterial roads are the only roads inside the city apart from the expressway.

[28] The congestion elasticity can be expressed as follow: $\frac{\partial S_{rt}}{\partial N_{rt}} \frac{N_{rt}}{S_{rt}} = \sigma_r(N_{rt})$

commuters choosing to reroute is defined by the following post-shutdown equilibrium equation:[29]

$$\underbrace{\frac{(1-x)}{\overline{S_e}(\overline{N_e}+N_e-\beta O_e)^{-\sigma_e}}}_{\substack{\text{travel time on the}\\ \text{non-pedestrianized stretch}}}+\underbrace{\frac{x}{\overline{S_r}(\overline{N_r}+(1-\beta)\frac{O_e}{n_a}+\frac{I_e}{n_a})^{-\sigma_a}}}_{\substack{\text{travel time on arterial roads with diverted}\\ \text{inner-city and suburban commuters}}}=\underbrace{\frac{1}{\overline{S_{r'}}(\overline{N_{r'}}+\beta\frac{O_e}{n_f})^{-\sigma_f}}}_{\substack{\text{travel time on the freeway with}\\ \text{diverted suburban commuters}}} \tag{12}$$

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 of people on these roads. Hence, for every r'$\in F$ the congestion elasticity can be written as: $\frac{\partial S_r'}{\partial N_r'}\frac{N_r'}{S_r'}=\sigma_f(\sigma_a,\sigma_e,N_r,N_{r'})$.

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.

V.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.

V.2.1 Parameter Estimation

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

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

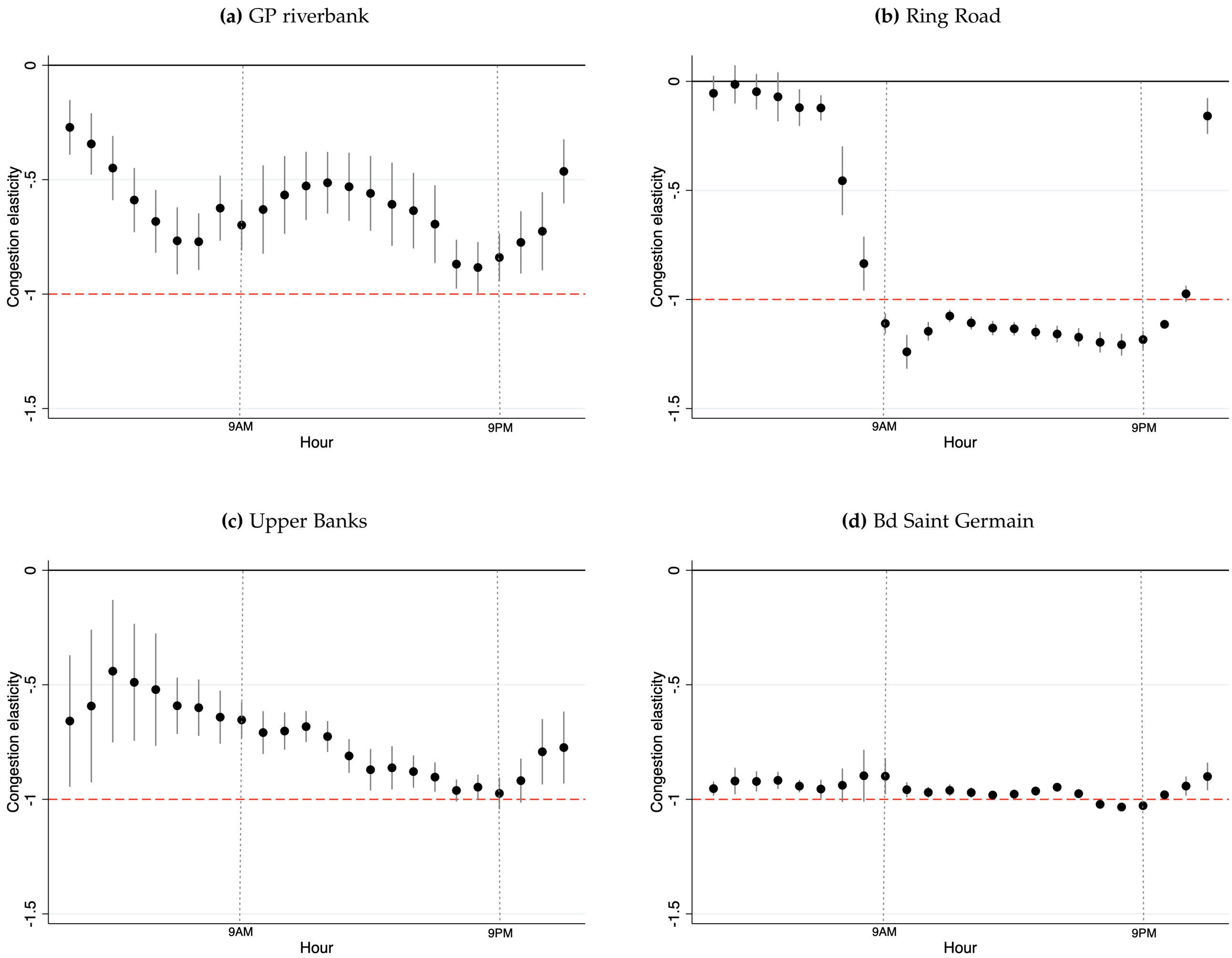
$$ln(S_{it})=\alpha-\sigma_t ln(N_{it})+\gamma_t+\gamma_i+\epsilon_{it} \tag{13}$$

where S_{it} is the average speed on road section *i* at time *t*, σ_t the elasticity of congestion (parameter of interest), N_{it} is the density of cars on road section i at time t, γ_t and γ_i are day of the sample and road section fixed effects respectively. Figure 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

[29]The equation holds for any t, therefore I remove t for conveniance.

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.[30]

Figure 6: Congestion Elasticities by hour of the day



Notes: I plot the estimates of equation (13) by road and hour of the day. The estimates are represents with the black dot. The vertical lines represent the 95% confidence intervals.

Estimating β. β 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:

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

[30]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.

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 E.2 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 α. 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 IV. I find an elasticity of -0.08% on local roads and -0.34% on the ring road.

V.2.2 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: $N^{pre}_{e,non-closed} - N^{post}_{e,non-closed} = \beta O_e$, with $\beta = 1$. Using the speed formula expressed in equation (9), I recover the speed impact by using (i) $N^{pre}_{e,non-closed} - N^{post}_{e,non-closed}$ 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: $N^{pre}_{e,closed} - O_e$ 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 γ_{model} displayed in figure G.25.[31]

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.[32]

V.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.

V.3.1 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".[33] This high number of visitors reflects the highly-valued amenities

[31]From table E.1, I recover the average car density O_e and $N^{pre}_{e,non-closed} - N^{post}_{e,non-closed}$. 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 $N^{pre}_{e,non-closed} - N^{post}_{e,non-closed}$ 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.

[32]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.

[33]https://www.lepoint.fr/societe/berges-de-seine-rive-droite-la-mairie-de-paris-affiche-son-succes-19-03-2018-2203750_23.php#11

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 D.

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.[34] Mink (2022) quantifies the health costs associated with an increase in NO_2 emissions in French urban areas and shows that an exposure of 1 μg/m3 costs 15.08€ per day per postcode. Since areas near the south ring road 2.5 times denser than areas in the center, the number of people exposed to the increased in pollution near the ring roads is higher than the number of people exposed to higher pollution levels near local roads (70k). Therefore, residents near the ring roads bear a cost of €1.1 million and residents near local roads bear a cost of €508,000. The annual cost associated to pollution represents €1.6 million. 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 loose 13 minutes, associated with a cost of 15.4M€.[35] 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 39M€, 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 39€.

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) subur-

[34] In 2016, air pollution was estimated to play a part in 7.6% of worldwide deaths (WHO, 2017).

[35] 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 E.1).

bans. The center of Paris is populated mostly by high-income residents. On the contrary, the peripheral area is inhabited by low-income residents (Figure G.24).

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 (Apur, 2016), the total time costs incurred by high-income residents is of 22.15M€, which represents 60% of the time costs.[36] Regarding the pollution cost, all residents near the local roads are considered high-income residents. They bear the 508k€ cost of extra emissions generated by the additional traffic on each road, which represents 30% 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 1.1M€, 70% 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 70% 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.[37] Below 2.6-kilometers of pedestrianization, suburban commuters prefer to shift to local roads as it would deliver a lower travel time.

V.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 G.26. Computation details can be found in Appendix E.

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

[36] 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.

[37] Computations are found in Appendix D.

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 G.26 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 E. 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.[38] 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.

VI 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*

[38] The center of the city is considered to be represented by the following *arrondissements*: 1,2,3 and 4.

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.[39]

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).[40] 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?[41] 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.

