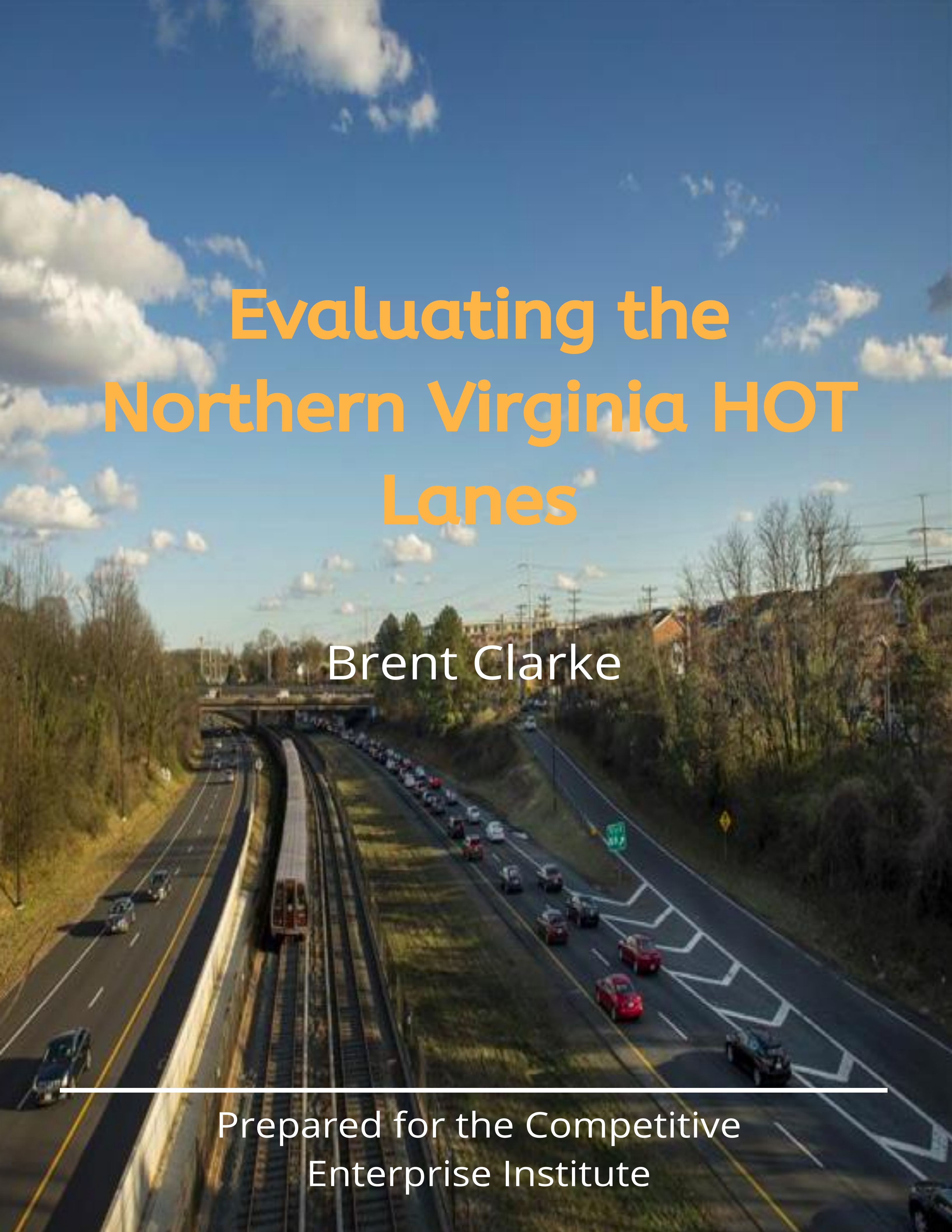
Evaluating the Northern Virginia HOT Lanes



Brent Clarke

Prepared for the Competitive Enterprise Institute

Acknowledgements

There are so many incredible people that have supported me throughout this project. First, I would like to thank Marc Scriber for encouraging me to work on the fascinating topic of congestion pricing and guiding me with his expertise in transportation policy.

Secondly, I thank all of my professors at Batten for driving my intellectual curiosity in public policy. To name a few, Lucy Bassett helped me develop the structure of my project in its early stages and kept me motivated after hitting several dead-ends in the pursuit of data. Leora Friedberg dedicated countless hours providing weekly feedback and helped me think through complex economic and econometric ideas. Finally, thank you to Sally Hudson for sparking my interest in econometric methods and causal inference and giving me the confidence to conduct my own difference-in-differences analysis for this project.

Of course, I also need to thank my friends and family for their support. Sarah Tmimi was always available to answer my many econometrics questions. Oscar Grady and Brianna Clarke provided much needed guidance on graphic design. Lastly, thank you to my dad for saving every *Washington Post* article on HOT lanes.

To each and every one of you, thank you!

Brent Clarke

Client Profile

This project was completed for the Competitive Enterprise Institute (CEI). “CEI is a non-profit public policy organization dedicated to advancing the principles of limited government, free enterprise, and individual liberty. CEI's mission is to promote both freedom and fairness by making good policy good politics” (cei.org).

Disclaimer

The author conducted this study as part of the program of professional education at the Frank Batten School of Leadership and Public Policy, University of Virginia. This paper is submitted in partial fulfillment of the course requirements for the Master of Public Policy degree. The judgements and conclusions are solely those of the author and are not necessarily endorsed by CEI, the Batten School, the University of Virginia, or any other entity.

Honor Pledge

On my honor as a student, I have neither given nor received aid on this assignment.

Brent Clarke

University of Virginia
Batten School of Leadership and Public Policy

Competitive Enterprise Institute

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Acronym Definition

DD: difference-in-differences
GP Lanes: general purpose lanes
HOT Lanes: high-occupancy toll lanes
HOV: high-occupancy vehicle
mph: miles-per-hour
NVTC: Northern Virginia Transportation Commission
PeMS: Performance Management System
SOV: single-occupancy vehicle
VDOT: Virginia Department of Transportation
VMT: vehicle miles traveled
WTP: willingness-to-pay

Executive Summary

In order to address the severe and growing traffic congestion in the Washington D.C. metropolitan area, the Virginia Department of Transportation (VDOT) has implemented a form of congestion pricing called high-occupancy toll (HOT) lanes throughout Northern Virginia. When using HOT lanes, single-occupancy vehicles (SOV) pay a toll that is dynamically priced in real-time based on the current usage of the road, while high-occupancy vehicles (HOV) ride for free. To evaluate the effectiveness of HOT lanes at increasing traffic flow, I conduct a difference-in-differences (DD) analysis comparing weekly speed and car volume trends on I-66 with a relevant comparison interstate, I-395. I find that adding HOT lanes on I-66 dramatically increased the number of miles driven on the interstate each week, while only slightly decreasing average speeds. Comparing my results with those from the literature, which finds that HOT lanes may actually decrease average car volumes on I-66 during peak hours, *I conclude that the I-66 HOT lanes increase the daily commuting capacity of the I-66 corridor*. Specifically, they provide drivers with a reliable, high-speed express lane during peak hours, while also incentivizing more flexible commuters to utilize the interstate outside of peak hours or transition to carpooling or transit.

In addition to analyzing commuting efficiency, I also consider the cost-effectiveness of the Northern Virginia HOT lanes. Given their limited constructions costs and significant time-savings, the I-66 HOT lanes have been a highly cost-effective investment. Alternatively, I find it unlikely that the I-495 HOT lanes are cost-effective, as they would have to save commuters roughly 1,600 hours per day in perpetuity to break even with their expensive up-front construction costs.

Lastly, I evaluate the equity of the Northern Virginia HOT lanes, which are often criticized for having exclusionary prices and being disproportionately utilized by affluent drivers. Ultimately, I conclude that the Northern Virginia HOT lanes have produced equitable results, creating time-savings for commuters on general purpose and substitute roads, while also generating transportation revenue in a more progressive manner than property or sales taxes. The I-66 HOT lanes have been especially equitable, creating roughly $20 million in funding for local transit improvement projects.

Problem Statement

Like many other major urban regions, the Washington, D.C. metropolitan area suffers from severe rush hour traffic, leading to long and unreliable commutes and excessive fuel costs. INRIX, a company that specializes in collecting and analyzing location-based data, ranked D.C. as the 5th most congested metropolitan area in the United States in its 2019 Traffic Scorecard Report (Reed, 2020). In order to manage this congestion, the Virginia Department of Transportation has implemented a form of congestion pricing called high-occupancy toll lanes throughout Northern Virginia. Yet, over seven years after the first HOT lanes were opened, it is still unclear how HOT lanes have changed commuting in the area. This evaluation will attempt to analyze the extent to which the Northern Virginia HOT lanes have improved DC-area commuting in an efficient, cost-effective, and equitable manner.

