Congestion Pricing, Traffic Outcomes, and Environmental Quality: Evidence from U.S. HOV and HOT Facilities

by

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Time spent ensnarled in traffic is not simply time wasted; for most of us, it is time miserably wasted.

- RICHARD ARNOTT AND KENNETH SMALL, 1994

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Abstract

Externalities from traffic congestion impose a large cost on society in the form of travel delays, pollution, accidents and wear to highway infrastructure. However, there is limited evidence on the effectiveness of the policies used to address the social costs of congestion. Exploiting the introduction of High-Occupancy Vehicle lanes and High-Occupancy Toll lanes across the United States, I find no evidence of improvements to traffic load or environmental quality. These findings suggest that existing lane management schemes are not effective in forcing drivers to internalize the social costs of driving.

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1 Introduction

Management of common-pool resources is a fundamental goal of public finance and environmental economics. Common-pool resources are rival in consumption, non-excludable, and consequently allow for problems of congestion and overuse. A public road is a prime example of a common-pool resource. The rivalry and non-excludability of public roads allow motorists to account for private marginal costs of road use without incorporating external costs in their decision to drive.[1] Traffic congestion and associated externalities are the focus of an extensive economic literature largely because the social costs of motor vehicle traffic are significant and the proposed remedies for congestion are often controversial, expensive, or believed to be ineffective.

I exploit the introduction of High-Occupancy Vehicle (HOV) and High-Occupancy Toll (HOT) lanes on U.S. interstates across busy commuter cities to identify the causal effect of lane management schemes on traffic outcomes and environmental quality. Using detailed traffic load data and high-resolution pollution concentrations, combined with a generalized difference-in-differences (DID) model, I estimate that HOV lanes do not deliver reductions in traffic load and that converting HOV lanes to HOT lanes significantly increases the load on urban interstates relative to before HOV introduction. Moreover, I find no evidence that either of these policies leads to improvements in environmental quality, as captured by ambient fine particulate matter concentrations. These findings suggest that HOV and HOT lanes are not effective in forcing drivers to internalize the social cost of driving.

My findings make several contributions to the existing literature. First, I contribute to the existing research on congestion and traffic demand (Arnott and Small, 1994; Duranton and Turner, 2011, 2012; Mohring, 1999; Cervero and Hansen, 2002). To my knowledge, this is the first paper in the literature to study the causal impact of conversion from HOV to HOT lanes on traffic outcomes. I identify no effects of HOV lanes on traffic load and estimate significant increases in interstate traffic load in the presence of an HOT congestion pricing scheme. These findings suggest that HOV lanes are not priced high enough to invoke carpooling on the margin and that HOT lanes actually induce inframarginal consumers to shift away from mass transit. Moreover, I use detailed panel data consisting of travel statistics for all classifications of roads to observe potential local spillover effects within urbanized areas. I also address the concern, which was presented by Duranton and

[1] The external cost of driving comprises time delays, car accidents, increased fuel consumption, wear to highway infrastructure, and air pollution.

Turner (2011), that changes in data reporting at the urbanized area level may bias estimates of traffic outcomes if reporting changes are correlated with treatment. I find no evidence of this bias within the context of my empirical specification.

Second, I contribute to the growing literature on congestion and environmental quality (Atkinson et al., 2009; Currie and Walker, 2011; Simeonova et al., 2018; Xu et al., 2017). Whereas most existing research has used a limited network of ground-based air quality monitors, I utilize high-resolution, geocoded $PM_{2.5}$ concentrations for the entire U.S. to identify ambient changes directly adjacent to busy interstates as well as within subsystems of urban roads. The ability to observe $PM_{2.5}$ levels for numerous geographic extents again allows me to observe potential spillover effects within urban areas. I find no evidence that HOV or HOT facilities improve air quality. However, given that interstates with HOT lanes are able to handle the increased load without sustaining increases in air pollution, they may also be successful at decreasing $PM_{2.5}$ if priced even higher.

The rest of this paper is structured as follows: Section 2 provides an economic framework for understanding congestion, surveys the existing literature, and introduces existing congestion control instruments; Section 3 provides an outline of my data and methodology. I use a combination of remotely-sensed pollution data, a variety of transportation and economic statistics, and geospatial vector data in tandem with two econometric models for studying congestion; Section 4 provides the results of my regressions and discusses their implications and limitations; Section 5 concludes.

2 The Trouble with Traffic

This study is built upon prior research in urban economics and public finance. In this section, I survey the existing literature on congestion theory and outline the importance of my outcomes of interest within the context of their social costs. Prior findings highlight a critical opportunity for new and innovative approaches to causal research on this subject.

2.1 The Economics of Traffic Congestion

Congestion is a fundamental problem in public finance. It distinguishes common-pool resources from public goods and results in large costs to society. In the context of vehicle travel, traffic congestion occurs because drivers only account for their private marginal cost when making the decision to

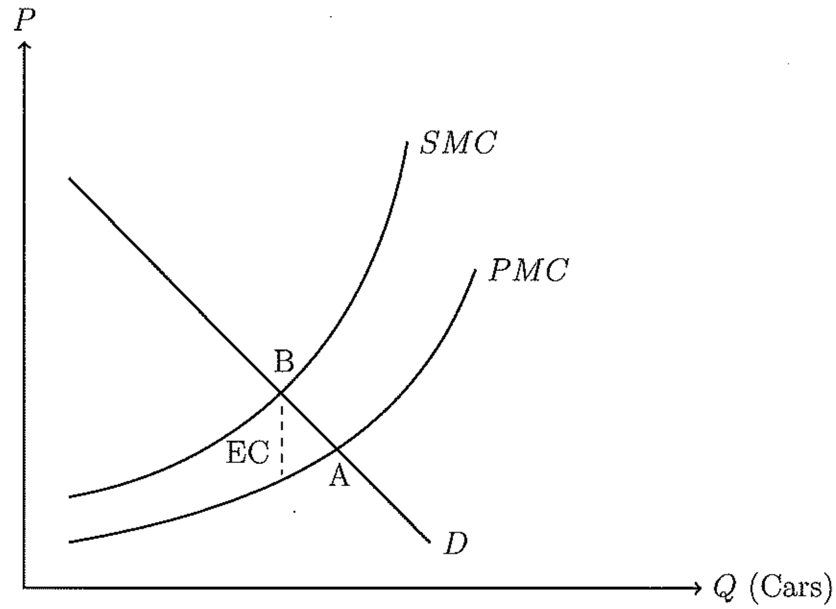


Figure 1: Simple Model of Traffic Congestion

drive. Because public roads are non-excludable and rival in consumption, the social costs of road use are greater than the private costs incurred by drivers. In equilibrium, drivers will consume too much and pay too little - resulting in an external cost equal to the difference between the social marginal cost of their action and their private marginal cost. Figure 1 illustrates this problem where point A is the equilibrium achieved under private decision making, point B is the social optimum where the social marginal cost is equal to demand, and *EC* is the external cost of road use. Vickrey (1969) suggested that external costs tend to vary as the square of traffic volume. As such, the external cost increases in magnitude as more cars enter the roadway.

Policymakers and activist groups often suggest increased investment in roadway infrastructure as a solution to the congestion problem. Under a basic model of supply and demand, the supply (private marginal cost) curve should shift out, the market price of driving should decrease, and equilibrium quantity demanded should be achieved at a lower price. The reality is much more complicated and an overwhelming amount of evidence rejects capacity investment as the solution to congestion (Duranton and Turner, 2011). A number of economists attribute this complication to latent demand for vehicle travel (Arnott and Small, 1994; Cervero and Hansen, 2002).

Latent demand for travel - often referred to as induced demand - occurs because congestion itself results in trips being canceled, diverted to other forms of transportation, or delayed (Arnott and Small, 1994). Duranton and Turner (2011) investigate the effect of lane miles of roads on daily vehicle miles traveled (DVMT) in busy US cities in order to evaluate the latent demand theory.[2] DVMT is widely used as a measure of traffic demand and is equal to

$$\frac{Length \times Vehicles}{Day}$$

where *Length* is the "centerline" road length which does not account for the number of available lanes. Duranton and Turner (2011) found that interstate DVMT has an elasticity with respect to lane miles of 1.03. In other words, DVMT increases proportionately to interstate lane miles. They report a slightly smaller elasticity for other types of roads in urban areas. Cervero and Hansen (2002) conduct a similar study and report an elasticity of 0.59, though their sample was limited to MSAs in California and DVMT was made up of mostly freeways and arterials.[3]

Since capacity investment does little to abate congestion, economists often suggest road pricing as an obvious alternative (Vickrey, 1969). "Congestion pricing" refers to any market mechanism used to force drivers to internalize costs of externalities. The price is set equal to the external cost of road use (a Pigouvian tax) in an effort to force the market toward the socially optimal equilibrium. Congestion pricing takes many forms. A number of cities around the world have introduced congestion pricing zones where fees are charged to cross a certain geographic boundary (Simeonova et al. (2018), Green et al. (2016), and Atkinson et al. (2009)). Others are smaller in scale and enforce prices only on specific lane segments (Xu et al., 2017). The latter policy is more relevant to this paper where my main concern is the introduction of High-Occupancy Vehicle (HOV) facilities in and around busy commuter cities and their occasional conversion to High-Occupancy Toll (HOT) facilities.