Table 6: Robustness Checks: Occupancy Rate

	(1)	(2)	(3)	(4)	(5)
		Occupancy rate (in log)			
		Ring Roads			
Treatment	0.112***	0.117***	0.112***	0.112***	0.112***
	(0.018)	(0.018)	(0.018)	(0.000)	(0.018)
Constant	3.146***	3.071***	3.158***	3.146***	3.146***
	(0.005)	(0.068)	(0.006)	(0.000)	(0.005)
Observations	765,044	765,044	765,047	765,044	765,044
R^2	0.569	0.297	0.372	0.569	0.569
		Local Roads			
Treatment	0.339***	0.357***	0.339***	0.339*	0.339***
	(0.080)	(0.084)	(0.079)	(0.108)	(0.080)
Constant	2.233***	2.142***	2.247***	2.233***	2.233***
	(0.024)	(0.091)	(0.015)	(0.033)	(0.024)
Observations	1,729,726	1,729,726	1,729,733	1,729,726	1,729,726
R^2	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	Road	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) the standard errors are clustered at the road level. Column (5) adds up a restriction to the data. The data is winsorized at the 1% level.

[39]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.

[40]The RER A is the main transport line in Paris' region that links the west and east of the city.

[41]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.

Table 7: Robustness Checks: Average Speed

	(1)	(2)	(3)	(4)	(5)
			Average Speed (in log)		
			Ring Roads		
Treatment	-0.165***	-0.176***	-0.165***	-0.165***	-0.165***
	(0.029)	(0.033)	(0.029)	(0.000)	(0.029)
Constant	3.243***	3.332***	3.225***	3.243***	3.243***
	(0.007)	(0.103)	(0.008)	(0.000)	(0.007)
Observations	627,122	627,122	627,127	627,122	627,122
R^2	0.586	0.197	0.482	0.586	0.586
			Local Roads		
Treatment	-0.175**	-0.223**	-0.178**	-0.175**	-0.175**
	(0.083)	(0.103)	(0.082)	(0.037)	(0.083)
Constant	2.420***	2.765***	2.377***	2.420***	2.420***
	(0.028)	(0.099)	(0.017)	(0.013)	(0.028)
Observations	1,461,407	1,461,407	1,461,416	1,461,407	1,461,407
R^2	0.692	0.257	0.655	0.692	0.692
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	Road	Arc
Trimmed data	No	No	No	No	Yes

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

Notes: The outcome is the log of the average speed in km/h. 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) the standard errors are clustered at the road level. Column (5) adds up a restriction to the data. The data is winsorized at the 1% level.

Table 8: Robustness Checks: Probability of Congestion

	(1)	(2)	(3)	(4)	(5)
			Probability of Congestion		
			Ring Roads		
Treatment	0.119***	0.128***	0.119***	0.119***	0.119***
	(0.022)	(0.022)	(0.022)	(0.000)	(0.022)
Constant	0.421***	0.384***	0.434***	0.421***	0.421***
	(0.005)	(0.059)	(0.007)	(0.000)	(0.005)
Observations	627,123	627,123	627,128	627,123	627,123
R^2	0.372	0.190	0.256	0.372	0.372
			Local Roads		
Treatment	0.101***	0.156***	0.101***	0.101	0.101***
	(0.031)	(0.033)	(0.031)	(0.040)	(0.031)
Constant	0.079***	0.070***	0.085***	0.079**	0.079***
	(0.011)	(0.017)	(0.007)	(0.014)	(0.011)
Observations	1,461,657	1,461,657	1,461,666	1,461,657	1,461,657
R^2	0.284	0.160	0.208	0.284	0.284
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	Road	Arc
Trimmed data	No	No	No	No	Yes

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

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. 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) the standard errors are clustered at the road level. Column (5) adds up a restriction to the data. The data is winsorized at the 1% level.

Table 9: Model predictions

	σ	γ_{model}	γ_{did}	95% CI	$\gamma_{model} \times \alpha$
			South outer Ring Road		
Morning	-1.18	-19.6%	-15.4%	[-22%, -9%]	1.76%
Evening	-1.2	-24%	-17.4%	[-24%, -11%]	2.16%
Dayweek & Daytime	-1.18	-14.5%%	-16.4%	[-22%, -10.5%]	1.3%
			Local roads		
Morning	-0.86	-12.5%	-11.3%	[-27%, 5.3%]	4.25%
Evening	-0.95	-13.8%	-17%	[-33%, -1.1%]	4.69%
Dayweek & Daytime	-0.87	-13%	-17.5%	[-34%, -1.1%]	4.42%

Notes: This table represents the treatment effect on speed computed by the model and estimated with the reduced-form. γ_{model} represents the average treatment effect on the average speed computed by using the theoretical framework. γ_{did} represents the average treatment effect on the average speed obtained by estimating equation 4. The 95% confidence interval of the reduced-form estimation is represented in the fourth column. In the last column, I compute the impact on pollution using the elasticity of NO_2 emissions to the average speed and the speed impact from the model.

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A 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^{th} of September 2016 through deliberation. The October 18^{th}, 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^{st} 2018, the administrative tribunal of Paris canceled the Paris Council's September 26, 2016 deliberation, and the town hall's 18^{th} of October 2016 decree creating a public walk on the location of this riverbank. However, on the 6^{th} 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^{nd}, 2018 the annulment was confirmed due to doubts concerning the environmental consequences of this project. Lastly, on June 21^{st} 2019, the Paris Council confirmed the 6^{th} of March 2018 decree while rejecting all the related annulment appeals.

B 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.[42]

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 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^{st}, 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 G.12 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

[42]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 G.13 represents these two lines in the Paris region.

public transportation[43]. Conversely, the remaining dyads[44] 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 E.6. To go further, I restrict the treated group to the east-west and west-east travels and the control group to the north-south and south-north travels.[45] 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 G.14.

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 G.15), where both train lines should be comparable.

I therefore estimate another version of equation (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 G.16 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.

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

[43] However, the difference is not statistically significant.

[44] All travels excluding west-east and east-west

[45] 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.

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.[46] 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 G.18). 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:

$$ln(HV_{it}) = \beta ln(BA_i) + \theta Rooms_i + \sum_{k=-2, k\neq -1}^{+2} \gamma_k Treated_i * Year_{k(t)} + \delta_{m(t)} + \delta_{n(i)} + \epsilon_{it} \quad (14)$$

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 G.22 represents the plots of the leads-and-lags regression of equation (14). 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 the implementation of new metro lines in the south of Paris.[47]

D 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.

D.1 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

[46] In between, I find almost no housing transactions since it is occupied by public social housings.

[47] `https://www.societedugrandparis.fr/gpe/actualite/la-nouvelle-feuille-de-route-du-grand-paris-express-1683`

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 tableE.5). 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. [48] 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.[49] 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 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 $15.08 \times 97 \times \frac{10}{2} \times 260 \times 3.75 = 7,226,034$.

D.2 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 E.8). 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 governement and used for cost/benefit analysis.[50] 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 E.9.

D.3 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

[48]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.

[49]The study is conducted on a representative sample of the administrative data on healthcare reimbursements from French National System of Health Data.

[50]`https://www.ecologie.gouv.fr/sites/default/files/V.3.pdf`

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.

E Calculating the Costs of Counterfactual Situations in Euro Value

E.1 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, loosing 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 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:

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

E.2 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.

E.3 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 woulf be:

$$\frac{D_{e,non-closed}}{S_{e,non-closed}} + \frac{D_{local}}{S_{local}} < \frac{D_{ringroad}}{S_{ringroad}}$$

$$\frac{9.7}{30} + \frac{3.3}{S^*} < \frac{10.4}{25}$$

$$S^* > 35.4$$

F Appendix Tables

Table E.1: Traffic by road

	Pre-shutdown			Post-shutdown		
	Density	Speed	Flow	Density	Speed	Flow
	Panel A: Non-pedestrianized stretch of the riverbank					
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
	Panel B: Pedestrianized stretch of the riverbank					
Morning	40.3	44.5	2,068	-	-	-
Evening	60	42.3	2,307	-	-	-
Dayweek & Daytime	46.3	44.6	2,083	-	-	-
	Panel C: South outer Ring Road					
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
	Panel D: Upper Banks					
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
	Panel E: Bd Saint Germain					
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
	Panel F: Bd Saint Germain & Upper Banks					
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 E.2: Average travel time in the pre-shutdown period

Itinerary	Time	Travel Time
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 E.1 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 E.3: Robustness Checks: Occupancy Rate