Background

Understanding the Problem

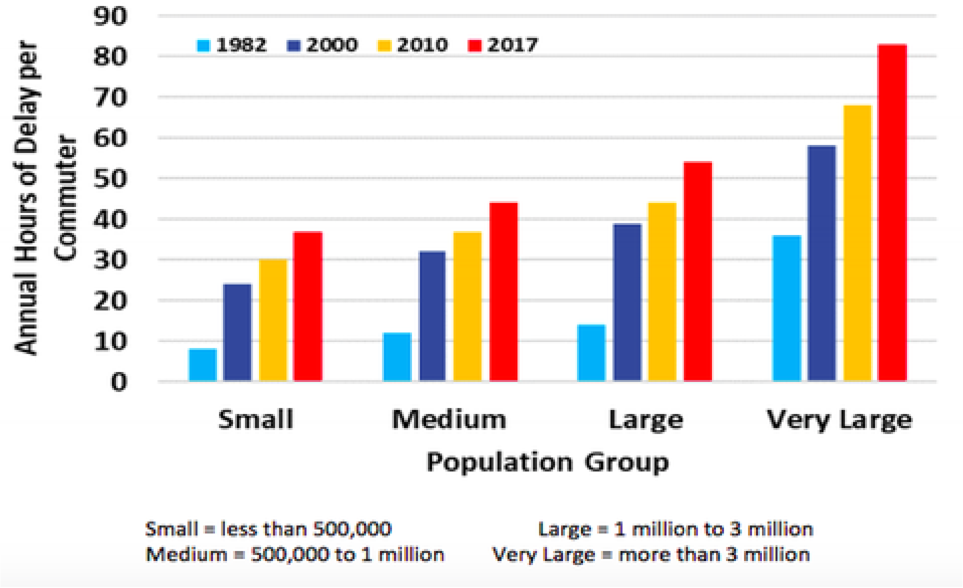
Not only does INRIX rank the Washington, D.C-area as one of the top 25 most congested urban areas in the world, the report also estimates that the average D.C.-area driver sacrifices roughly 124 hours and $1,835 annually from time lost in traffic (Reed, 2020). Similarly, the Texas A&M Transportation Institute ranked the D.C. area as the third worst U.S. region in terms of average delay times and second worst in terms of excess fuel wasted in congestion (Schrank, et. al., 2019).

While the most salient problems caused by congestion are commute-related, congestion also has broader environmental and health-related impacts. Since traffic congestion increases travel time and forces drivers to constantly accelerate and decelerate, vehicles emit more pollutants that degrade air quality, including greenhouse gas (GHG), carbon monoxide (CO), volatile organic compounds (VOCs), particulate matter (PM), and nitrogen oxides (NOx) (Zhang & Batterman, 2014) (Hao, et. al., 2017). This is especially problematic for people who live close to major roadways. One study from the Harvard School of Public Health found that air pollution from traffic congestion in 83 of the nation's largest urban areas is the leading cause of 2,200 premature deaths, increasing national healthcare costs by roughly $18 billion (Levy, 2010). Another study found that traffic-related air pollution can significantly increase the mortality risk of both drivers and the near-road population of major rush-hour roadways (Zhang & Batterman, 2014).

Contextualizing D.C.'s Traffic Congestion Problem

Growing traffic congestion is not a D.C.-specific problem. Data from the American Community Survey shows that the average national commute time has grown consistently over the years, as has the percentage of people making extremely long (greater than one hour) commutes (Ingraham, C., 2017). Moreover, as shown below, congestion growth is not unique to "very large" urban areas like the D.C. area, but has rather grown in regions of all population sizes (Schrank, 2019).

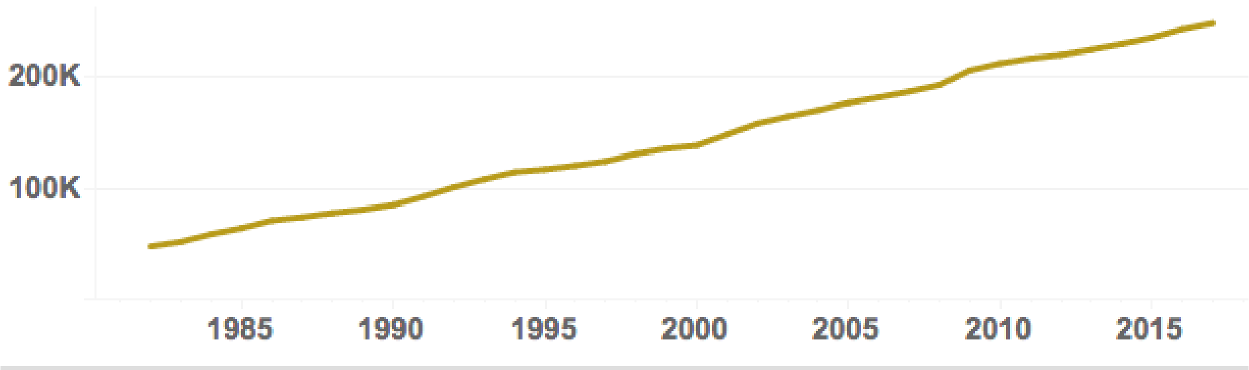
Annual Hours of Delay per Commuter based on Residential Population Size



Source: Schrank (2019), Texas A&M Transportation Institute

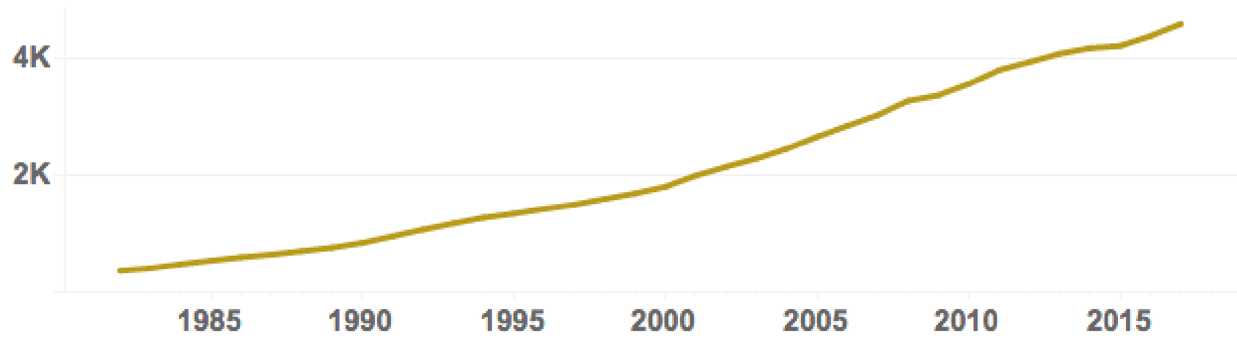
Yet, D.C.-area traffic remains among the worst in the nation and has grown substantially in recent years. As shown in the two graphics below, the Texas A&M Transportation Institute finds that D.C.'s total annual delay times and per-commuter congestion costs have risen dramatically over the past 30 years ("Congestion Data," 2017).

Total Annual Hours of Delay for D.C. Commuters



Source: "Congestion Data" (2017), Texas A&M Transportation Institute

Annual Congestion Costs ($) per D.C. commuter



Source: "Congestion Data" (2017), Texas A&M Transportation Institute

Population growth is largely to blame for increased congestion in the D.C. area. The Weldon Cooper Center at the University of Virginia estimates that Northern Virginia's population grew by about 13% from 2010 to 2018, while the national population only grew by about 6% over that time span ("Virginia Population Estimates," 2019). Moreover, the Cooper Center projects that, by 2040, Northern Virginia's population will have grown by another 30% ("Virginia Population Estimates," 2019). Amazon's decision to locate is second headquarters in Arlington, Virginia, which will bring roughly 25,000 Amazon employees to the area over the next ten years, will only exacerbate this population explosion (Cain & Premack, 2018).