An HOV facility is a designated lane (or set of lanes) that is only available to vehicles with multiple occupants.[4] HOV lanes are usually introduced on interstates or busy state routes in and

[2] Lane miles are defined as the length of a given road multiplied by the number of lanes it comprises; Duranton and Turner (2011) report their findings in lane kilometers and vehicle kilometers traveled (KMT).

[3] In the literature and throughout this paper road types are referred to by their FHWA classifications which include "interstates", "other freeways and expressways", "other principal arterials", "minor arterials", "major and minor collectors", and "local roads". See Appendix B for official definitions of each of these road types.

[4] Some cities call these "carpool" lanes or "express" lanes; "High-Occupancy" generally refers to two or more occupants (HOV 2+) but some facilities require at least three (HOV 3+).

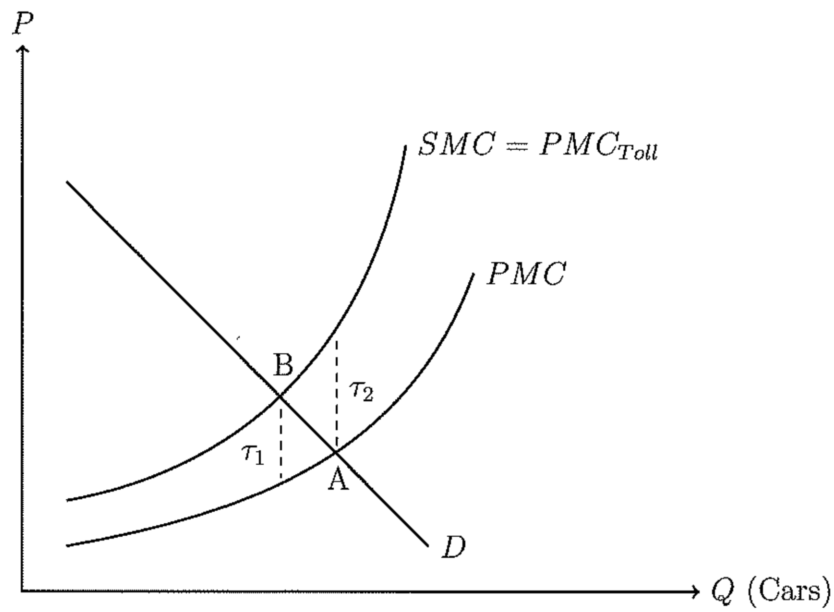


Figure 2: Congestion Pricing with a Dynamic Toll ($\tau_2 > \tau_1$)

around urban commuting zones. The introduction can involve the creation of entire lanes separate from the existing general purpose roadway or re-designating existing general purpose lanes as HOV. While there is no physical cash transaction associated with the use of an HOV lane, it is a pricing mechanism in the sense that drivers must pay the "price" associated with carpool coordination.[5] Single-Occupancy Vehicles (SOVs) can also "buy" access to these lanes in the sense that the fine for being caught in violation is their price.[6]

HOV lanes act as a subsidy for mass transit (Mohring, 1999). By posing SOVs with an opportunity cost, policymakers expect to see a shift towards carpooling, lessening the load on congested interstates. In a number of cases, however, U.S. cities have observed underutilization of HOV lanes and have resorted to selling excess capacity back to SOVs. These types of facilities are called High-Occupancy Toll (HOT) lanes and they dynamically price traffic so that vehicles can maintain a constant, congestion-free speed. As load gets heavier, the price of entering increases. This is illustrated in Figure 2 where τ, a toll equal to external cost, is increasing in Q. A successful pricing

[5]This cost can be broken down into the inconvenience of pick-ups, drop-offs, lack of privacy, etc.

[6]Fines can be expensive and often increase with each transgression. On the I-495 HOV/HOT lanes outside of Washington, D.C., fines begin at $125 for a first offense and increase to $1,000 plus three points on your driving record for a fourth violation. For more see: `http://www.virginiadot.org/travel/hov-rulesfaq.asp`.

mechanism will shift PMC such that PMC_{Toll} is equal to the social marginal cost.

HOT lanes are always introduced at existing HOV facilities and generally involve installation of an electronic toll collection (ETC) system so that vehicles can seamlessly transition onto HOT lanes without stopping at a toll booth. Drivers of HOVs flip a switch on their ETC transponders to indicate that they meet the HOV 2+ or HOV 3+ restriction and to prevent a toll from being collected. Still, the effectiveness of these pricing mechanisms is uncertain and the potential for local spillover effects hinders the ability to predict congestion outcomes.

While the use of pricing to combat negative externalities is often the least expensive solution, congestion pricing remains a topic of much contention. Policymakers and activists note potential regressive distributional impacts on lower-income commuters who must spend a larger portion of their income on travel (Vickrey, 1969; Arnott and Small, 1994). Moreover, some level of congestion is usually optimal - the elimination of congestion entirely would in and of itself create large social costs. These concerns are important within the public finance literature and are deserving of additional research, but are largely beyond the scope of this paper.

Below I outline the potential effects of HOV and HOT policies on daily traffic load. Daily traffic load is measured in units of vehicles per day and is calculated by dividing DVMT by road length. This is not a measure of congestion - it tells us nothing about vehicle speeds or the magnitude of time delays. However, the standard models of congestion provided in Vickrey (1969) and Arnott and Small (1994) suggest that external costs increase with traffic load and so I make predictions under that assumption.

Potential Outcomes of HOV Introduction

The introduction of HOV facilities can come in the form of newly built lanes parallel to existing interstates or as a re-designation of existing lanes. The conversion of existing interstate lanes to HOV lanes is essentially an increase in the price of interstate use for drivers of SOVs. *Ceteris paribus*, this price increase should cause a decrease in the daily traffic load on interstates as a result of behavioral responses from drivers of SOVs. These drivers either stay on interstates but carpool with other drivers or substitute towards other major urban roads or public transportation in order to make their commute.[7] The potential for spillover effects further complicates the policy's outcome.

[7] "Other major urban roads" include "other freeways and expressways", "other principal arterials", "minor arterials", "major and minor collectors", and "local roads".

Forcing SOVs off of the interstate increases the load on arterials, collectors, and local roads. While the objective is for net daily traffic load to decrease, the potential for increased load on non-priced urban roads may compete away net benefits of the policy.

Introducing an HOV facility as a supplement to existing interstate capacity leads to an increase in the total supply of roads. These new lanes are priced higher than the general purpose lanes that they run parallel to because they can only be used by HOVs. There is potential for an increase in interstate load as some vehicles shift to the priced lanes, making room for others to populate the unused capacity. Net outcomes are unclear, however, as induced demand effects have the potential to compete away the price drop generally associated with an outward shift in supply, leading to potential outcomes comparable to the re-designation scenario outlined above (Duranton and Turner, 2011; Cervero and Hansen, 2002).

Potential Outcomes of Conversion to HOT

The price drop associated with conversion to HOT could elicit a number of potential outcomes dependent on local spillover effects between interstates, other major urban roads, and public transportation. Identifying the competing effects associated with an HOT conversion is important in understanding the effectiveness of congestion pricing mechanisms.

With the introduction of HOT lanes at an existing HOV facility, SOVs can use the lanes for a small toll rather than an expensive fine for violation. This raises the opportunity cost of driving an SOV on both general purpose interstate lanes and on other major urban roads. Consequently, interstates may experience an increase in load relative to the load they experience under an HOV policy. This effect is the goal of an HOV conversion which sets out to sell underutilized interstate capacity to drivers of SOVs. The challenge for policymakers is pricing the HOT lanes such that interstate load does not increase relative to the pre-HOV period. Additional increases to interstate load could come from drivers of HOVs and consumers of public transportation who substitute towards SOV use in the presence of the price drop. Substitutions from smaller roads onto interstates could compete away benefits if dynamic pricing is unsuccessful at keeping HOT lane users moving at a constant speed.