	(1)	(2)	(3)	(4)	(5)
			Occupancy rate (in log)		
			Ring Roads		
Treatment	0.112***	0.117***	0.112***	0.112***	0.112***
	(0.018)	(0.018)	(0.018)	(0.024)	(0.018)
Constant	3.146***	3.071***	3.158***	3.146***	3.146***
	(0.005)	(0.068)	(0.006)	(0.006)	(0.005)
Observations	765,044	765,044	765,047	765,044	765,044
R^2	0.569	0.297	0.372	0.569	0.569
			Local Roads		
Treatment	0.339***	0.357***	0.339***	0.339***	0.339***
	(0.080)	(0.084)	(0.079)	(0.089)	(0.080)
Constant	2.233***	2.142***	2.247***	2.233***	2.233***
	(0.024)	(0.091)	(0.015)	(0.027)	(0.024)
Observations	1729726	1729726	1729733	1729726	1729726
R^2	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 E.4: Robustness Checks: Flow

	(1)	(2)	(3)	(4)	(5)
			Flow of cars (in log)		
			Ring Roads		
Treatment	-0.061***	-0.059***	-0.061***	-0.061***	-0.061***
	(0.013)	(0.013)	(0.013)	(0.012)	(0.013)
Constant	8.395***	8.405***	8.389***	8.395***	8.395***
	(0.003)	(0.076)	(0.002)	(0.003)	(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
			Local Roads		
Treatment	0.264***	0.362***	0.257***	0.264***	0.264***
	(0.048)	(0.055)	(0.048)	(0.075)	(0.048)
Constant	7.189***	7.196***	7.176***	7.189***	7.189***
	(0.017)	(0.079)	(0.013)	(0.026)	(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 E.5: Yearly levels of NO2

	Ring Road		**Upper Banks**	
Year	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_2 emissions two sensors: the one located on the upper banks and the one on the east of the ring road. NO_2 emissions are measure in μg/m3.

Table E.6: Impact on the share of people commuting by public transportation

	(1)	(2)
	Share of public transportation commuters	
Treatment	0.002	-0.001
	(0.002)	(0.006)
Constant	0.405***	0.709***
	(0.000)	(0.001)
Observations	38,921	3,362
R^2	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 E.7: 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 E.8: 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 E.9: 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.

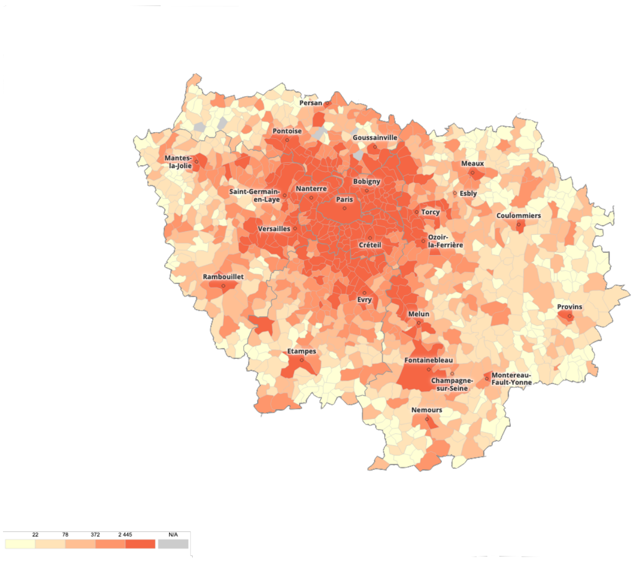
Table E.10: Speed - Counterfactuals Situations

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.

G Appendix Figures

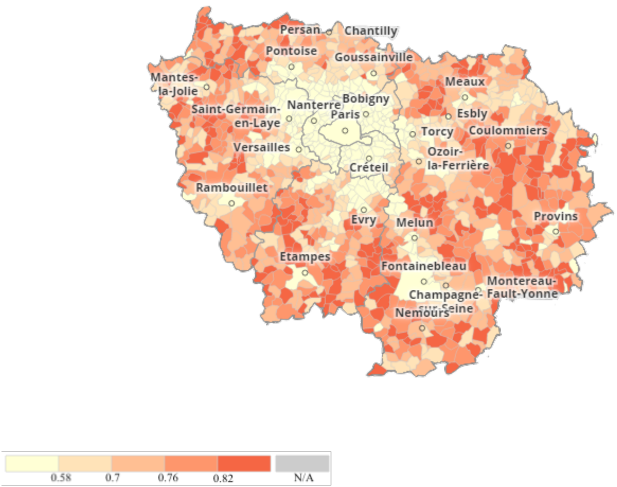
Figure G.1: Job concentration in 2015



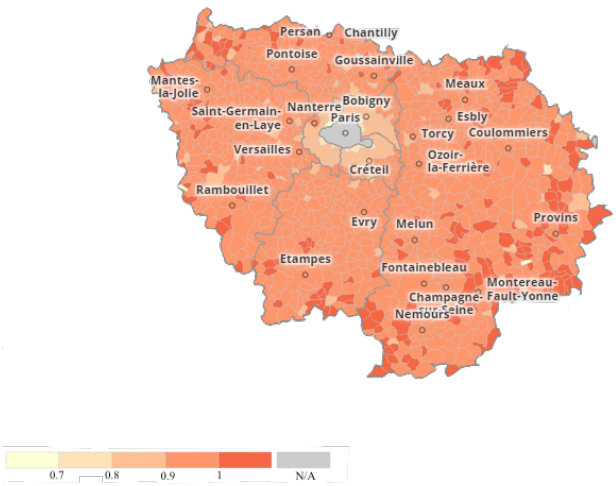
Notes: The job concentration is represented on this graph which is the absolute value of the number of jobs taken from the DADS (Déclaration Annuelle de Données Sociales). The brighter the color, the fewer the number of jobs in the region.

Figure G.2: Fraction of people commuting by car in Ile-de-France (2015)

(a) All journeys



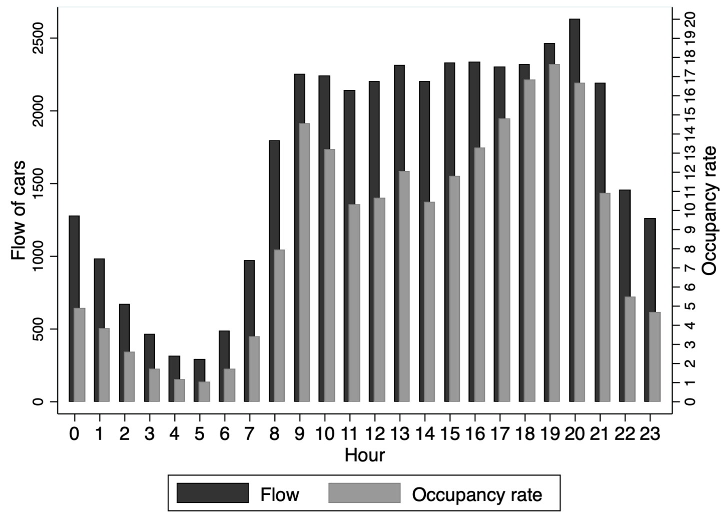
(b) Suburb-to-suburb journeys



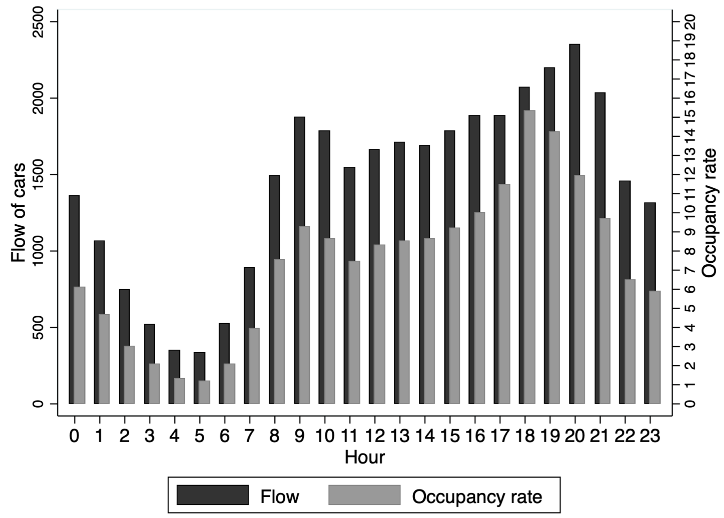
Notes: These graphs represent the fraction of individuals commuting by car in Ile-de-France. The data is taken from INSEE - "Recensement 2015". A low fraction of car commuters is represented by a brighter color.