A Potential Solution: HOT Lanes in Northern Virginia

Background

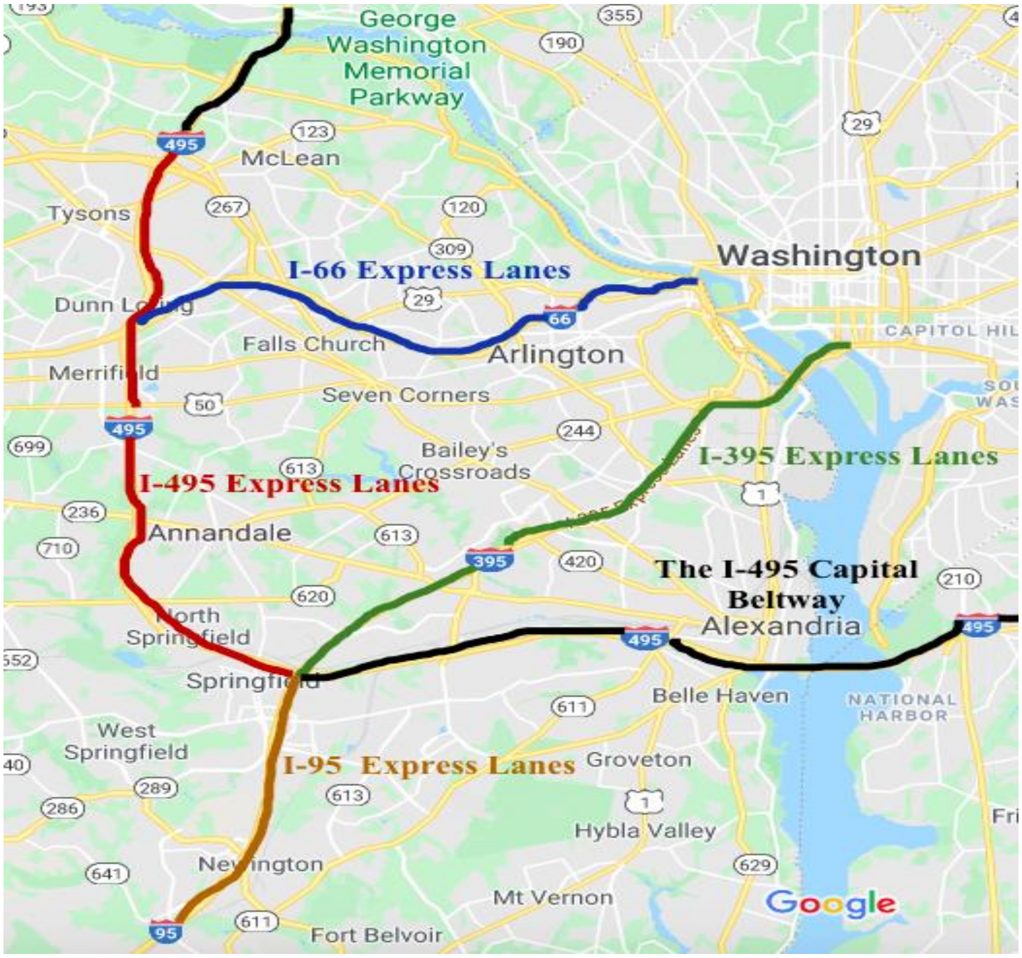
The Virginia Department of Transportation has implemented a form of congestion pricing called high-occupancy toll lanes throughout Northern Virginia to combat congestion. HOT lanes are express lanes where high-occupancy vehicles ride for free, while single-occupancy vehicles must pay a toll that is dynamically priced in real-time based on the current demand for the road. The HOT lane tolling algorithm is designed to maximize express lane usage while still maintaining free-flowing conditions. Therefore, congestion is reduced on general purpose (GP) lanes, while drivers who have a high enough willingness-to-pay (WTP) are able to utilize a reliable express route. SOV drivers pay the toll electronically using an E-ZPass, while HOV drivers designate their high-occupancy status by setting their E-ZPass to HOV mode.

HOT lanes were gradually rolled out across Northern Virginia. Specifically, in April of 2005, VDOT agreed to a deal with Transurban, a private road operator, to operate HOT lanes between Springfield and Georgetown pike on I-495. Construction began in the summer of 2008 and involved an addition of four express lanes (two in each direction) to the interstate. This project cost approximately $2 billion in initial capital costs, with the state of Virginia paying roughly $400 million ("Innovative Finance in Action: Virginia I-495 HOT Lanes," 2009). The I-495 HOT lanes opened on November 17, 2012. Next, on December 29, 2014, VDOT once again partnered with Transurban in opening 29 miles of HOT lanes on I-95. This project involved expanding the express lines by nine miles to Stafford County and adding two reversible express lanes, costing $925 million, with $71 million in state investment ("I-95 Express Lanes," n.d.).

Next, in a slightly different approach, VDOT simply converted the peak-hour HOV lanes on I-66 inside of the Beltway to HOT lanes, instead of adding new express lanes to the interstate's infrastructure. VDOT collects all of the revenue from these express lanes, as opposed to utilizing a public-private partnership with revenue and cost-sharing. Single-occupancy hybrid vehicles, which were previously allowed to use the HOV lanes, now have to pay the toll to use the express lanes. VDOT recently began construction to add a third lane to I-66 inside of the beltway, which it plans to open by 2021. Additionally, VDOT plans on converting I-66 from HOV-2 to HOV-3 by 2022.

Finally, in November of 2019, VDOT and Transurban opened eight miles of HOT lanes on I-395 from near Edsall Road to the 14th Street bridge in Washington, D.C. The project involved converting the two existing HOV lanes to HOT lanes and adding an additional reversible express lane.

Northern Virginia HOT Lanes



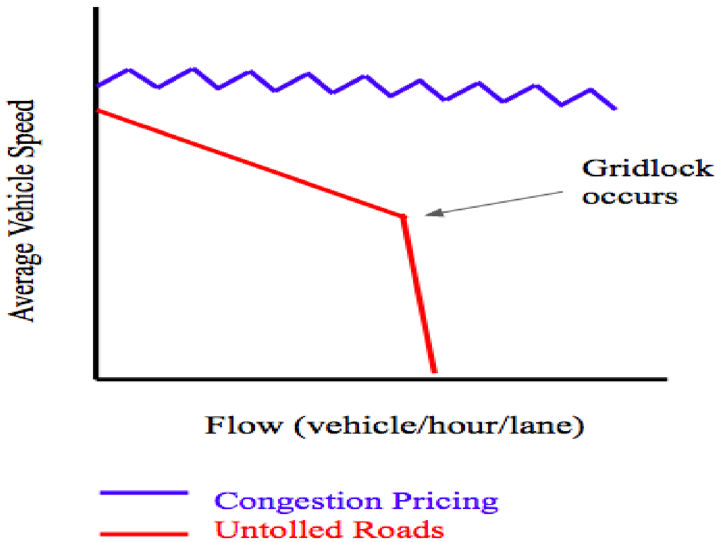
Source: Google Maps

Economic Basis for HOT Lanes

The economic reality of commuting in any major metropolitan region is that the demand for road space usually far exceeds its supply. Moreover, as a public good, roads tend to be over-utilized, since the individual marginal costs of using a road are less than the social marginal costs. Yet, by instituting a user fee pricing mechanism where the costs of using the road are borne directly by the drivers themselves, individual marginal costs are increased to more closely reflect social marginal costs, disincentivizing drivers from over-utilizing the road to the point of gridlock.

As shown by the red line in the model below, drivers on congested interstates typically use the road until it reaches its maximum capacity, at which point vehicle speed and traffic flow decrease to zero. Alternatively, as shown by the blue line, HOT lanes maintain a steady flow of traffic, increasing the cumulative volume of cars that can pass through the interstate while only slight decreasing average vehicle speed (Kutz, 2003). This stable, efficient flow of traffic is achieved by repeatedly pricing out the drivers who would push the interstate into gridlock and more evenly distributing entry onto the interstate across rush-hour.

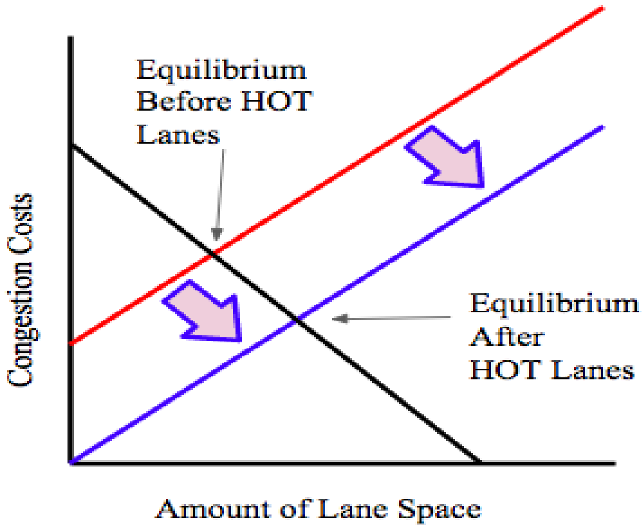
Effect of Congestion Pricing on Speed-Flow Relationship



For the I-66 HOT lane project, the primary goal is to increase peak-hour express lane capacity through the optimization process explained above. Specifically, by attracting SOVs from other roads through a price-based mechanism, as opposed to simply opening the HOV lanes to all drivers, I-66 is able to handle a greater total capacity of cars without significantly reducing speed.

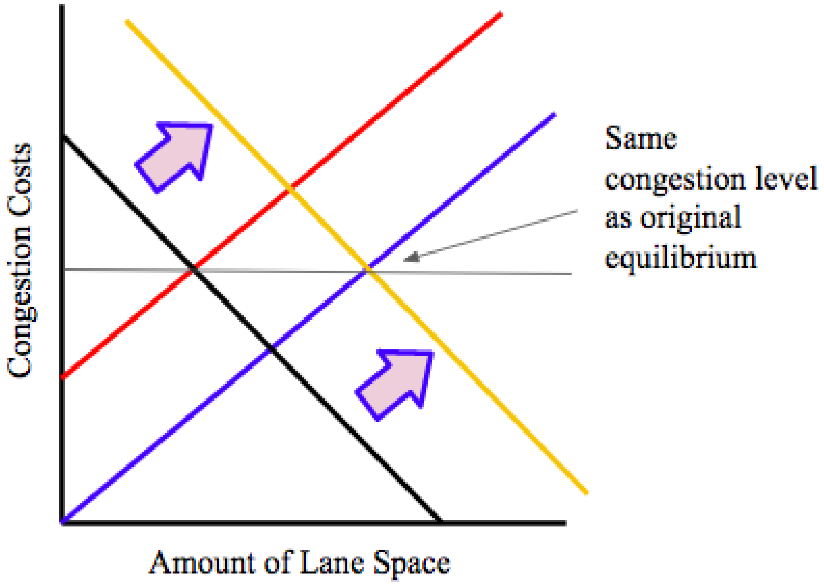
While the I-495/95/395 HOT lane projects also focus on optimizing road usage by converting former HOV lanes to HOT lanes, another goal of these projects is to expand interstate capacity by increasing the supply of roads through constructing new lanes. Specifically, VDOT identified these interstates as being severely under-supplied relative to their regional demand. Thus, as shown in the model below, VDOT has sought to bring the supply of roads closer to a more efficient market equilibrium.