The ambiguous effects of these policies and the current lack of causal research on HOV and HOT lanes reiterate the need for a rigorous empirical study. In an effort to better understand drivers' behavioral responses to both an increase and a decrease in road price, I attempt to identify the direction and magnitude of effects on traffic load. Contributing to the understanding of motorists' behavioral responses is an important step towards designing effective congestion controls.

2.2 The Social Costs of Congestion

The most studied externality from traffic congestion is the cost society faces due to time delays. Duranton and Turner (2011) note that American households spend on average almost three hours per day in a motor vehicle and that commuting is among their least preferred activities. Arnott and Small (1994) estimated the social cost of driving delays in the United States at $48 billion annually without even taking into account the costs of extra fuel consumption, inconvenience, accidents, or air pollution. Schrank and Lomax (2007) estimated the cost - with inclusion of costs from extra fuel consumption - at $70 billion annually. Only two years later, Schrank and Lomax (2009) estimated the cost at over $87 billion. Time delay is likely the most studied traffic externality because economists can estimate the monetary value of time delays using foregone wages and increasing fuel prices. It is more difficult to assess the dollar value of costs due to environmental degradation and thus this topic has been addressed less frequently within the congestion literature.

Congestion and Air Pollution

Motor vehicles are large contributors to air pollution in the United States. Pollutants originating from motor vehicles often increase with acceleration, deceleration, and idling - the three activities which best characterize traffic congestion (Currie and Walker, 2011). Abu-Allaban et al. (2007) found that motor vehicles contributed between 20% and 76% of fine particulate pollution ($PM_{2.5}$) in select U.S. urban areas, largely because $PM_{2.5}$ is a byproduct of combustion. $PM_{2.5}$ is regulated under the Clean Air Act due to the role it plays in respiratory illness, premature mortality, and cardiac disease (EPA, 2015).[8] In this regard, the social cost of congestion induced air pollution can be estimated with medical spending data. Currie and Walker (2011), for example, estimated $444 million in avoided medical costs due to reductions in preterm births to women living near toll plazas that were converted to E-ZPass in New Jersey and Pennsylvania.[9]

[8] I further discuss the Clean Air Act and historical $PM_{2.5}$ trends in Appendix B.

[9] E-ZPass is a form of electronic toll collection used to collect payment from vehicles without forcing them to stop. Currie and Walker (2011) found that implementing E-ZPass at existing toll booths helped reduce pollution by allowing vehicles to continue driving at high speeds instead of decelerating and idling in a toll booth queue.

Simeonova et al. (2018) provide evidence of a causal relationship between the implementation of a congestion pricing scheme and reductions in PM_{10} in Stockholm, Sweden. Their paper is convincing and innovative, however, they do not have extensive pre-intervention data and are unable to study $PM_{2.5}$ due to data constrictions. Atkinson et al. (2009) conduct a similar study of the introduction of a congestion pricing scheme in London, UK. They found reductions in PM_{10} after the policy shock, but note that the reductions are still evident during non-pricing hours. Their estimates cannot be interpreted as causal because the introduction of congestion pricing in London coincided with other traffic control and emissions policies. Xu et al. (2017) provide a before and after analysis of HOT lane implementation on Interstate-85 outside of Atlanta, Georgia. They found that an HOV-to-HOT lane conversion was associated with a 40% decline in $PM_{2.5}$ emissions and 30% decline in carbon monoxide emissions in a 1-mile segment of the project corridor. However, this study is a before and after analysis and does not provide causal evidence. Additionally, it is built upon a vehicle emissions simulation model rather than actual monitoring data. Moreover, the authors note that accounting for fleet turnover may imply that emissions actually increased after the conversion. I contribute to this existing literature with new, remotely-sensed $PM_{2.5}$ data and a causal econometric model.

3 Data and Empirical Specifications

I use detailed traffic time-series data in tandem with geocoded pollution levels in order to study traffic outcomes and environmental quality in busy U.S. urban areas.[10] Appendix B provides additional information pertaining to my data and outlines the GIS mapping methods I used to aggregate spatial data.

3.1 Traffic Statistics

I use traffic statistics from the Federal Highway Administration's (FHWA) Highway Statistics series for the period from 1989 to 2016.[11] These data are reported annually to FHWA by each state through the Highway Performance Monitoring System (HPMS) and include "centerline" road length, DVMT,

[10] I use "urban area", "urbanized area", "city", and "commuting zone" interchangeably when referring to urbanized areas officially designated by the U.S. Census Bureau.

[11] Data are not available for 2009; See: `https://www.fhwa.dot.gov/policyinformation/statistics.cfm`.

population, land area, and a number of other characteristics for U.S. urban areas. Road length and DVMT are available for each individual subsystem of urban roads.

In order to observe net effects within each urban area, I aggregate "centerline" miles and DVMT for interstates, other freeways and expressways, other principal arterials, minor arterials, major and minor collectors, and local roads into a measurement of total load such that

$$TotalLoad_{it} = \sum_{class=1}^{6} \frac{DVMT_{class,t}}{Length_{class,t}} \tag{1}$$

where $\{class \in \mathbf{Z} \mid 1 \leq class \leq 6\}$ denotes interstates, other freeways and expressways, other principal arterials, minor arterials, major and minor collectors, and local roads, respectively. I provide the official FHWA definitions of these road types in Appendix B. Interstate load is interstate DVMT divided by interstate length. I refer to roads other than interstates as "other major urban" (OMU) roads. OMU load is the difference between total load and interstate load. Dividing traffic data up into these three categories allows me to observe changes in driver behavior on different subsystems throughout each urban area.

FHWA reports these data for "urbanized areas" which are defined as areas with more than 50,000 people that at a minimum, encompass the land area delineated by the Census Bureau. I use 34 of these cities to generate a panel dataset of traffic statistics. These were chosen because they have major interstates - often in the form of a ring road - with heavy traffic load. These cities also have dense subsystems of other major urban roads. One limitation of using "urbanized areas" is that the official geographic boundaries were changed by the Census Bureau in 2000 and 2010. Some changes in road length and DVMT may be due to increasing the land area of an "urbanized area", potentially biasing my DID estimates. I address this potential bias in Section 4.[12]

3.2 Air Pollution Data and Geoprocessing Methods

This paper distinguishes itself from the existing literature by using new, high-resolution, remotely-sensed air quality data (rather than roadside monitoring data) to identify ambient concentrations of fine particulate matter in U.S. commuting zones. I obtained unreleased, historical $PM_{2.5}$ concentration data from Meng et al. (2019). This dataset consists of geographically gridded $PM_{2.5}$ con-

[12]Duranton and Turner (2011) also make a note of the limitations of using "urbanized areas" due to the inconsistently defined boundaries across time. These limitations prevent them from calculating reliable IV estimates of roadway elasticity of demand within urbanized areas.

centrations at points spanning the extent of North America. Meng et al. (2019) used a combination of chemical transport modeling, satellite remote sensing, and ground-based pollution measurements to generate a 0.01° by 0.01° resolution, georeferenced grid (i.e. spatial points are roughly 1.1 km apart) of yearly-average fine particulate matter concentrations for the period from 1981 to 2016. I make use of their data for the 1989-2016 period.

I use GIS mapping methods to estimate mean $PM_{2.5}$ concentrations within each urban area as well as within a 1 km buffer of the interstate, and outside the 1 km buffer, but within the urban area boundary. Appendix B provides a visual representation of the process.

3.3 Treatment Identification

There are two treatments considered in this study: HOV and HOT introduction in and around U.S. urban areas. Both the introduction of HOV lanes and the conversion of HOV lanes to HOT lanes provide interesting exogenous variation allowing me to study causal effects of congestion pricing on air quality and traffic load.

I chose 34 U.S. urbanized areas from the FHWA Highway Statistics dataset. 12 cities in my sample never implement HOV or HOT lanes during the period of interest (1989 through 2016). 11 cities implement HOV lanes at some point but never convert to HOT. The remaining 11 cities implement HOV and convert to HOT during the period of interest. I identified the year of HOV introduction using a comprehensive FHWA report of all U.S. HOV facilities (FHWA, 2008).[13] Year and month of HOT introduction were identified through individual city transportation authority reports; a full list of sources can be found in Appendix B. There are no cities that introduce HOT lanes without already having an HOV facility. Additionally, all cities that convert to HOT remain treated by HOV for the remainder of the study period.

Table 1 presents descriptive statistics for the treated and untreated urbanized areas. The "Never Treated" category refers to the 12 cities that never implement HOV or HOT lanes during the period from 1989 to 2016. "HOV Only" specifies cities that implement HOV lanes during this period but do not convert any of them to HOT lanes. Finally, "HOV-to-HOT" denotes cities that convert an existing HOV facility to HOT during the observation period. The first column presents the mean $PM_{2.5}$ concentration within the urbanized area (UA) boundaries for each group. The second column

[13]Since this report was released in 2008, I corroborated it with additional sources to ensure that treatment information is still correct.