Figure G.3: Descriptive statistics of the riverbank - 2015

(a) 13 km riverbank

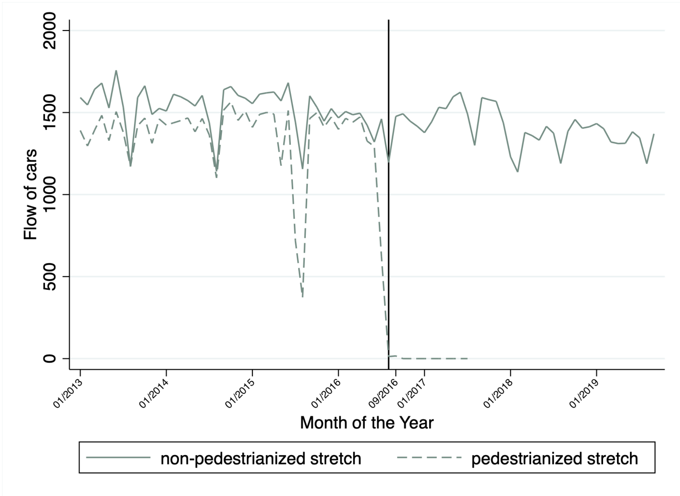


(b) 3.3 km closed in 2016



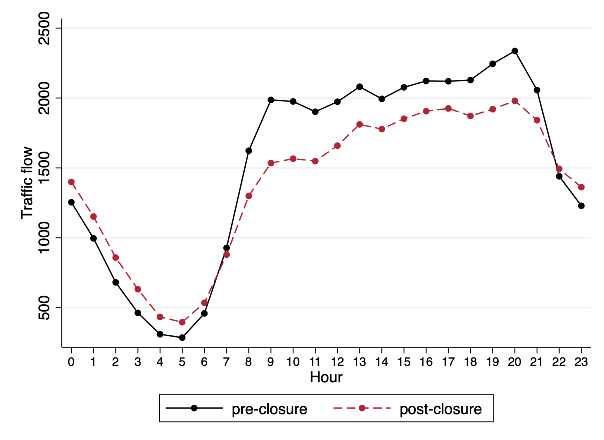
Notes: Data come from the open data source of the city hall. The sample in Figure G.3 (a) is composed of the 33 road sections that compose the GP riverbank inside the city. The sample in Figure G.3 (b) is composed of 7 road sections that represent the part of the GP riverbank to be pedestrianized.

Figure G.4: Flow on the pedestrianized stretch



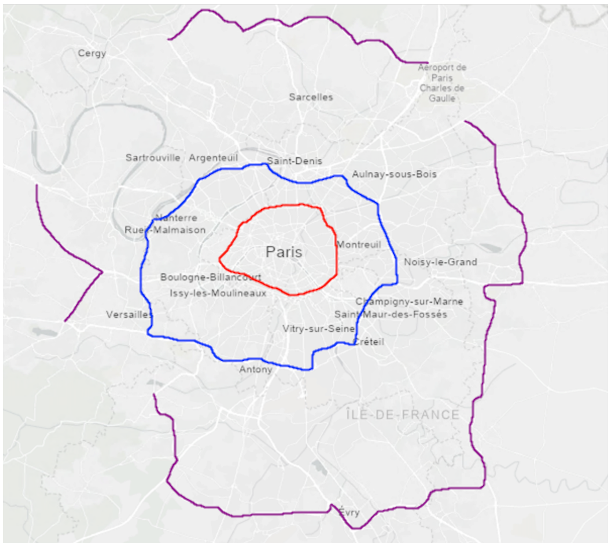
Notes: The sample is restricted to the 7 road sections that are pedestrianized as of 2016. The outcome is the flow of cars averaged on the pre-shutdown and post-shutdown period.

Figure G.5: Flow difference of the non-pedestrianized stretch, before and after the 2016 shutdown



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 G.6: 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*.

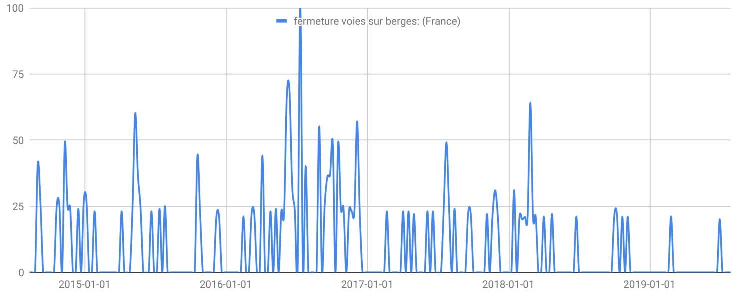
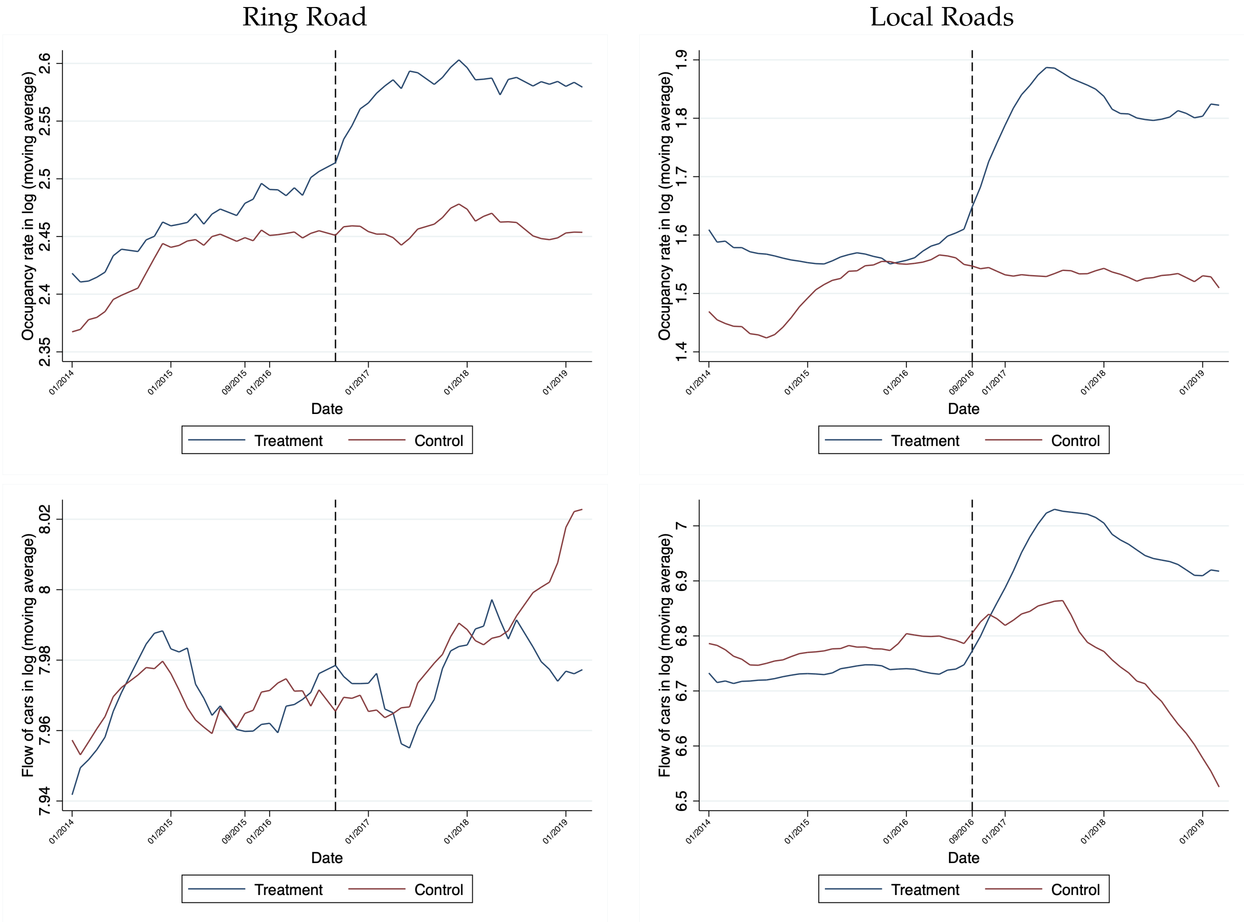


Figure G.7: Google trend

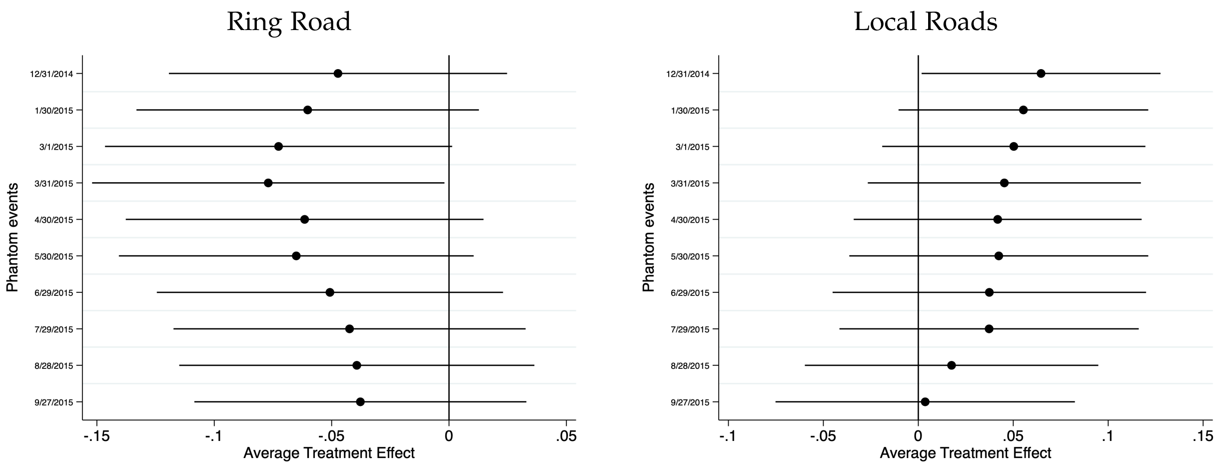
This graph represents the *Google trend* of the number of times that people in France googled "Fermeture des voies sur berges", which literally means "Riverbanks closure".