Effect of Lane Expansion on Congestion



When operating efficiently, newly constructed lanes can reduce congestion by giving cars more room to operate. However, as shown in the model below, if these new express lanes induce a greater demand for the interstate by attracting drivers who otherwise would not have used the road, this reduction in congestion is offset. Thus, road expansion projects are often highly cost-ineffective and inefficient, merely increasing the volume of traffic on an interstate without reducing congestion. With that being said, as cities grow and more people need to enter urban areas, increasing interstate capacity without significantly reducing congestion may still achieve the goal of increasing the economic productivity of the area by ensuring that more commuters can enter the city.

Effect of Lane Expansion on Congestion with Induced Traffic Demand



Reviewing the Literature on Congestion Pricing Effectiveness

Overview

In 1991, Congress authorized the Congestion Pricing Pilot Program (now called the Value Pricing Pilot Program [VPPP]) to investigate the effectiveness of congestion pricing strategies at reducing roadway congestion ("Value Pricing," 2019). Consequently, numerous states have implemented congestion pricing projects, both as permanent policies and for study purposes. The most common congestion pricing policies involve expanding roadways by constructing high-occupancy toll lanes (like the I-495 Express Lanes) or converting underutilized high-occupancy lanes to HOT lanes (like the I-66 Express Lanes). Currently, nine states have implemented HOT lane policies in an attempt to limit traffic around major metropolitan cities, including San Diego, Atlanta, Miami, Seattle, and Minneapolis (Urban Land Institute, 2013).

Evaluations of these programs have consistently produced positive results, suggesting that HOT lanes immediately alleviate roadway congestion (Wood, et. al., 2016) (Poole & Orski, 1999) (Urban Land Institute, 2013) (Krol, 2016). Specifically, HOT lanes have been found to attract a substantially higher volume of vehicles than previously underutilized HOV express lanes, while also maintaining free-flowing conditions and more evenly distributing usage of the express lanes across the duration of rush hour (Wood, et. al., 2016) (Supernak, et. al., 2001). Research also suggests that HOT lanes often decrease congestion on a highway's general purpose, non-express lanes (Wood, et. al., 2016) (Poole & Orski, 1999). Lastly, while there is often initial public opposition to HOT lanes, public support of congestion pricing tends to grow with time (Krol, 2016).

San Diego's award-winning Interstate-15 is an exemplar of effective HOT lane implementation. In 1996, the San Diego Association of Governments (SANDAG) launched a landmark three-year study to investigate the effect of converting the previously under-utilized HOV-2 lanes on I-15 to HOT lanes. Ultimately, Supernak, et. al. found that express lane utilization increased by 48% over the three-year study period, while the average commuter saved roughly 20 minutes on I-15's non-express lanes during the worst periods of traffic congestion (Supernak, et. al., 2001). Moreover, the project's high level of revenue helped fund a new express bus service, in addition to increasing police enforcement on I-15. Lastly, at the conclusion of the program, more than half of I-15 carpoolers and over 90% of regular users of the express lanes thought the project was a success (Supernak, et. al., 2001).

While the literature largely confirms that HOT lanes are effective at reducing congestion, there are potential negative consequences of HOT lane implementation. First, some argue that HOT lanes are primarily utilized by affluent drivers, while low-income drivers are forced to continue using the highway's GP lanes, which can remain congested (Southern Environmental Law Center, 2013) (Ecola & Light, 2009) (Brownstone, et. al., 2003). Yet, even if this is the case, HOT lanes still produce positive benefits for non-express lane users.

First, if HOT lanes are predominantly utilized by high-income drivers, collecting transportation revenue through high-occupancy tolls is more progressive than generating revenue from sales or property taxes (Bipartisan Policy Center, 2010). Moreover, revenue from congestion pricing initiatives is often allocated to transit improvement projects; in fact, the Northern Virginia Transportation Commission (NVTC) recently approved $20 million in transit improvement projects funded by the I-66 HOT lanes (Repetski, S., 2019). Furthermore, given that HOT lanes often improve overall levels of congestion on highways, drivers using non-express lanes are still left better off under congestion pricing systems (Wood, et. al., 2016). Lastly, some congestion pricing proposals have included tax credits for low-income drivers; for example, New York City's congestion pricing proposal includes a tax credit for drivers earning less than $60,000 per year (Paybarah, 2019).

Next, while many claim that HOT lanes reduce vehicle emissions by limiting stop-and-go traffic, this may not always be the case. There is a vast literature that shows positive environmental impacts of congestion pricing schemes; however, most of these studies evaluate Cordon pricing schemes, not HOT lanes (Ecola & Light, 2009). Cordon pricing involves paying a toll for driving into a designated zone or city, thereby reducing the overall amount of car travel into those areas. Alternatively, HOT lanes have been shown to increase overall vehicle usage, since the road is capable of effectively handling more cars, and former HOV carpoolers convert to single-occupancy vehicle travel (Supernak, et. al., 2001) (Wood, et. al., 2016). Thus, more research needs to be conducted on HOT lanes to evaluate the net change in vehicle emissions resulting from more efficient traffic flow but greater overall car volumes.

Another potential consequence of HOT lane policies is that they run the risk of revenue shortfalls. Government officials in Houston, Atlanta, and Seattle have consistently overestimated HOT lane revenue (Jaffe, 2013). For example, the "worst-case" revenue estimate for the SR-167 HOT lanes in Seattle overstated toll revenue by almost $2 million in 2012 ("SR 167 HOT Lanes," 2019). Yet, this is most likely attributable to the steep learning curve of HOT lanes (Jaffe, 2013). It takes time for drivers to adjust to and understand the new tolling system, and transportation planners need time and data in order to optimize the tolling price algorithm. By 2018, the SR-167 revenue estimate was within $100,000 of the actual revenue total ("SR 167 HOT Lanes," 2019). Moreover, even if HOT lane revenue remains difficult to predict, they still remain cost-effective; when the SR-167 revenue was overestimated by millions of dollars, it still produced a fiscal gain for the Seattle government ("SR 167 HOT Lanes," 2019).

Overall, this literature review has demonstrated general academic and public support for HOT lane policies. While there may be varying effects for different localities, HOT lanes tend to increase express lane utilization, while decreasing overall congestion. The primary argument against HOT lanes is that they disproportionately benefit the wealthy; however, HOT lanes are generally a net-positive for low-income drivers too, and there are additional policy mechanisms that can be utilized to address equity concerns.

Literature Review of Northern Virginia HOT Lanes

The I-495 HOT Lanes

Given that the I-495 HOT lanes are managed by a private road operator, there is limited public data available for analysis. One study, published by Venkatanarayana and others at VDOT, analyzes post-implementation changes in travel speed and traffic volume on I-495 and nearby arterial roads six months after HOT lane implementation (Venkatanarayana, et. al., 2014). As referenced in the table below, they find that average speed and volume increased dramatically for the interstate as a whole, especially in the northbound direction. The express lanes account for a higher proportion of these speed and volume increases, but the GP lanes are, at worst, unaffected by the HOT lane policies. Specifically, in the A.M. peak period, the added lane space does appear to induce greater demand for the GP lanes, offsetting potential increases in speed from the lane expansion. In the P.M. period, however, the lane expansion does not induce greater traffic demand for the GP lanes, leading to dramatic increases in speed. Moreover, the study found no discernible change in speeds on nearby arterial roads.

Percent Change in Traffic Volume and Speed on I-495N/S after HOT Lane Implementation

	AM Peak	PM Peak	All day	Notes
Traffic Volumes	+9% (SB) +29% (NB)	+13% (SB) +10% (NB)	+10% (SB) +15% (NB)	GP and Exp Lanes (TMS data)
	+4% (SB) +8% (NB)	-2% (SB) 0% (NB)	+3% (SB) +5% (NB)	GP Lanes (TMS data)
Traffic Speeds	+2% (SB) +36% (NB)	+9% (SB) +44% (NB)	-	GP and Exp Lanes (Inrix data)
	+1% (SB) -1% (NB)	+30% (SB) +15% (NB)	-	GP Lanes (Transurban data)

Source: Venkatanarayana, et. al. (2014), VDOT

The I-66 HOT Lanes

Reports published by VDOT suggest that the I-66 HOT lanes are incentivizing more efficient commuter behavior. Specifically, one study published in December of 2018 found that the average rush hour speed increased by nearly nine miles-per-hour after HOT lanes were implemented (Lazo, L. & Harden, J., 2018). Additionally, while the study found that there were substantially fewer vehicles on I-66 during peak-hours, it attributes this decrease in car volume to an increase in carpooling, greater Metro ridership, and shifts in commuter timing to avoid I-66 during peak hours. Each of these changes in commuter behavior are positive indicators that the tolls are working as they should. With that being said, average traffic volume on Route 29, a substitute arterial road, increased by about 4.6% after HOT lane implementation, suggesting that the decrease in peak-hour car volume on I-66 is partly attributable to negative spillover onto other routes.