Table 1: Summary Statistics by Treatment Group

	Year	$PM_{2.5}$ ($\mu g/m^3$)			Traffic Load (1,000s of vehicles/day)		
		(UA)	(< 1 km)	(> 1 km and < UA)	(Total)	(Interstate)	(OMU)
Never Treated	1989	18.51	19.08	18.30	135.91	66.46	69.45
(N=12)		(1.07)	(1.06)	(1.07)	(7.33)	(4.24)	(4.45)
	2016	7.65	7.87	7.56	184.16	95.26	88.89
		(0.15)	(0.14)	(0.16)	(8.86)	(4.55)	(5.14)
	Difference	-10.86	-11.21	-10.74	48.25	28.80	19.44
		(0.31)	(0.31)	(0.31)	(3.32)	(1.80)	(1.96)
HOV Only	1989	16.93	17.70	16.77	171.76	81.89	85.26
(N=11)		(0.99)	(0.93)	(0.99)	(11.05)	(5.80)	(5.83)
	2016	7.12	7.36	7.07	223.68	113.16	110.52
		(0.35)	(0.36)	(0.34)	(16.29)	(7.76)	(10.21)
	Difference	-9.81	-9.57	-9.70	51.92	31.27	25.26
		(0.32)	(0.30)	(0.32)	(5.94)	(2.92)	(3.54)
HOV-to-HOT	1989	17.52	18.29	17.29	221.21	108.28	112.87
(N=11)		(1.59)	(1.61)	(1.57)	(22.52)	(12.06)	(11.81)
	2016	7.54	7.81	7.45	303.92	154.53	147.00
		(0.54)	(0.54)	(0.53)	(23.31)	(11.34)	(12.66)
	Difference	-9.98	-10.48	-9.84	82.71	46.25	34.13
		(0.51)	(0.51)	(0.50)	(9.77)	(5.00)	(5.22)

NOTES: Standard errors are in parentheses. "UA" denotes the Urbanized Area boundary. "OMU" denotes other major urban roads

refers to mean $PM_{2.5}$ concentrations within a 1 km buffer of the interstate and the third column presents the mean outside this buffer but inside the UA boundary.

All three groups experienced large decreases in $PM_{2.5}$ between 1989 and 2016. This is not surprising and is likely due to a combination of increasingly stringent Federal regulations, improvements in vehicle efficiency, and fleet turnover within urban areas. Interestingly, the cities that were never treated had the highest average $PM_{2.5}$ concentrations both in 1989 and in 2016 but also saw the largest declines. Cities that converted HOV lanes to HOT saw larger declines than cities that only had HOV.

While the "Never Treated" cities saw the largest decline in $PM_{2.5}$, they also experienced the smallest increase in daily traffic load. Columns five and six present daily traffic load in 1,000s of vehicles per day for interstates and other major urban roads. "HOV Only" cities saw only slightly larger increases in daily traffic load above the untreated group. Cities that converted from HOV to HOT, however, saw increases almost double those of the other two groups. Whereas total load increased by 48,250 and 51,900 on average in the untreated and "HOV Only" groups, respectively, cities that implemented HOT lanes saw an average increase in load of 82,700 vehicles per day.

While the descriptive statistics in Table 1 do not directly reveal average levels of congestion, it is widely accepted that increases in traffic load are accompanied by increases in external costs (Vickrey, 1969; Arnott and Small, 1994). An additional notable observation is that total traffic load is almost evenly split between interstates and other major urban roads across all groups and years. This is interesting because it indicates that interstates serve as many or more than all other roads combined, further reinforcing the importance of understanding congestion on interstates.

3.4 Generalized Difference-in-Differences

In order to identify a causal relationship between congestion pricing and traffic outcomes or pollution, I administer a generalized difference-in-differences (DID) regression. My empirical specification is different from the standard DID model because treated units in my sample are first exposed to HOV or HOT lanes at different times. Unlike the standard DID, there is no singular "post" period for treated units and no designated "post" period at all for untreated units.

In order to capture a causal effect, I use the two-way fixed effects specification for DID with variation in treatment timing. These fixed effects capture any unobserved heterogeneity across cities and across years. Year-level fixed effects will absorb advancements in vehicle efficiency, vehicle fleet turnover, national economic trends, and other effects that are present in all urban areas, but that vary over time. City-level fixed effects will absorb local attitudes towards driving, climate characteristics, vehicle fleet composition, and other effects that are constant over time but varying across cities.

I use the following equation to estimate the effect of HOV and HOT lanes on my outcomes of interest:

$$y_{it} = \gamma_i + \lambda_t + \beta_1 HOV_{it} + \beta_2 HOT_{it} + \mu \mathbf{X}_{it} + \epsilon_{it} \tag{2}$$

where y_{it} is the outcome of interest, γ_i is a city fixed effect, λ_t is a year fixed effect, HOV_{it} is a dummy equal to 1 if city i is exposed to HOV lanes in year t, HOT_{it} is a dummy equal to 1 if city i is exposed to HOT lanes in year t, and $\mathbf{X}_{it}$ is a vector of city- and year-level control variables. Controls include real unemployment rate, per capita income, and population. The coefficients β_1 and β_2 are the DID estimators for the effects of HOV lanes and HOT lanes on y_{it}.

Outcomes of interest are $PM_{2.5}$ concentrations (in $\mu g/m^3$) and daily traffic load (in 1,000s of vehicles per day). For traffic load, I report net effects within the urban area and effects for interstates. Additionally, I group expressways, principal arterials, minor arterials, collectors and local roads into "other major urban" roads. For $PM_{2.5}$ concentrations, I report effects at the city level, within a 1 km buffer of the interstate, and within the city but outside the interstate buffer.

An alternative specification of this model is used to more closely examine HOT introduction using a weighted dummy for HOT based on the month of introduction. I use the following equation:

$$y_{it} = \gamma_i + \lambda_t + \beta_1 HOV_{it} + \beta_2 WeightedHOT_{it} + \mu \mathbf{X}_{it} + \epsilon_{it} \tag{3}$$

where y_{it}, γ_i, λ_t, and HOV_{it} are defined as in Equation (2). I weight the HOT_{it} dummy from Equation (2) such that

$$WeightedHOT_{it} = \begin{cases} 0 & \text{if } HOT_{it} = 0 \\ \frac{(m-1)}{12} & \text{if } HOT_{it} = 1 \text{ and } HOT_{it-1} = 0 \\ 1 & \text{if } HOT_{it} = 1 \text{ and } HOT_{it-1} \neq 0 \end{cases} \tag{4}$$

where $\{m \in \mathbf{Z} \mid 1 \leq m \leq 12\}$ is the month HOT lanes opened. In the absence of reliable data on opening month for all HOV facilities, HOV_{it} is not weighted. As in Equation (2), $\mathbf{X}_{it}$ is a vector of city- and year-level control variables including per capita income, unemployment, and population.

3.5 Event Study

In order to evaluate pre-treatment effects on air pollution and traffic load, I conduct event study analyses for HOV and HOT introduction. The major benefit of the event study is the ability to display the effects of an intervention graphically and to identify potential signs of selection bias. I regress air pollution and traffic load on a set of binary explanatory variables representing pre-treatment and post-treatment years. Because treated cities are first introduced to HOV and HOT lanes at different times, I normalize observations such that the base year is the year of introduction. I use the following regression to estimate pre- and post-treatment coefficients:

$$y_{it} = \gamma_i + \lambda_t + \sum_{\tau=0}^{m} \delta_{-\tau} D_{i,t-\tau} + \sum_{\tau=1}^{q} \delta_{+\tau} D_{i,t+\tau} + \epsilon_{it} \tag{5}$$

where y_{it} is the outcome of interest, γ_i is a city fixed effect, and λ_t is a year fixed effect. Summations allow for m pre-treatment dummies and q post-treatment dummies. Additionally, since the goal is to identify pre- and post-treatment effects relative to a base year, I set $D_{i,t+\tau}$ equal to 0 when $\tau = 0$. I report the results of these regressions graphically in Section 4 and Appendix A.