Figure G.8: Common Trends



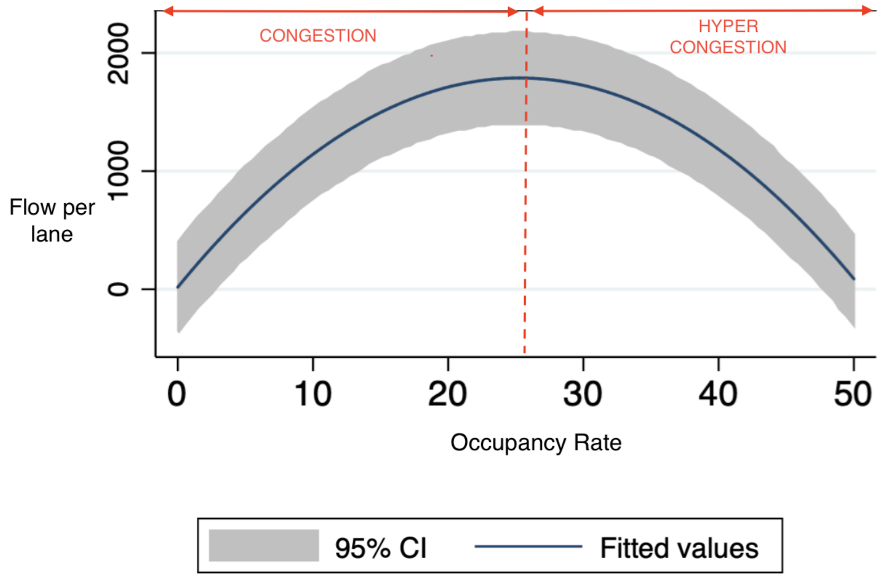
Notes: Theses graphs represent the common trend assumptions of the difference-in-difference research design. The first row is the common trends on the occupancy rate. The second row is the common trends on the flow of cars. The average occupancy rate is calculated with a moving average of a window of (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 G.9: Placebo Tests



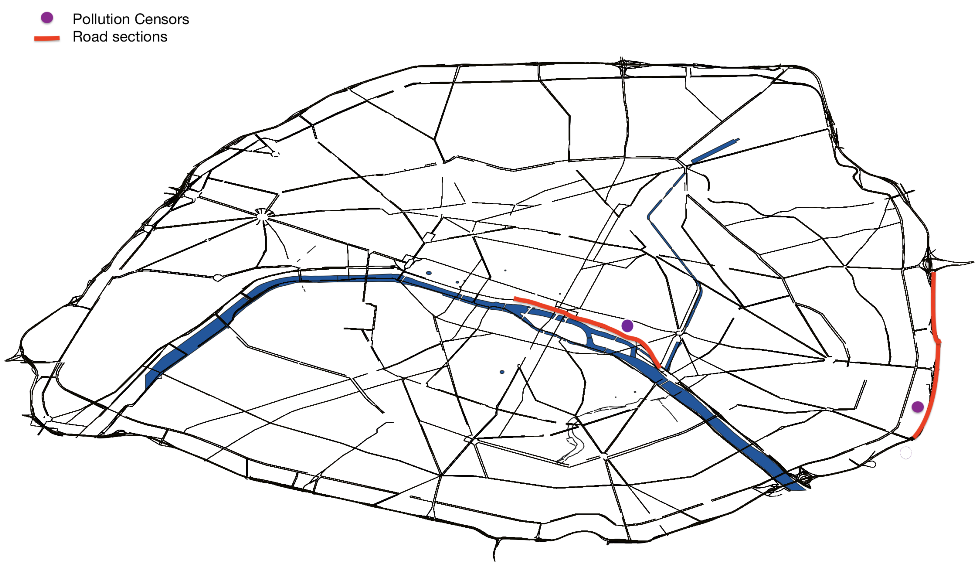
Notes: I use data from January 1, 2013 to September 1, 2016. Starting from January 1, 2015 I create every 30 days a phantom event and run regression (4) during the day and for weekdays with the average speed as the outcome variable. These graphs plot the estimates and 95% confidence intervals of this regression.

Figure G.10: Fundamental Diagram



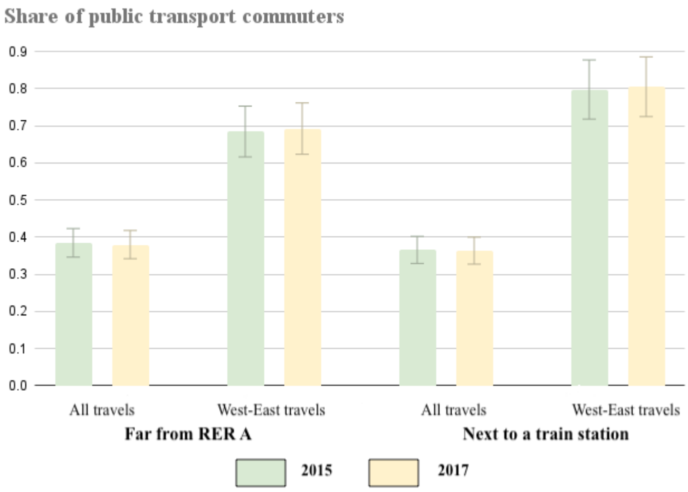
Notes: I estimate the concave relationship between Flow per lane and occupancy rate of one arc of road. The ascendant part of the graph is what we define as the *congested* part, while the descendant part is the *hyper-congested* one.

Figure G.11: Pollution monitors and road sections selected



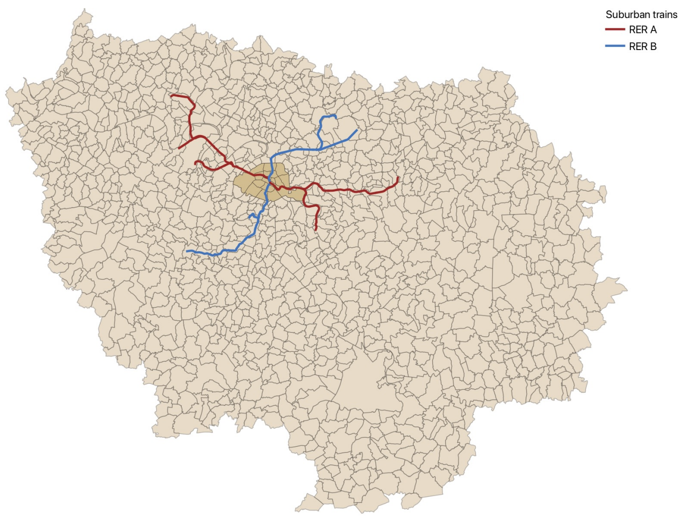
Notes: This map represents the two monitors I use for my analysis. One is located in the center near the upper east and one on the east of the ring road. The line in red represents the arcs of road selected near each monitor.