Another VDOT study published in February of 2020 supports many of these findings. Specifically, it found that, since HOT lane implementation, the I-66 corridor inside of the Beltway has accommodated roughly 700 more commuters each day, while reducing the total number of vehicles during morning peak-hours (Smith, 2020). Similarly, the study found slight increases in carpooling and transit ridership, suggesting that much of the interstate's gains in efficiency are attributable to drivers commuting before or after the peak-hour period. It is important to note that all of the aforementioned studies of the Northern Virginia HOT lanes are simple before-and-after comparisons; thus, while the introduction of HOT lanes certainly produced many of these observed changes, there is uncertainty regarding the level of causality that we can attribute to HOT lane implementation. I therefore hope to contribute to this literature by offering an analysis that controls for exogenous factors and isolates the causal effect of HOT lane implementation on I-66.

Empirical Methods for Evaluating Congestion Pricing Policies

There have been a variety of empirical techniques employed to analyze the effects of HOT lane implementation. First, Supernak, et. al. conduct an informal difference-in-differences approach by comparing pre-and post-implementation traffic patterns on San Diego's I-15, where HOT lanes where introduced, and a nearby corridor, I-8 (Supernak, et. al., 2001). Specifically, they find that the introduction of HOT lanes to I-15 reduced overall congestion levels and average commute duration, while also limiting emissions growth in the nearby area. However, there are potential drawbacks to this empirical approach. First, Supernak, et. al. fail to mention potential spillover effects between I-8 and I-15. Additionally, they note how there was significant residential development in San Diego at the time of the study, suggesting that the historical, pre-implementation data that was utilized may not provide a reliable comparison benchmark.

Other researchers have applied even more rigorous econometric approaches when evaluating HOT lane policies. As opposed to simply measuring average commute duration, Liu, et. al. evaluate the reliability of HOT lanes by measuring the amount of variation in congestion levels (Liu, et. al., 2011). By constructing time-based, speed-volume diagrams, they find that the average vehicle speed on HOT lanes decreases more rapidly during peak hours than baseline models would predict. Overall, though, HOT lanes are effective at producing reliable transportation routes, maintaining average speeds of 45 miles per hour or higher for 95% of peak hours.

Gross and Brent take a more microscopic approach by analyzing how drivers individually respond to changes in the toll rate (Gross and Brent, 2017). Given that HOT lanes are designed to maintain free-flowing conditions at all times, one would hope that drivers are sensitive to toll rate changes and decrease their HOT lane usage as the toll rate increases. Using data from the SR-167 express lanes in Seattle, which delivers updated HOT lane prices and car volumes in five-minute increments, Gross and Brent conduct a time-series regression. After correcting for autocorrelation in traffic patterns by first-differencing (FD) the data, they find that incremental increases in HOT lane rates significantly decrease HOT lane usage. Specifically, a 10% increase in the toll rate produces a 2% reduction in HOT lane usage. This challenges a number of previous studies that found opposite results, largely because of a failure to fully control for the fact that HOT lane traffic volumes are inherently higher during peak hours, when the HOT lane prices are higher.

Lastly, both Small et. al. and Brownstone et. al. measure the extent to which HOT lanes have heterogeneous effects for different types of drivers. Specifically, using a logit model that predicts the probability of using HOT lanes, Small et. al. estimate the relative consumer surplus gains of various HOT lane policies for different strata of drivers constructed by age, sex, household size, per-capita income, total trip distance, and trip purpose (Small, et. al., 2006). Alternatively, Brownstone et. al. utilize a revealed preference approach to demonstrate how various socio-economic indicators help predict a driver's willingness-to-pay to utilize HOT lanes (Brownstone, et. al., 2002). Unsurprisingly, both studies found significantly higher gains from congestion pricing for higher-earning drivers commuting to work.

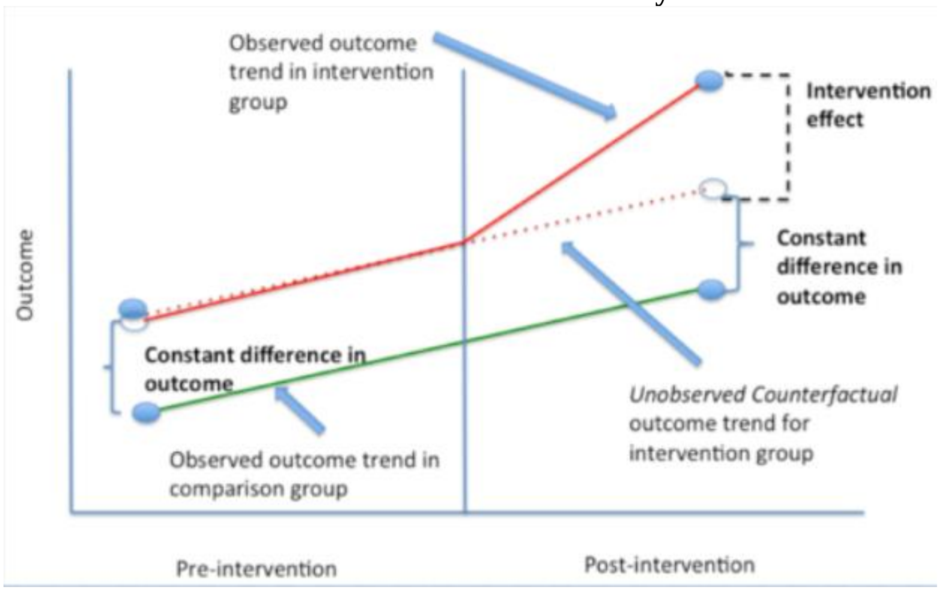
Ultimately, there are a variety of ways to evaluate the effectiveness of congestion pricing. Depending on whether an analyst's focus is on aggregate traffic impacts, commute reliability, the environment, or equity, the appropriate econometric approach will vary significantly. Moreover, as evaluation strategies become more rigorous and complex, they often lose transparency, presenting a tricky balance that researchers must consider when producing their analysis.

Evaluating HOT Lane Effectiveness Using Difference-in-Differences Analysis

Methodology

In order to analyze the effectiveness of HOT lanes at optimizing traffic flow, I conduct a series of difference-in-differences analyses comparing traffic trends on I-66 and I-395 before and after HOT lane implementation on I-66.[1] By employing the DD technique, I am able to implement a quasi-experimental research design that, under reasonable assumptions, isolates the causal effect of HOT lane implementation from other events that impact traffic. Specifically, as shown in the graphic below, by using an appropriate counterfactual, researchers can estimate the causal effect of a treatment by comparing actual post-implementation results with what would have occurred if the treated group had continued on the same trend as the counterfactual (Columbia School, n.d.).

Difference-in-Differences Analysis



Source: "Difference-in-Difference Estimation," Columbia University Mailman School of Health (2020)

Traffic is often highly responsive to population changes and regional factors, like weather and sporting events; yet, by comparing relative changes in traffic between I-66 and I-395, I am effectively controlling for confounding factors unrelated to HOT lane implementation that both interstates simultaneously experience. I assume that I-66 and I-395 are appropriate comparison groups because they are exposed to the same regional events by being in close proximity, yet they are rarely used as substitute routes, meaning HOT lane implementation on I-66 should not directly impact traffic on I-395.

The specific traffic data I analyze are average speed (measured as miles-per-hour [mph]) and total vehicle miles traveled (VMT) on each interstate from December 25, 2016 to December 9, 2018 (HOT lanes were implemented on I-66 on December 4, 2017). All of the data is extracted from the Virginia Department of Transportation's Performance Measurement System

[1] Unfortunately, the same DD analysis cannot be conducted for I-495, since the PeMS database lacks data beyond 50 days prior to HOT lane implementation on I-495.

(PeMS) and collected in weekly, time-series form. VMT is effectively a measure of volume, since it captures how many miles are driven on an interstate for a fixed period of time, while speed measures the rate at which the average driver is traveling. By comparing relative changes in speed and volume, I am able to assess *whether* I-66 is operating more efficiently overall and *how* it is operating more efficiently. In other words, an interstate can achieve greater efficiency through either increased volume or increased speed, as long as the gains to one proportionally outweigh the losses to the other.

The formal equation for these DD regressions takes the following form: $Y_{mph/VMT} = \alpha + \beta \mathit{I\text{-}66} + \gamma \mathit{Post} + \delta\, (\mathit{I\text{-}66} \times \mathit{Post}) + \varepsilon_{mph/VMT}$, where α is equal to the average weekly mph/VMT for I-395 before HOT lanes were implemented; β is equal to the difference in average weekly mph/VMT between I-66 and I-395 before HOT lanes were implemented; γ is equal to the difference in average weekly mph/VMT before and after HOT lanes were implemented; δ is equal to the causal effect of HOT lane implementation on I-66's weekly average mph/VMT; and ε is an error term accounting for unexplained variation in each interstate's average weekly mph/VMT.

In addition to this simple DD analysis, I run additional regressions controlling for anticipation effects. Specifically, commuters may have adapted their behavior prior to implementation, perhaps due to uncertainty over the timing of implementation or merely to test alternate routes to be prepared for the policy change. Additionally, construction of the new tolling signs could have produced increased congestion on I-66 prior to implementation. I control for these potential anticipation effects by excluding all observations 15 weeks prior to implementation.