4 Empirical Findings and Discussion

4.1 Difference-in-Differences Estimates

Table 2 presents the results of my DID estimation for effects of HOV and HOT lanes on daily traffic load. Column (1) presents effects on total load as defined in Equation (1). I find no statistically significant effect of HOV introduction on total daily traffic load. If anything, estimates are positive but noisy. This finding is contrary to the goal of HOV facilities - to reduce the net load in busy cities by subsidizing mass transit. A potential reason that HOV facilities fail to reduce net load is through substitution away from public transportation. Congestion prevents policymakers from observing the public's true demand for travel and, consequently, overlooking latent demand when designing traffic policies is bound to lead to unintended consequences. Alleviating congestion within a city has the potential to induce demand such that congestion improvements are partially or completely competed away. Another simple explanation for the ineffectiveness of HOV lanes could be that prices are set too low to invoke carpooling on the margin. This suggests that drivers who carpool under HOV were likely already carpooling in the absence of the policy. A potential solution to this would be to use HOV 3+ in place of HOV 2+ in order to invoke carpooling amongst inframarginal drivers.

Columns (4) and (7) break down the net traffic load effects within an urban area into two subsystems. I find no significant effects of HOV introduction on interstates or other major urban roads. Columns (2), (5), and (8) add controls for the real unemployment rate, population, and per capita income, and columns (3), (6), and (9) weight the HOT_{it} dummy by introduction month as in Equation (3). My findings are robust to the addition of both controls and weighting. One limitation of these findings is the inability to identify spillover effects within the interstate subsystem. In most cases, HOV lanes do not comprise all of the interstate lanes, allowing for potential substitutions between priced and non-priced roadways. The insignificant effect of HOV introduction on interstates may be confounded by unobserved behavioral changes occurring within interstate lanes rather than across road systems.

Table 2: DID Estimates - Traffic Load (in 1,000s of vehicles per day)

	Total			Interstate			Other Major Urban		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
HOV	6.938	7.277	7.299	4.308	4.760	4.777	2.523	2.492	2.495
	(5.832)	(5.871)	(5.862)	(3.936)	(3.845)	(3.835)	(2.918)	(3.112)	(3.111)
HOT	8.419	8.972*	10.11*	6.333**	6.439**	7.343**	2.274	2.817	2.957
	(5.047)	(4.743)	(5.050)	(3.052)	(2.990)	(3.207)	(2.690)	(2.412)	(2.529)
N	870	838	838	917	883	883	870	838	838
adj. R^2	0.649	0.635	0.636	0.680	0.665	0.667	0.460	0.453	0.453
City Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Weighted HOT	No	No	Yes	No	No	Yes	No	No	Yes

NOTES: Standard errors are clustered at city level and are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

In the absence of controls, I find no significant effect of HOT conversion on total load. Controlling for unemployment, population, and income, however, does reveal a significant increase of almost 9,000 vehicles per day relative to cites with no HOV or HOT lanes. This increase is primarily driven by the large and significant increase in load on urban interstates. I estimate an increase of about 6,300 vehicles per day on interstates relative to load experienced in the absence of HOV and HOT. These effects are robust to the addition of controls and weighting. While an increase in interstate load relative to HOV would be consistent with the goal of the HOT lanes - to increase use of underutilized interstate lanes - the effects in Table 2 are relative to cities with no lane management at all. Thus, HOT lanes actually have the potential to increase external costs relative to the control scenario. There are a number of potential explanations for the behavioral responses implied by the DID estimates. I identified in Section 2 that the conversion from HOV to HOT lanes imposes an opportunity cost on drivers of SOVs on other major urban roads, potentially drawing them towards interstates. Additionally, commuters who use public transport may find interstates more attractive in light of this price drop.

While the actual effects of HOV and HOT lanes conflict with goals set by policymakers, they are consistent with findings from the behavioral economics literature. Gneezy and Rustichini (2000) suggest that imposing a fine on adverse behavior can have the opposite of the intended effect if there was previously an incomplete contract between users and providers of a resource. To many drivers, the actual price of using HOV lanes is unclear because it is not stated in dollars. The introduction of HOT lanes on existing HOV facilities more clearly defines the social cost of driving and, on the

Table 3: DID Estimates - Air Pollution (μg/m^3)

	UA			< 1 km			> 1 km and < UA		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
HOV	0.386	0.360	0.362	0.387	0.376	0.378	0.378	0.354	0.357
	(0.534)	(0.477)	(0.475)	(0.537)	(0.480)	(0.477)	(0.531)	(0.475)	(0.472)
HOT	0.722	0.823	0.949	0.707	0.810	0.939	0.727	0.825	0.949*
	(0.577)	(0.530)	(0.564)	(0.586)	(0.537)	(0.570)	(0.573)	(0.527)	(0.560)
N	952	884	884	952	884	884	952	884	884
adj. R^2	0.848	0.848	0.849	0.857	0.857	0.858	0.846	0.846	0.846
City Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Weighted HOT	No	No	Yes	No	No	Yes	No	No	Yes

NOTES: Standard errors are clustered at city level and are shown in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

margin, invokes carpooling drivers to shift towards SOVs because it is less expensive to do so.

Because we do not see a significant decrease in load on other major urban roads, it appears unlikely that HOT lanes are pulling many drivers away from this subsystem. This further reinforces the theory that increases in interstate load are driven by substitution away from carpools and public transportation. I further break down the other major roads subsystem into the five classifications it comprises. Table A.1 presents the DID estimations for for this specification. I estimate no significant effects of HOV or HOT on traffic load for any of the roadways that make up other major urban roads. This supports the finding that other major urban roads do not experience significant traffic load change in cities with HOV and HOT lanes. These findings provide further clarification that there are no significant spillover effects within non-prices subsystems. The lack in change at the "other major urban" level is due to insignificant changes in driver behavior at all levels below it, rather than to significant trade-offs between arterials, collectors, local roads and expressways.

Table 3 presents my DID estimates of the effects of HOV and HOT introduction on ambient air quality. In columns (1), (4), and (7), we see that, on average, HOV and HOT lanes do not lead to improvements in ambient air quality. Effects are, for the most part, indistinguishable from zero and are similar across geographic extents. Moreover, these findings are largely robust to the addition of controls and weighting.

Given that HOV lanes do not lead to significant changes in traffic load, it is unsurprising that they also have no effect on air quality. There are two mechanisms through which HOV lanes can affect ambient air quality: contributions to net load and management of vehicle speed. If HOV lanes are able to reduce load as intended, the consequence could be a decrease in air pollution. This could also happen if HOV lanes are able to regulate vehicle speed such that acceleration, deceleration, and idling decrease. Even though HOV lanes have the potential to reduce $PM_{2.5}$ through these two mechanisms, they are not designed with this benefit in mind and thus, in practice, are not priced high enough to reap these benefits.

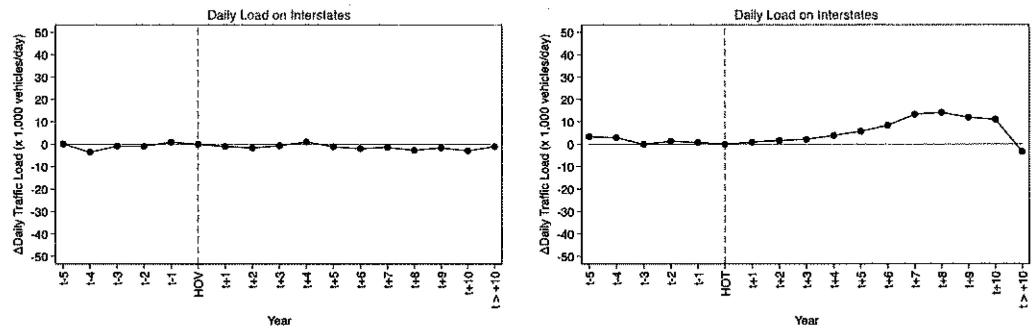
It is interesting that, even in the presence of large increases in interstate load relative to the control scenario, ambient air quality is not affected by HOT introduction and does not significantly increase relative to non-prices cities. This may imply that the dynamic tolling used by HOT lanes is successful at keeping vehicles moving at congestion-free speeds, thereby decreasing acceleration, deceleration, and idling. This would explain why we do not observe an increase in $PM_{2.5}$ within the 1 km buffer of the interstate. While we find no evidence of increased $PM_{2.5}$ within urban areas with HOT lanes, we also observe no improvements. As in the case of HOV lanes, it is unsurprising given that these pricing mechanisms are not designed to cover the social costs origination from air pollution. However, given that interstates with HOT lanes are able to handle the increased load without sustaining increases in air pollution, they may also be successful at decreasing $PM_{2.5}$ if priced even higher.

4.2 Event Studies, Robustness, and Limitations

Figures 3 and 4 present the graphical results of my event studies. I use Equation (5) with 10 pre-treatment dummies m and ten post-treatment dummies q. Additionally, I assign pre- and post-treatment observations where $\tau > 10$ to a "$t < -10$" and a "$t > +10$" dummy, respectively. The visuals plot effects for the five years prior to intervention, and the ten years after the intervention.