Figure G.12: Share of public transport commuters in 2015 and 2017



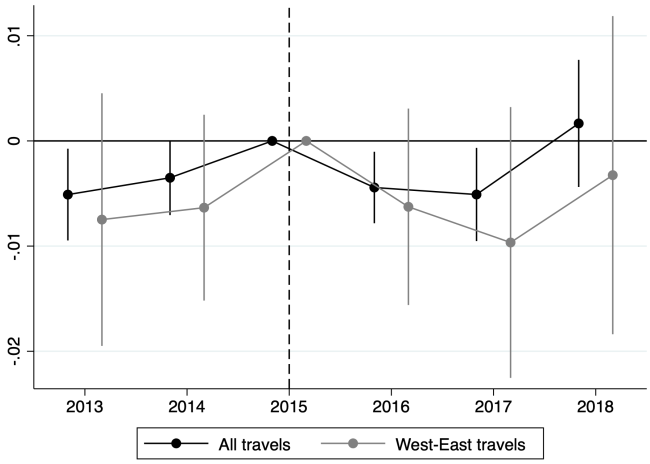
Notes: This chart compares the share of people commuting in public transportation in 2015 and 2017. The outcome is the mean of the share of public transportation usage in the dyads considered. The first part of the chart considers the dyads whose home municipalities do not have a station of the RER A: "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 G.13: Public Transportation - RER A and RER B



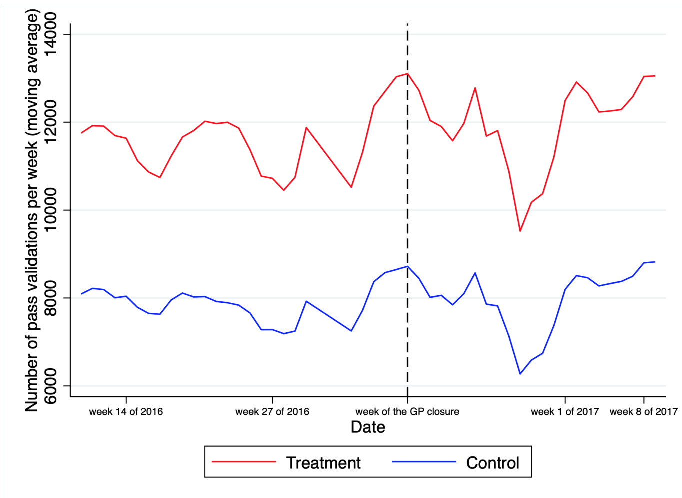
Notes: This figure represents the two train lines used in the analysis. The A-line is represented by the red line. The B-line by the blue line.

Figure G.14: Share of public transportation



Notes: This graph represents the estimates of equation:
$Y_{it} = \lambda_t + \psi_i + \sum_{k=2013}^{2018} \beta_t \mathbb{1}_{treated_i=1} \mathbb{1}_{t=k} + \epsilon_{it}$ 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.

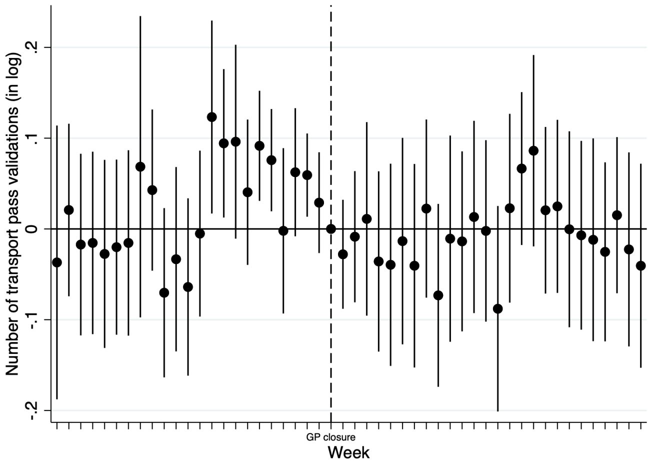
Figure G.15: Weekly number of validations - RER A and RER B



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.

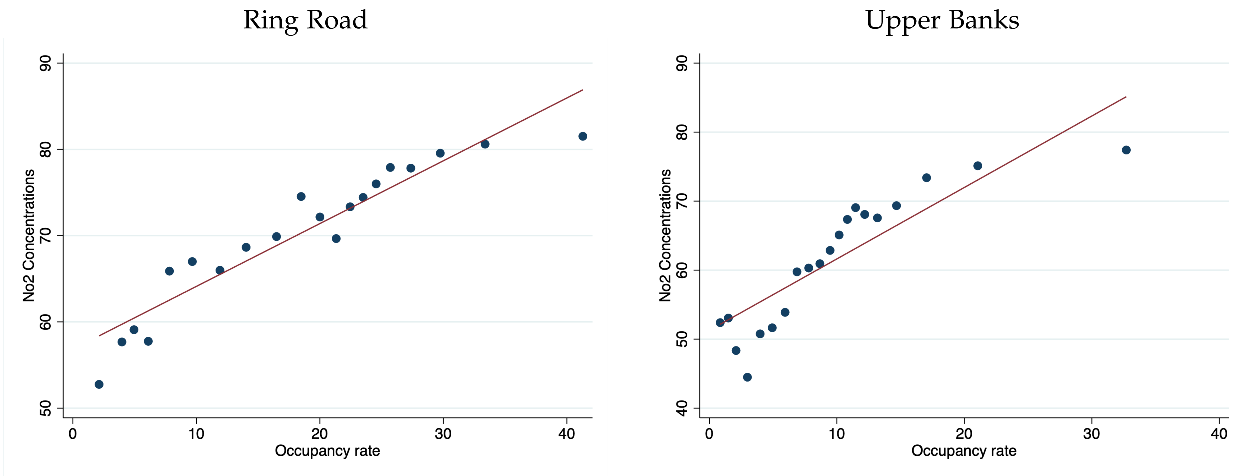
I therefore estimate another version of equation (5) using the data from March 2016 to end of January 2017, where Y_{it} now represents the number of weekly entries of station i at time t. The graphical results are shown in figure G.16 and suggest again the absence of significant change in the use of the A-line right after the GP closure.

Figure G.16: Impact on the RER A



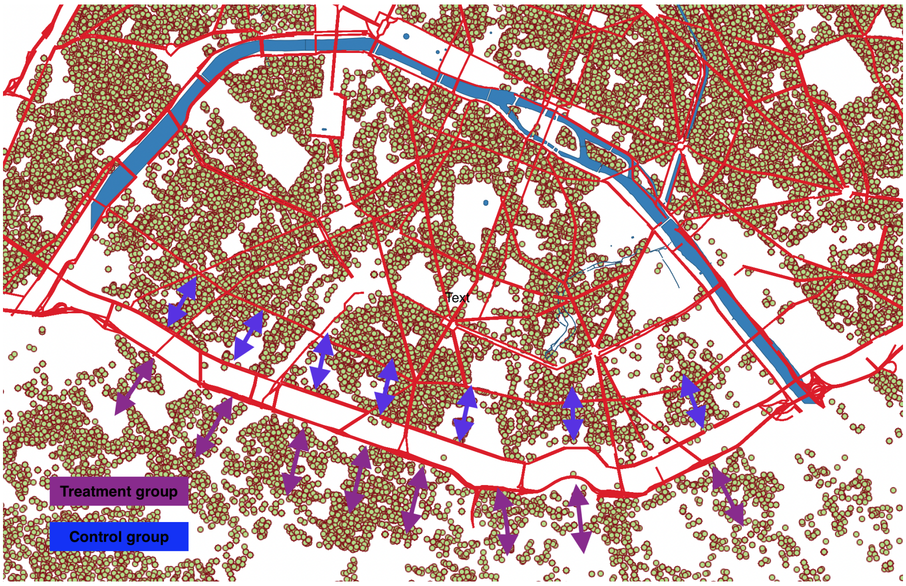
Notes: In this graph, I plot the estimates of equation (5). λ_t and ψ_i are year and station fixed effects, respectively. The indicator variable $\mathbb{1}_{post=1}$ equals 1 if the reform has been adopted (after September 1, 2016) and 0 otherwise. The dummy $\mathbb{1}_{treated_i=1}$ takes the value 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 G.17: Link between NO_2 emissions and occupancy rate



Notes: These graphs plot the relationship between average occupancy rates on the road near the pollution censor and NO_2 concentrations.

Figure G.18: 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.

	Pre-closure	**Post-closure**
	Occupancy Rate	$\widehat{OccupancyRate}$
Upper Bank	11.47	16.86
St Germain	12.06	14.71
Ring Road	28.8	31.96
Closed GP	11.72	0
	$\hat{NO_2}$	
Upper Bank	71.98	76
St Germain	72.24	74.44
Ring Road	71.52	73.7
Closed GP	72.24	59.15

Notes: The first part of the table represents the values of the occupancy rate on each road in the pre-shutdown period (column 1) and the predicted value of the occupancy rate in the post-shutdown period using equation 4. The second part of the table shows the predicted values of NO2 concentrations when plugging the values of the occupancy rate of the first part of the table to equation 6.