Lastly, I also utilize the event study approach, which assesses whether statistical differences occur between I-66 and I-395 at various intervals in the pre and post-implementation periods. Specifically, I produce an interaction term between the interstate indicator variable and a month variable produced for each 4-week interval. By running a regression on speed and vehicle miles traveled on each interaction term for both the before-and-after implementation intervals, I am able to assess the proportion of periods before the HOT lane intervention that are statistically different and whether the introduction of HOT lanes was an impactful intervention. This regression takes the following equation form: $Y_{mph/VMT} = \alpha + \beta \mathit{I\text{-}66} + \gamma \mathit{Month1} + \gamma \mathit{Month2} \ldots \gamma \mathit{Month26} + \delta\, (\mathit{I\text{-}66} \times \mathit{Month1}) + \delta\, (\mathit{I\text{-}66} \times \mathit{Month2}) + \ldots\, \delta\, (\mathit{I\text{-}66} \times \mathit{Month26}) + \varepsilon_{mph/VMT}$.

Accounting for Spillover Effects

In addition to measuring the impact of HOT lane implementation on I-66, itself, I also estimate its spillover effect onto I-495. This spillover analysis involves the same DD structure as the previous analysis, comparing speed and volume on I-495 and I-395 before and after I-66 implemented HOT lanes. Similar to the previously mentioned equation, this regression takes the following form: $Y_{mph/VMT} = \alpha + \beta \mathit{I\text{-}495} + \gamma \mathit{Post} + \delta\, (\mathit{I\text{-}495} \times \mathit{Post}) + \varepsilon_{mph/VMT}$, where I-495 is now the treatment interstate, while the intervention is still I-66 HOT lane implementation. Moreover, I run additional regressions controlling for anticipation effects as mentioned above. Lastly, I again support the simple DD analysis with the event study approach, assessing the proportion of statistically different intervals in the pre and post-implementation periods. This regression takes the following equation form: $Y_{mph/VMT} = \alpha + \beta \mathit{I\text{-}495} + \gamma \mathit{Month1} + \gamma \mathit{Month2} \ldots \gamma \mathit{Month26} + \delta\, (\mathit{I\text{-}495} \times \mathit{Month1}) + \delta\, (\mathit{I\text{-}495} \times \mathit{Month2}) + \ldots\, \delta\, (\mathit{I\text{-}495} \times \mathit{Month26}) + \varepsilon_{mph/VMT}$, where I-495 is now the treatment interstate, while the intervention is still I-66 HOT lane implementation.

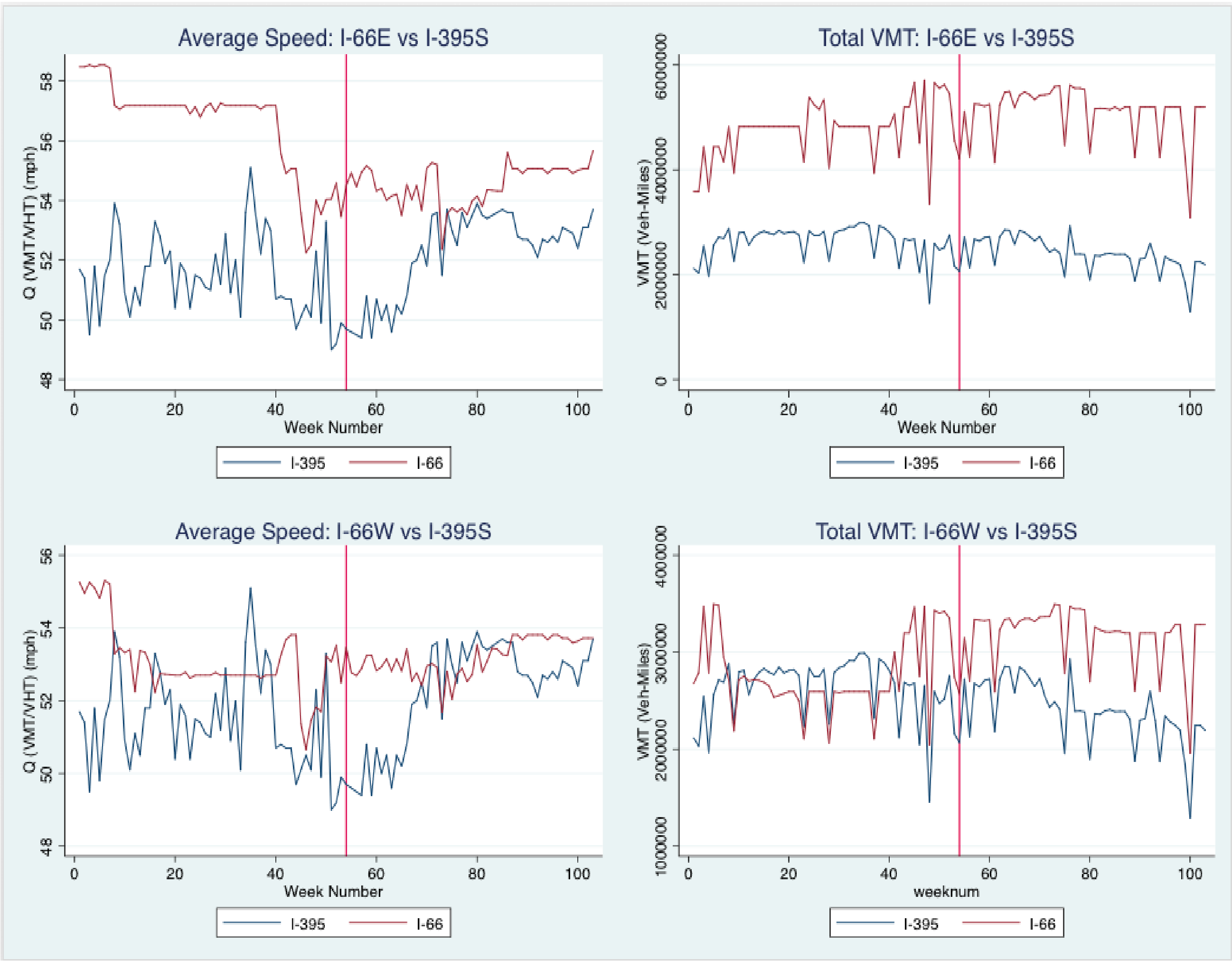
I-66 and I-495 are certainly not perfect substitutes; if PeMS had data for smaller arterial roads, like Route 50 or Route 29, I would have used those routes for this spillover analysis. However, it is likely that some people use I-495 to access the George Washington Parkway as a route for entering and exiting Washington D.C., in order to avoid high toll prices on the I-66 HOT lanes, suggesting some level of potential substitution between the interstates.

Results

The Effect of HOT Lanes on I-66

Assessing Parallel Trends between I-66 and I-395

Before examining the results of the DD regressions, it is important to measure the strength of the parallel trends assumptions; if I-66 and I-395 were not trending in the same direction before HOT lanes were implemented, one cannot attribute the effect of post-implementation differences on the HOT lanes, themselves. As shown in the plots below, I-66E has much more similar pre-implementation speed and volume trends with I-395S than I-66W does; thus, we should have more confidence in the estimates produced by the I-66E vs I-395S DD regression. Additionally, parallel trends are extremely weak between both I-66E/W and I-395N, so we exclude the DD regression estimates for the I-395N comparisons from this analysis.



Summarizing the DD Regression Results

As shown in the table below, HOT lane implementation on I-66 produced small but statistically significant decreases in average speed in both the east and west directions; however, it produced relatively larger and statistically significant increases in vehicle miles traveled. Thus, HOT lane implementation made I-66 operate more efficiently overall, increasing its capacity to handle a much greater flow of cars at only a small reduction in speed. Specifically, using the I-66E vs I-395S comparison, HOT lane implementation decreased average weekly vehicle speed by 2.8 mph, a 4.9% decrease from the pre-implementation average. At the same time, though, the new tolls increased average weekly VMT by 575,197.5 miles, a 12.1% increase from the pre-implementation average. Assuming that every vehicle drives the entire 9.3-mile length of the express lanes, HOT lane implementation increased average weekly vehicle volumes by over 60,000 cars, a conservative estimate given that many commuters do not drive the entire length of the interstate.

Even though the I-66W vs I-395S comparison had weaker parallel trends, this regression produced comparable results, showing that HOT lanes produced a 1.2% decrease in average speed and a 23.4% increase in VMT. It is important to note that the VMT estimates for I-66E/W produce relatively large standard errors (121,297.6 and 93,055.1, respectively). Thus, while we are confident that HOT lanes dramatically increased VMT on I-66, there is uncertainty over the precise magnitude of this increase.

DD Results: Effects of HOT Lane Implementation on I-66

	(1) Effect on Speed (mph)	(2) Percent Change from pre-period	(3) Strength of Parallel Trends	(1) Effect on VMT (miles)	(2) Percent Change from pre-period	(3) Strength of Parallel Trends
I-66E vs I-395S	-2.8** (0.36)	-4.9%	Moderate-Strong	575,197.5** (121,297.6)	12.1%	Strong
I-66W vs I-395S	-0.6* (0.31)	-1.2%	Moderate	645,806.8** (93,055.1)	23.4%	Weak-Moderate

*Column (1) shows the results from a simple DD regression between I-66E/W vs I-395S. A p-value < 0.05 is denoted by **, while a p-value < 0.1 is denoted by *. Column (2) shows the treatment effect as a percentage change from the I-66 average in the pre-period. Column (3) gives a qualitative assessment of the strength of the parallel trends assumption.