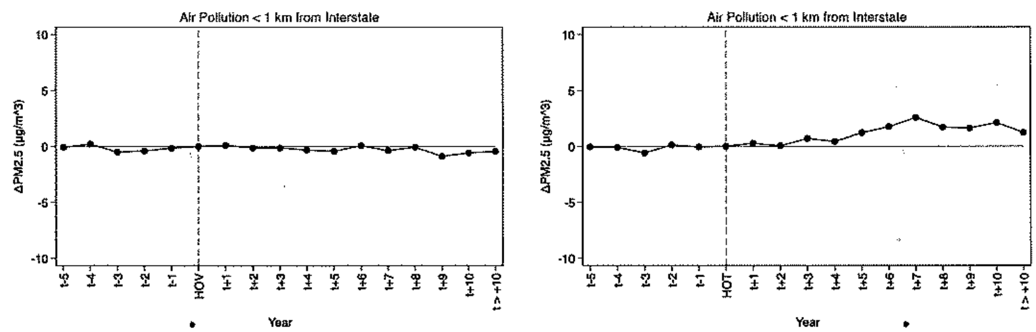
Most importantly, I find no significant evidence of pre-intervention effects on traffic load for HOV or HOT introduction. Consistent with my DID estimates, Panel (a) of Figure 3 shows no significant effect of HOV lanes on interstate traffic load. In Panel (b), we can clearly see the significant increases in interstate traffic load over the course of the post-HOT period. These effects peak eight years after introduction and subsequently begin to diminish. Effects of HOV and HOT lanes on $PM_{2.5}$ concentrations reinforce the DID estimates in Table 3. I identify no significant effects of HOV or HOT on air quality, nor do there appear to be effects in the pre-treatment period.

The remaining event study graphs are presented in Apendix A. Figures A.1 and A.2 identify



(a) HOV Introduction (b) HOT Introduction

Figure 3: Event Study: Traffic load on interstates (in 1,000s of vehicles/day)



(a) HOV Introduction (b) HOT Introduction

Figure 4: Event Study: $PM_{2.5}$ (in $\mu g/m^3$) within 1 km of Interstate

no significant effects of HOV or HOT lanes in for other major urban roads or for total load. These findings further support the DID estimates. Similarly, A.3 and A.4 confirm that there are no significant net effects on pollution within urban areas that implement HOV and HOT lanes. The lack of pre-treatment effects in any of the event study specifications helps address any concerns that selection bias is impacting my DID estimates.

In Section 3 I introduced the FHWA Highway Statistics data series and noted that official U.S. Census Bureau urbanized area boundaries changed in 2000 and 2010. These boundary changes lead to large, sudden changes in road length, DVMT, population and land area. If boundary re-designation is correlated with treatment, the DID estimates of for traffic load may be biased. Sudden changes in load may reflect discrepancies in data reporting rather than causal effects of HOV and HOT lanes. This issue is made more complicated by the differences in treatment timing across urbanized areas.

The direction of bias depends on whether and how many control and treated cities experience boundary changes in the year of treatment. If control cities see a sudden jump in load due to the change in the land area, effects on traffic load in treated cities will be underestimated. Overestimation would occur if land area changes occur in treated cities in the year of treatment. To address this bias, I control for the percent change in land area between years. I find that my estimates are robust to this specification and that percent change in the land area has no significant effect on traffic load. Table A.1 presents the estimates under this specification. These estimates do not include controls for unemployment, income or population, nor do I weight month of HOT introduction.

5 Conclusion

In this paper, I provide some of the first causal estimates of the effects of High-Occupancy Vehicle and High-Occupancy Toll facilities on traffic outcomes and environmental quality. I find little evidence to suggest that HOV lanes incite the behavioral responses intended by policymakers. Additionally, HOT lanes increase interstate load relative to the control scenario and I find no evidence to suggest this alleviates congestion on other major urban roads. I suggest that these estimates, while contrary to policy intentions, are in line with findings in the behavioral economics literature.

These estimates highlight the difficult nature of effective policy design, particularly in the presence of induced demand. While economists largely rely on market mechanisms to combat externalities, in the absence of accurate estimates of market demand, price instruments can lead to large variations in equilibrium quantity. Future research should seek to better understand latent demand for vehicle travel in order to better inform pricing of common-pool resources.

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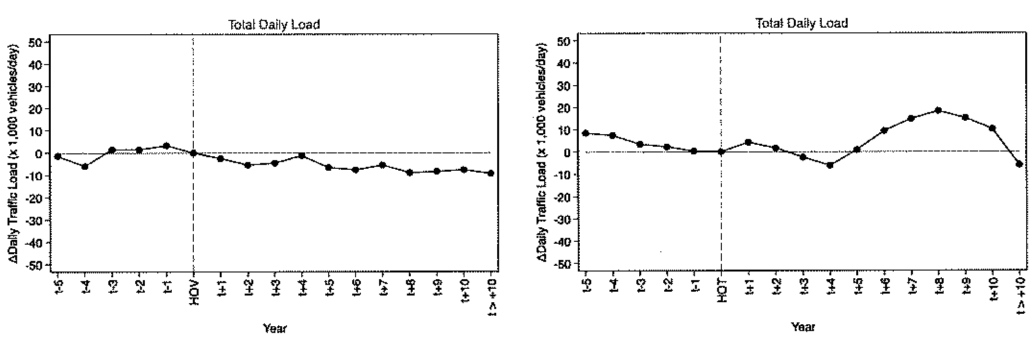
A Additional Figures and Tables

Table A.1: DID Estimates - Traffic Load (in 1,000s of vehicles per day)

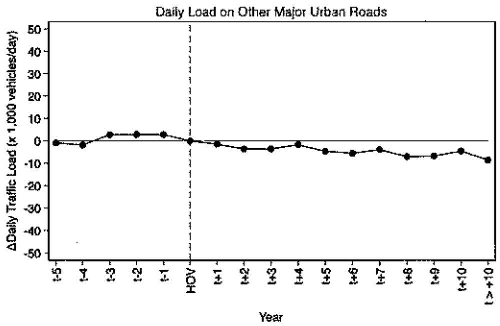
	Total	Interstate	Express	Arterial	Minor Arterial	Collector	Local
HOV	6.880	4.308	2.201	0.275	-0.291	-0.162	0.196
	(5.832)	(3.936)	(2.225)	(0.596)	(0.687)	(0.450)	(0.139)
HOT	8.494	6.333**	1.764	0.656	-0.305	-0.667	0.0778
	(5.035)	(3.052)	(2.679)	(0.547)	(0.636)	(0.423)	(0.0927)
N	870	917	911	917	917	876	917
adj. R^2	0.650	0.680	0.375	0.315	0.203	0.103	0.022
City Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

NOTES: Standard errors are clustered at city level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

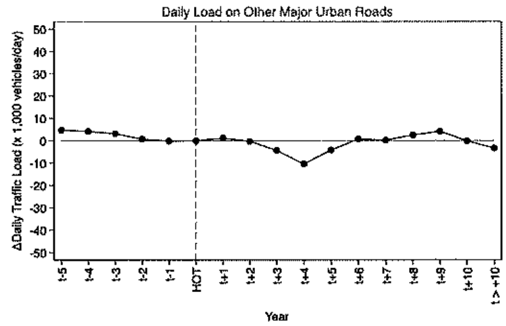


(a) HOV Introduction (b) HOT Introduction

Figure A.1: Event Study: Total traffic load (in 1,000s of vehicles/day)

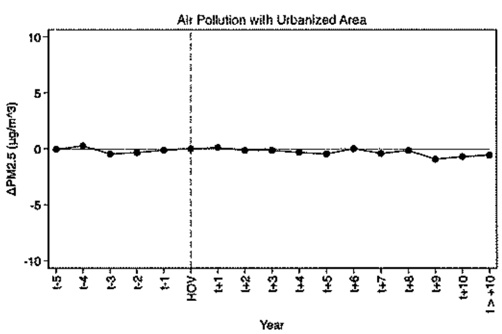


(a) HOV Introduction

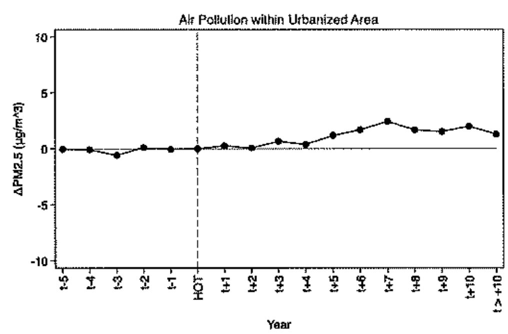


(b) HOT Introduction

Figure A.2: Event Study: Traffic load on other major urban roads (in 1,000s of vehicles/day)