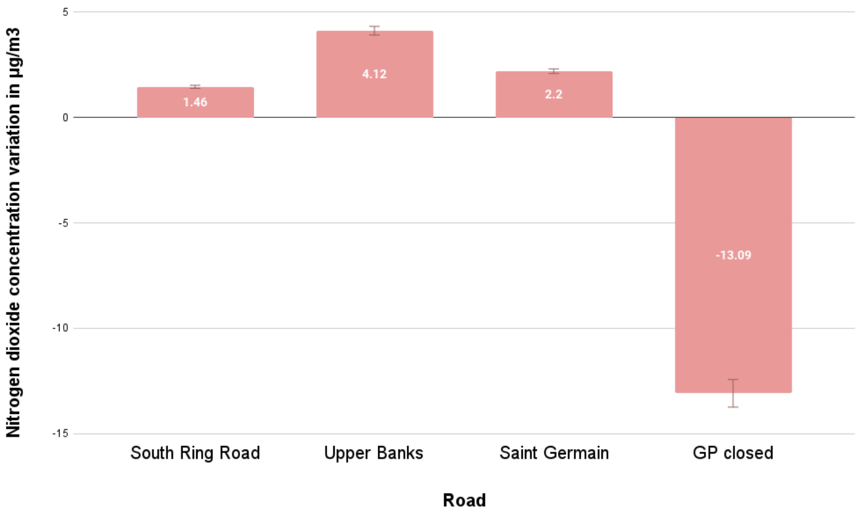


Figure G.19: Difference in No_2 levels after the GP closure

Figure G.20: Difference in No_2 levels after the GP closure

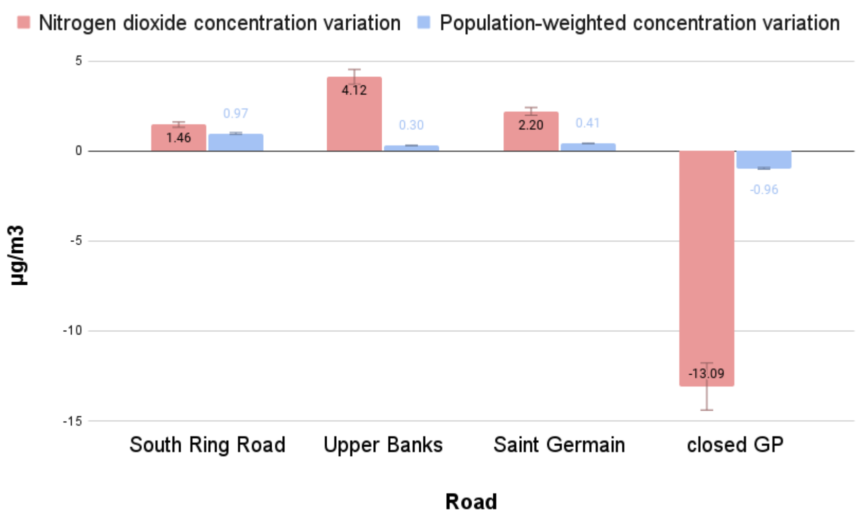
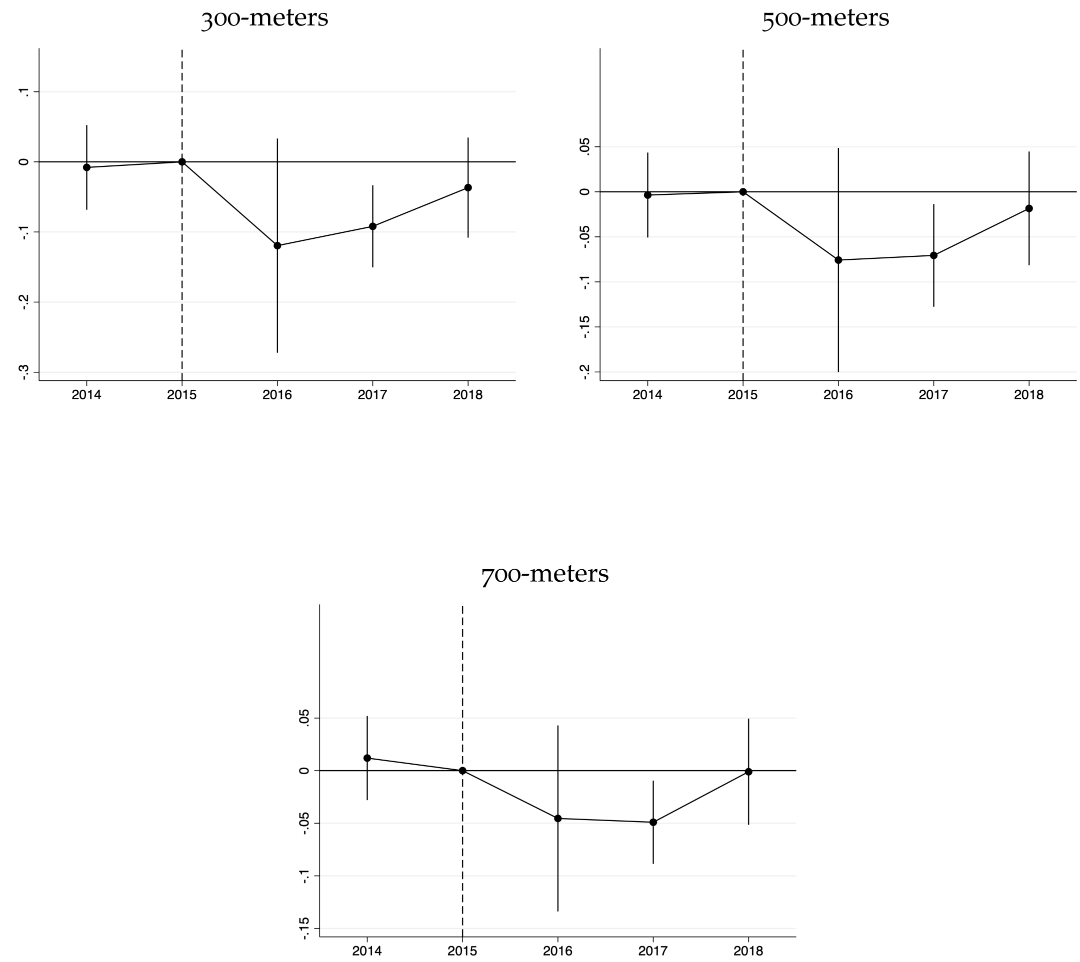


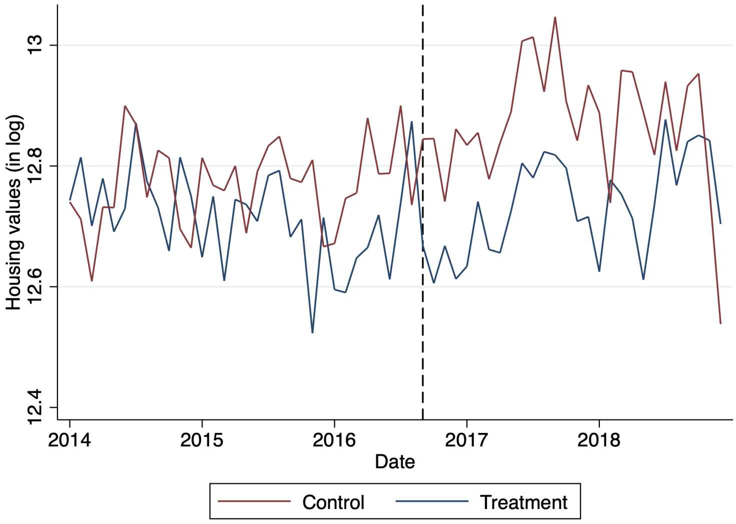
Figure G.21: Difference in No_2 levels after the GP closure once accounting of population density

Figure G.22: Impact on housing prices



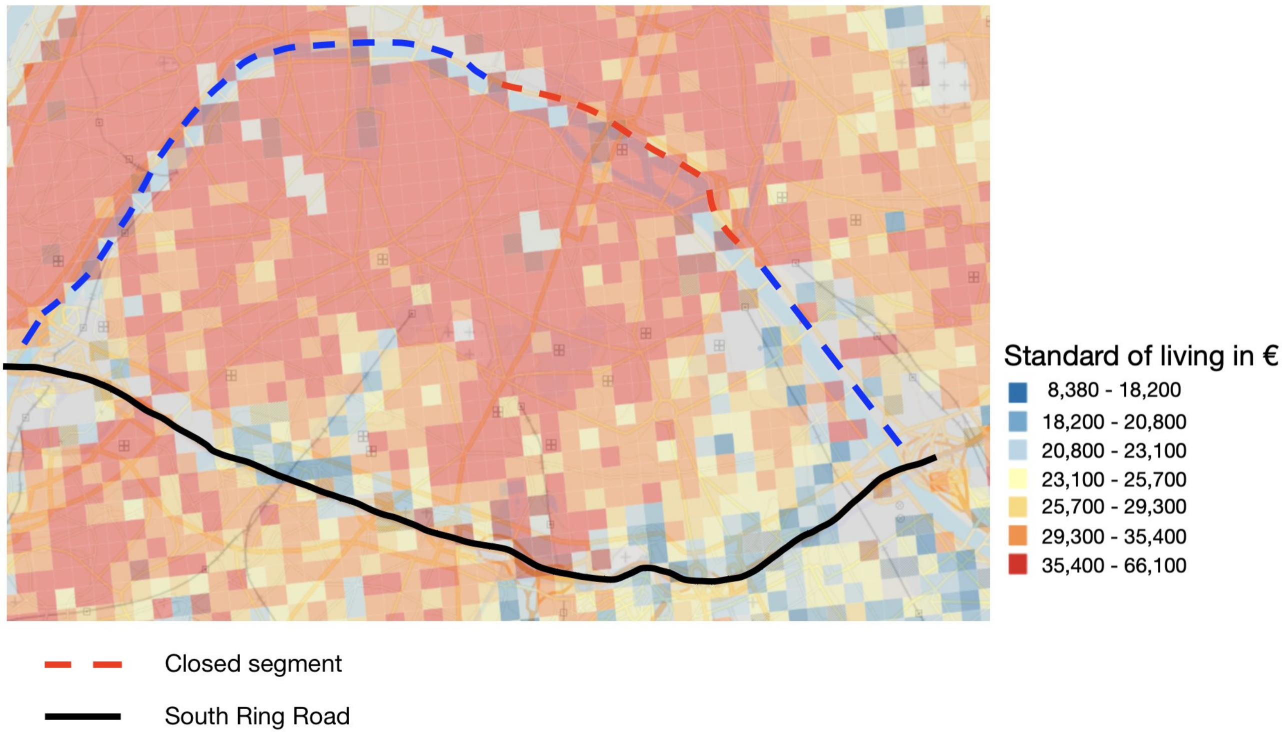
Notes: The outcome is the log of the transacted price. The reference year is 2015, a year before the GP shutdown. The regression is run on apartments only. Townhouses are removed from the sample. The sample consisting of transactions within 300-meters of the major road is composed of 5,769 observations. 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 G.23: 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 G.18.