Next, I control for potential anticipation effects by dropping observations that occur in the 15 weeks prior to HOT lane implementation. As shown in the original DD plots above, parallel trends seem to slightly diverge around 15 weeks prior to implementation, especially for the I-66W-vs-I-395S comparison. Specifically, I-66 appears to have had a greater increase in both speed and VMT relative to I-395S leading up to implementation, suggesting that people were already shifting their commuting behavior as they prepared for the new HOT lane policies.

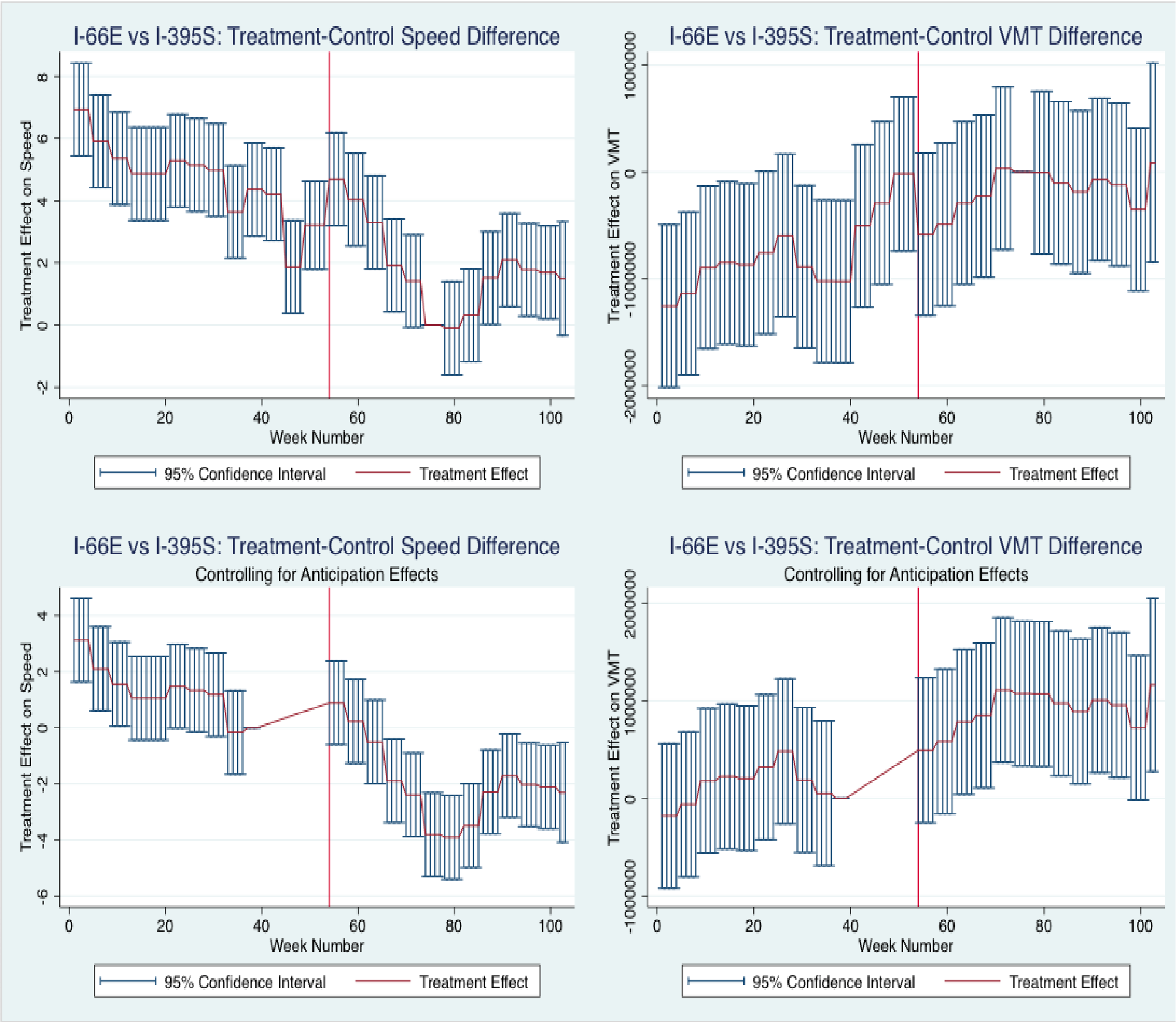
As shown in the table below, after dropping these observations, the direction and significance of the I-66E estimates remain the same, showing a statistically significant decrease in speed and a statistically significant increase in VMT; however, the magnitude of these estimates grows, increasing to -3.24 mph and 742,817.2 VMT. For I-66W, the estimated effect of the HOT lanes on speed, which was previously significant at a 90% confidence level, no longer remains significant after controlling for the policy anticipation effects. Alternatively, the estimated effect on VMT becomes more dramatic, increasing to 813,718.4 vehicle miles per week.

Effect of HOT Lane Implementation on I-66 Controlling for Anticipation Effects

	(1) Original DD	(2) Controlling for Anticipation Effects	(1) Original DD	(2) Controlling for Anticipation Effects
	Speed		*VMT*	
I-66E vs I-395S	-2.8**	-3.2**	575,197.6**	742,817.2**
	(0.36)	(0.31)	(121,297.6)	(121,297.6)
I-66W vs I-395S	-0.6*	-0.4	645,806.8**	813,718.4**
	0.31	(0.33)	(93,055.07)	(91,458.5)

*This table shows how controlling for anticipation effects changes the treatment effect estimate of HOT lane implementation on I-66E/W. Column (1) shows the original DD estimate, while Column (2) shows the estimates after dropping observations sooner than 15 weeks before HOT lane implementation. A p-value < 0.05 is denoted by **, while a p-value less than 0.10 is denoted by *.

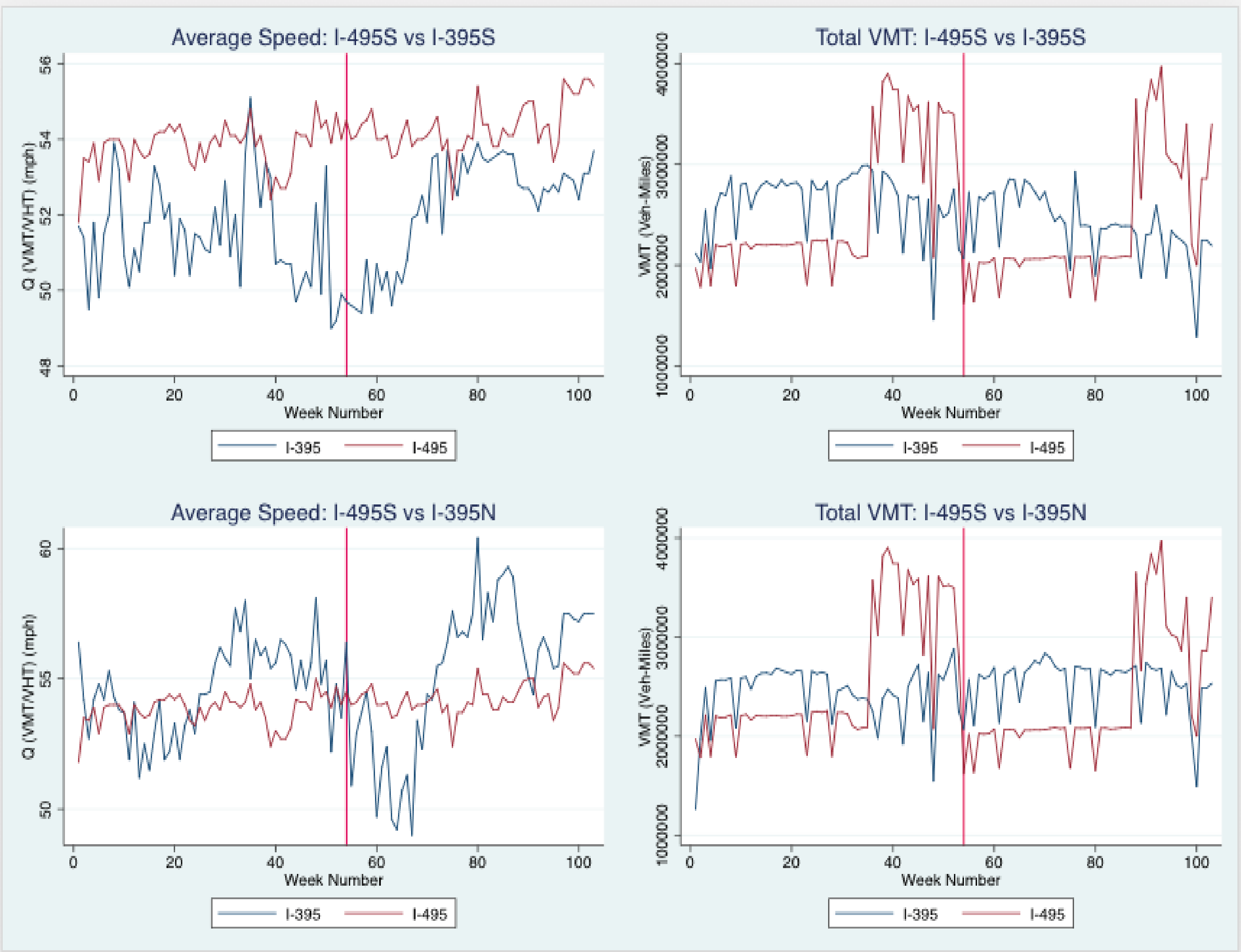
Lastly, I utilize the event study approach to assess statistical differences between I-66 and I-395 at month-level intervals in the pre and post-implementation periods. As shown in the plots below comparing I-66E and I-395S, using a simple event study regression without controls shows that there were statistically significant differences in the pre-period but not in the post period, suggesting that there were weak parallel trends before implementation and that HOT lanes were not an impactful intervention. However, after controlling for the anticipation effects of implementation, the event study results more closely mirror the DD results, with stronger parallel trends in the pre-period, a statistically significant decrease in average speed, and a statistically significant increase in VMT. Moreover, after controlling for anticipation effects, the I-66W-vs-I-395S event study suggests no significant treatment effect on speed in the post-period, yet it also shows strong parallel trends and treatment effects for VMT (Appendix Figure 1).