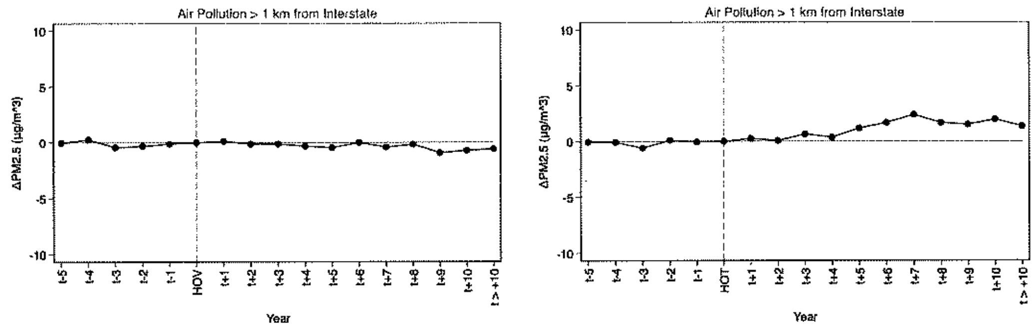


(a) HOV Introduction



(b) HOT Introduction

Figure A.3: Event Study: $PM_{2.5}$ (in $\mu g/m^3$) within Urbanized Area



(a) HOV Introduction

(b) HOT Introduction

Figure A.4: Event Study: $PM_{2.5}$ (in $\mu g/m^3$) more than 1 km from Interstate

Table A.2: DID Estimates - Traffic Load (in 1,000s of vehicles/day)

	Total	Interstate	Other Major Urban
HOV	7.296	4.051	3.297
	(5.629)	(3.645)	(2.973)
HOT	8.661	6.854**	2.315
	(5.152)	(3.029)	(2.941)
$\frac{\Delta LandArea}{LandArea_{i,t-1}}$	-3.776	-1.602	-2.443
	(4.709)	(2.386)	(2.581)
N	758	782	758
adj. R^2	0.645	0.680	0.460
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes

NOTES: Standard errors are clustered at city level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

B Additional Data and Methods

B.1 The Clean Air Act and Historical $PM_{2.5}$

The Clean Air Act of 1970 and the accompanying Amendments of 1977 and 1990 set the foundation for regulating ambient air quality in the United States. The regulation sets minimum standards used to improve human health but individual states can, and often do, set more stringent requirements than those stipulated therein. The Clean Air Act requires the U.S. Environmental Protection Agency (EPA) to define a set of National Ambient Air Quality Standards (NAAQS) to carefully control what are referred to as "criteria" air pollutants. These "criteria" pollutants include ground-level ozone (O_3), carbon monoxide (CO), particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and lead (Pb). The U.S. is split up into "attainment" zones and "non-attainment" zones which, respectively, either meet the ambient air quality standards or are in violation. Each criteria air pollutant has its own standards for attainment EPA (2015).

Air quality in the U.S. has greatly improved over the three decades. Figure B.1 displays trends in $PM_{2.5}$ concentrations from 1989 to 2016 for the cities in my sample. The upper left panel illustrates the trend in annual $PM_{2.5}$ as the mean of 3-year averages of the 34 urbanized areas in my data set. The upper right panel shows the same 3-year average trend but is limited to the 12 cities in my sample without HOV or HOT lanes during the period. The lower left panel shows the 3-year average of the 11 cities that have HOV facilities at some point during the observation period but never implement HOT lanes. Finally, the lower right panel displays the 3-year average trend for the 11 cities in my sample that implement HOT lanes between 1989 and 2016.

In 2012, the EPA revised the primary annual $PM_{2.5}$ standard from 15.0 $\mu g/m^3$ (which had been in place since 1997), to a more stringent 12.0 $\mu g/m^3$. Attainment is achieved when the 3-year average of the annual arithmetic mean does not exceed the standard EPA (2015). Figure B.2 displays a bar chart of the count of cities in my sample that meet the 15.0 $\mu g/m^3$ standard for each year overlaid with the count of cities in the sample meeting the current 12.0 $\mu g/m^3$ standard by year. It is important to note that this does not represent official EPA attainment or non-attainment designation for any of these cities - these graphs are solely based on the 3-year average $PM_{2.5}$ concentration within the urbanized area boundaries in my data set.

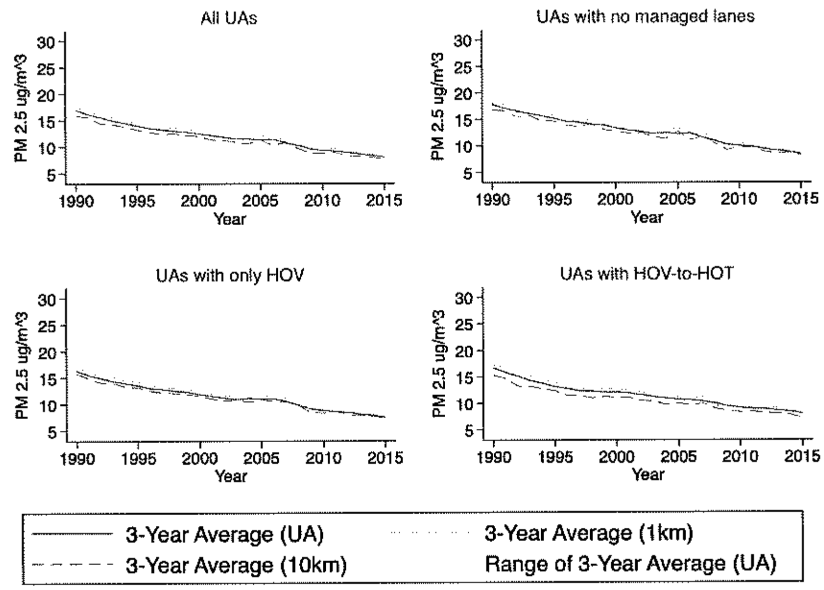


Figure B.1: $PM_{2.5}$ trends for sub-samples of UAs

Note: 3-year averages are used under direction of the National Ambient Air Quality Standards (NAAQS)

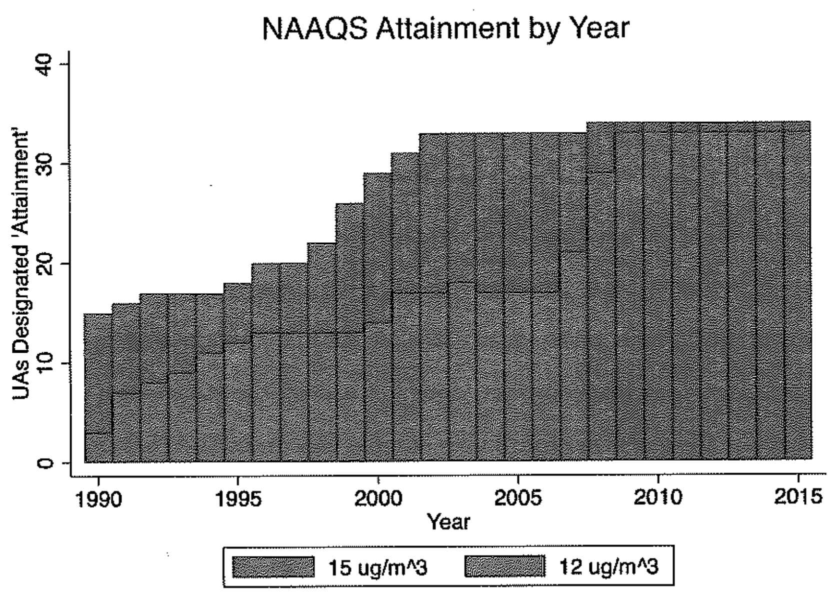


Figure B.2: NAAQS attainment count by year

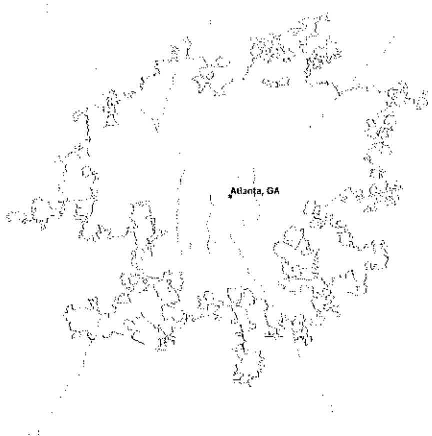
Note: This figure does not represent official EPA "attainment" designation.