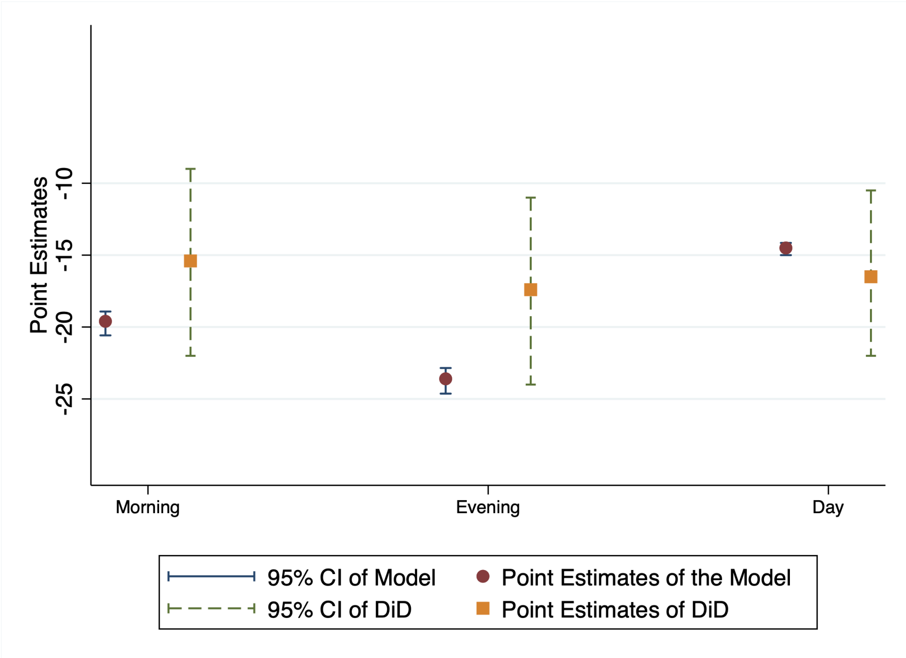
Figure G.24: Standard of living across the Paris region



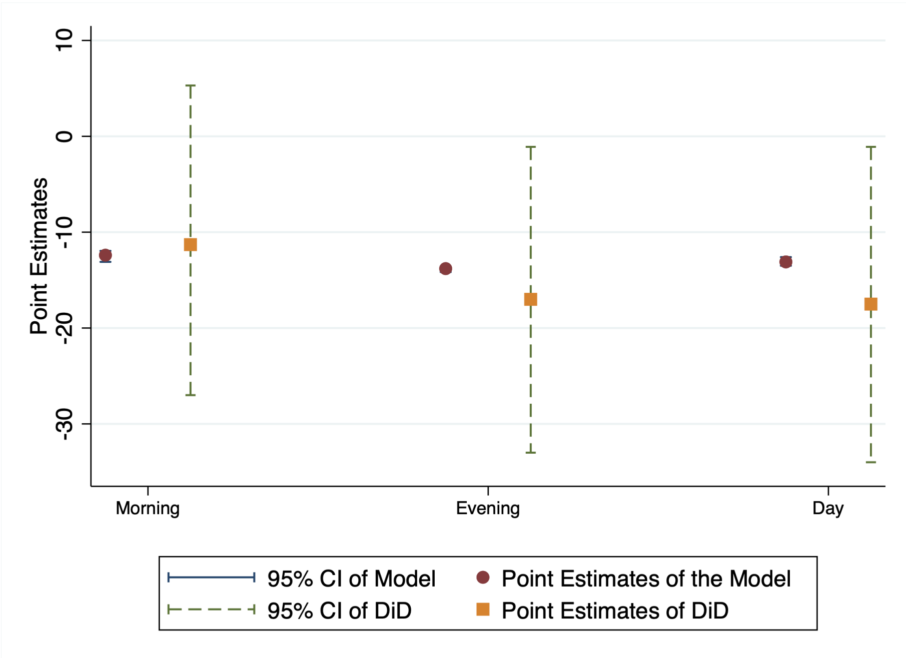
Notes: This map represents the spatial distribution of income near the treated roads. Red squares represent richer areas while blue squares represent poorer areas.

Figure G.25: Model Estimates Versus DiD Estimates

(a) Ring Road



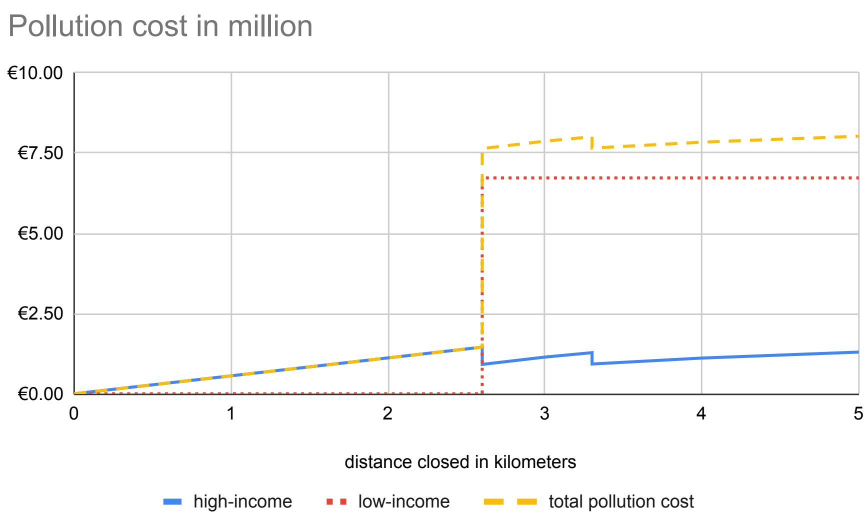
(b) Local Road



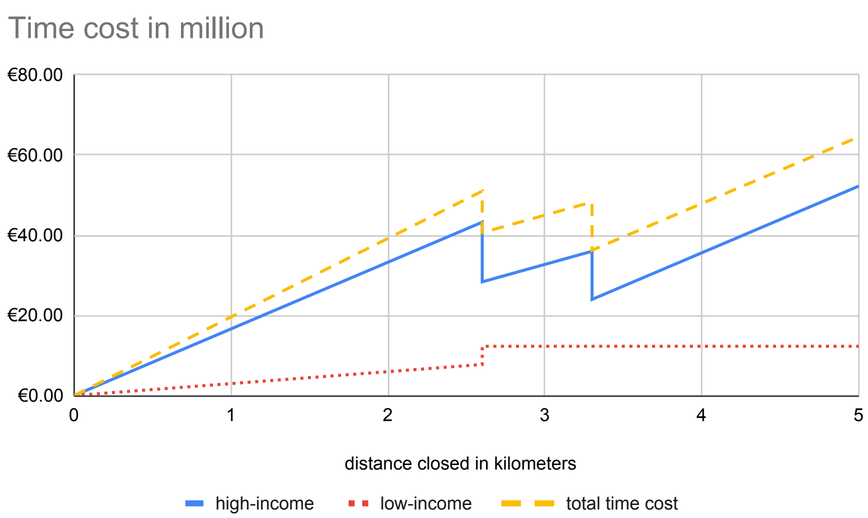
Notes: These graphs show the difference in point estimates between the impact of the GP closure on the average speed computed using the model, and the one computed using the difference-in-difference strategy. The model estimates are computed using the congestion elasticity σ of each time period.

Figure G.26: 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 E. All costs are computed using the speed impacts from the model's predictions.