B.2 GIS Methods

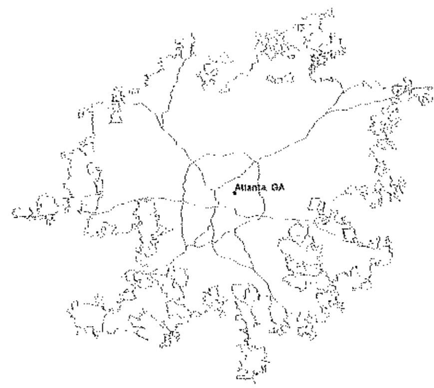
I retrieved spatial data from the U.S. Census Bureau's TIGER/Line database. I use the 2010 urbanized areas shapefile in tandem with a shapefile for U.S. primary roads which was released in 2016. Figure B.4 displays the U.S. primary roads vector dataset with points indicating cities in my sample. This shapefile includes georeferenced vector data of U.S. primary roadways which comprise interstates and U.S. routes.

Panel A of Figure B.3 shows U.S. primary roads overlaid with the raw urbanized area boundary for Atlanta, GA. Using these spatial datasets and GIS software, I clipped the primary roadways vector data to the urbanized area boundaries. The resulting data product can be seen in Panel B. I proceeded to created a 1 km buffer around the interstate. This is displayed in Panel C. I then subtracted this area from the urban area boundary in order to create a shapefile containing only the area within the urbanized area but outside of the interstate buffer. Panel D displays this boundary for Atlanta.

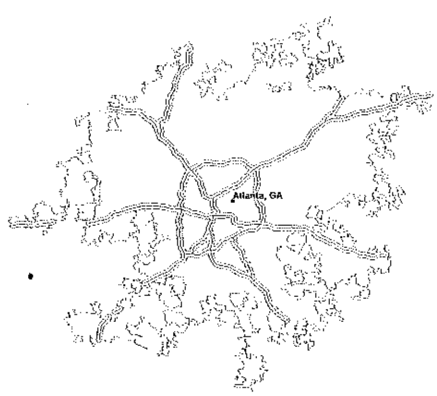
Within the UA boundaries and each of the sub-geometries, I calculated the mean $PM_{2.5}$ concentration for each year from 1989 to 2016 using the gridded pollution concentrations provided by Meng et al. (2019).



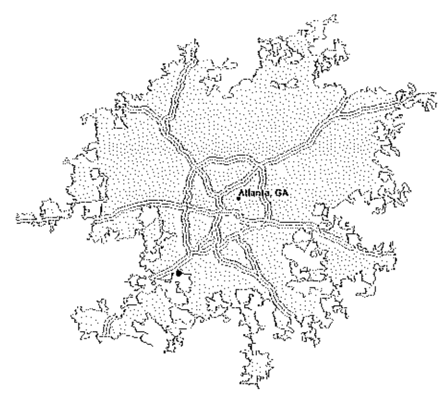
(a) Atlanta Urban Area Boundary



(b) Interstate Clipped to UA Boundary



(c) 1 km Buffer Around Interstate



(d) Outside 1 km Buffer

Figure B.3: Geoprocessing Methods

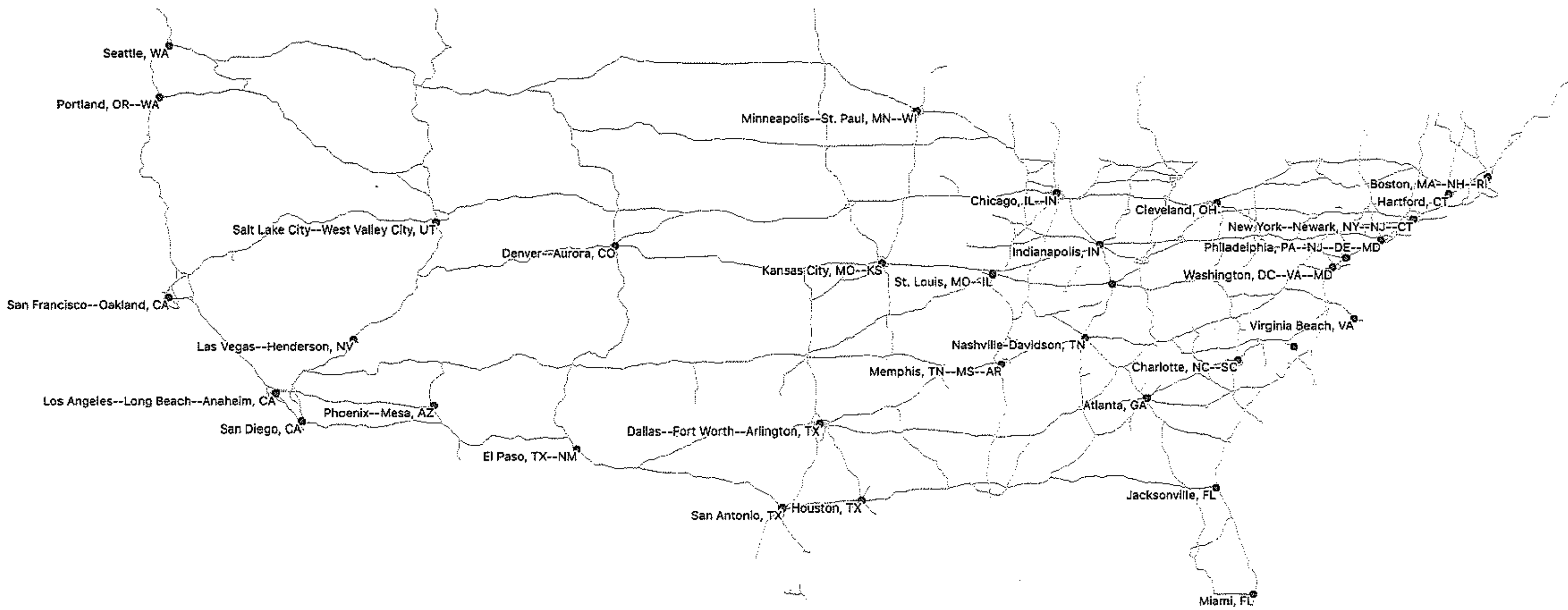


Figure B.4: U.S. Primary Roads and Sample Urbanized Areas

Note: Data from U.S. Census Bureau (2016)

B.3 Additional Data Definitions and Sources

Table B.1: Highway Functional Classifications

	Class (from Equation(1))	Definition
Interstates	1	"A superior network of limited access, divided highways offering high levels of mobility while linking the major urban areas of the United States"
Other Freeways & Expressways	2	"The roads in this classification have directional travel lanes are usually separated by some type of physical barrier, and their access and egress points are limited"
Other Principal Arterials	3	"These roadways serve major centers of metropolitan areas, provide a high degree of mobility and can also provide mobility through rural areas"
Minor Arterials	4	"Minor Arterials provide service for trips of moderate length, serve geographic areas that are smaller than their higher Arterial counterparts and offer connectivity to the higher Arterial system"
Major and Minor Collectors	5	"Collectors serve a critical role in the roadway network by gathering traffic from Local Roads and funneling them to the Arterial network"
Local Roads	6	"Not intended for use in long-distance travel, except at the origin or destination end of the trip, due to their provision of direct access to abutting land"

NOTES: This table includes official road classificationd descriptions from: https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

Table B.2: HOT Treatment Identification

	Date	Route	Source
Atlanta, GA	10/2011	I-85	Xu et al. (2017)
Dallas, TX	10/2014	I-635	Texas A&M Transportation Institute (2016)
Denver, CO	06/2006	I-25	Colorado Dept. of Transportation
Los Angeles, CA	11/2012	I-110	LA Metro: Metro ExpressLanes Performance Update (2013)
Miami, FL	12/2008	I-95	Washington State Dept. of Transportation: Case study of I-95 Express Lanes
Minneapolis, MN	05/2005	I-394	Minnesota Dept. of Transportation
Salt Lake City, UT	09/2006	I-15	FHWA: "I-15 Express Lanes" – I-15, Salt Lake City, UT, HOV to HOT Conversion Project (2010)
San Diego, CA	12/1996	I-15	FHWA:I-15 Congestion Pricing Project Monitoring and Evaluation Services Task 13 Phase II Year Three Overall Report
San Francisco, CA	09/2010	I-680	FHWA: CALIFORNIA: I-680 SMART Carpool Lanes in Alameda County Progress Report (2018)
Seattle, WA	05/2008	SR-167	Washington State Dept. of Transportation: Measuring Delay and Congestion Annual Update
Washington, D.C.	11/2012	I-495	Virginia Dept. of Transportation: Virginia's 495 Express Lanes: Funding, Construction and Operations

NOTES: This table contains the sources I used to identify the introduction date for each HOT facility. There is not currently a well-kept database of this information.