I-66E vs I-395S: Treatment-Control Speed Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-66E vs I-395S: Treatment-Control VMT Difference
Treatment Effect on VMT
Week Number
95% Confidence Interval
Treatment Effect
I-66E vs I-395S: Treatment-Control Speed Difference
Controlling for Anticipation Effects
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-66E vs I-395S: Treatment-Control VMT Difference
Controlling for Anticipation Effects
Treatment Effect on VMT
Week Number
95% Confidence Interval
Treatment Effect

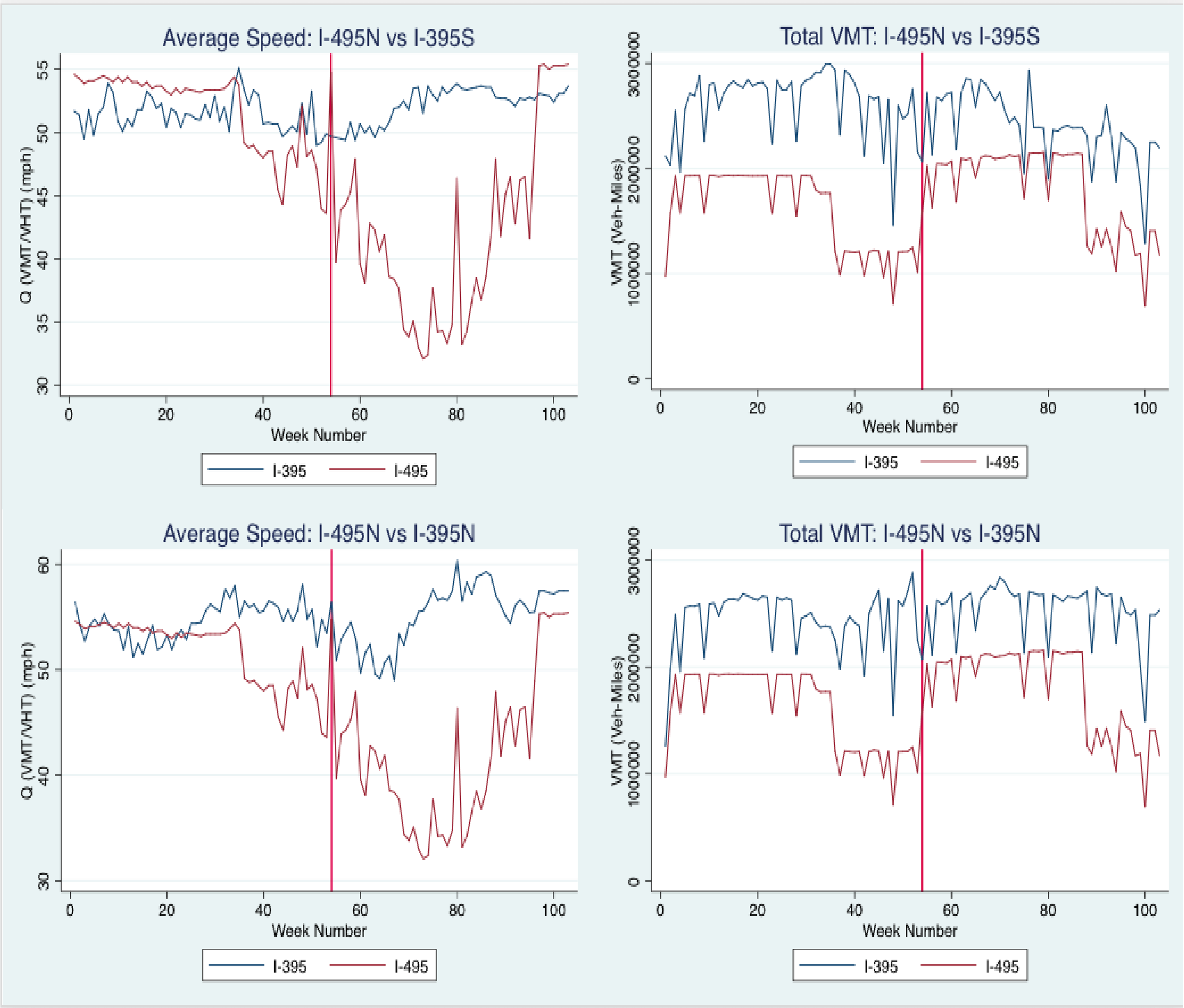
Spillover Analysis of I-495

Assessing Parallel Trends between I-495 and I-395

In order to determine whether a 495-vs-395 DD analysis measuring the spillover effects of the I-66 HOT lanes is feasible, we must again assess the strength of the parallel trends assumption. As shown below, there are fairly weak parallel trends in the pre-period when comparing I-495S to both I-395S and I-395N, suggesting that we should be hesitant in attributing causality and validity when interpreting these regression estimates.



Alternatively, there are strong parallel trends in the pre-period when comparing I-495N with both I-395S and I-395N. Given that I-495N had stronger parallel trends with both I-395S and I-395N, it is possible that I-495S was more prone to extreme incidents or involves a fundamentally different type of commute than I-495N. Regardless, we are more confident in using the I-495N DD regression results when estimating the spillover effect of the I-66 HOT lanes.



Average Speed: I-495N vs I-395S
Q (VMT/VHT) (mph)
Week Number
I-395
I-495
Total VMT: I-495N vs I-395S
VMT (Veh-Miles)
Week Number
I-395
I-495
Average Speed: I-495N vs I-395N
Q (VMT/VHT) (mph)
Week Number
I-395
I-495
Total VMT: I-495N vs I-395N
VMT (Veh-Miles)
Week Number
I-395
I-495

Summarizing the DD Regression Results of I-66 Spillover Effects

As shown in the table on the following page, the I-495S and I-495N DD regressions produce dramatically different results, as the I-495N results shows much more severe spillover effects. It is unsurprising that the treatment effect estimates differ so much, given the substantial variation in pre-treatment traffic trends between I-495S and I-495N. Specifically, the I-495S analysis shows no significant effect of HOT lane implementation on speed. Moreover, while the I-495S-vs-395S analysis suggests no significant effect on VMT, the I-495S-vs-395N analysis shows that the I-66 HOT lanes dramatically decreased VMT on I-495S.

Alternatively, when analyzing the I-495N results, we find that HOT lane implementation on I-66 produced a dramatic decrease of about 10 mph in average speed on I-495N, roughly 19% lower than the pre-implementation average. Similarly, while the 495N-vs-395S estimate shows no significant change in VMT, the 495N-vs-395N regression estimate shows an increase in VMT of roughly 430,000 on I-495N, a 27% increase from the pre-implementation average. Thus, while there are inconsistent results on how the I-66 HOT lanes affected I-495N VMT, it appears as though they substantially decreased I-495N's average speed.

If we look at the time-series trends in the plots above, it is clear that these decreases in average speed and increase in total VMT occur immediately HOT lane implementation and quickly return to near pre-implementation levels over time. Thus, it appears as though there may be a brief learning curve associated with HOT lanes, with drivers returning to I-66 once they become accustomed to the new tolls. Moreover, I-66 toll prices were noticeably high upon implementation on I-66 and were artificially adjusted in 2018, suggesting that there is also a learning curve in designing the algorithm that sets the toll prices.

DD Results: Spillover Effect of I-66 HOT Lane Implementation on I-495						
	(1) Effect on Speed (mph)	(2) Percent Change from pre-period	(3) Strength of Parallel Trends	(1) Effect on VMT (miles)	(2) Percent Change from pre-period	(3) Strength of Parallel Trends
I-495S vs I-395S	-0.2 (0.30)	-0.4%	Moderate-Strong	37,667.6 (142,39.60)	1.5%	Weak-Moderate
I-495S vs I-395N	-0.2 (0.48)	-0.4%	Weak-Moderate	-299,283.2** (139,618.20)	12.0%	Weak-Moderate
I-495N vs I-395S	-10.2** (1.13)	-19.8%	Strong	429,446.6** (99,445.76)	26.9%	Strong
I-495N vs I-395N	-10.2** (1.19)	-19.2%	Strong	92,495.8 (95,426.33)	4.6%	Strong

*Column (1) shows the results from a simple DD regression between I-495N/S vs I-395N/S. A p-value < 0.05 is denoted by **. Column (2) shows the treatment effect as a percent change from the I-495 average in the pre-period. Column (3) gives a qualitative assessment of the strength of the parallel trends assumption.

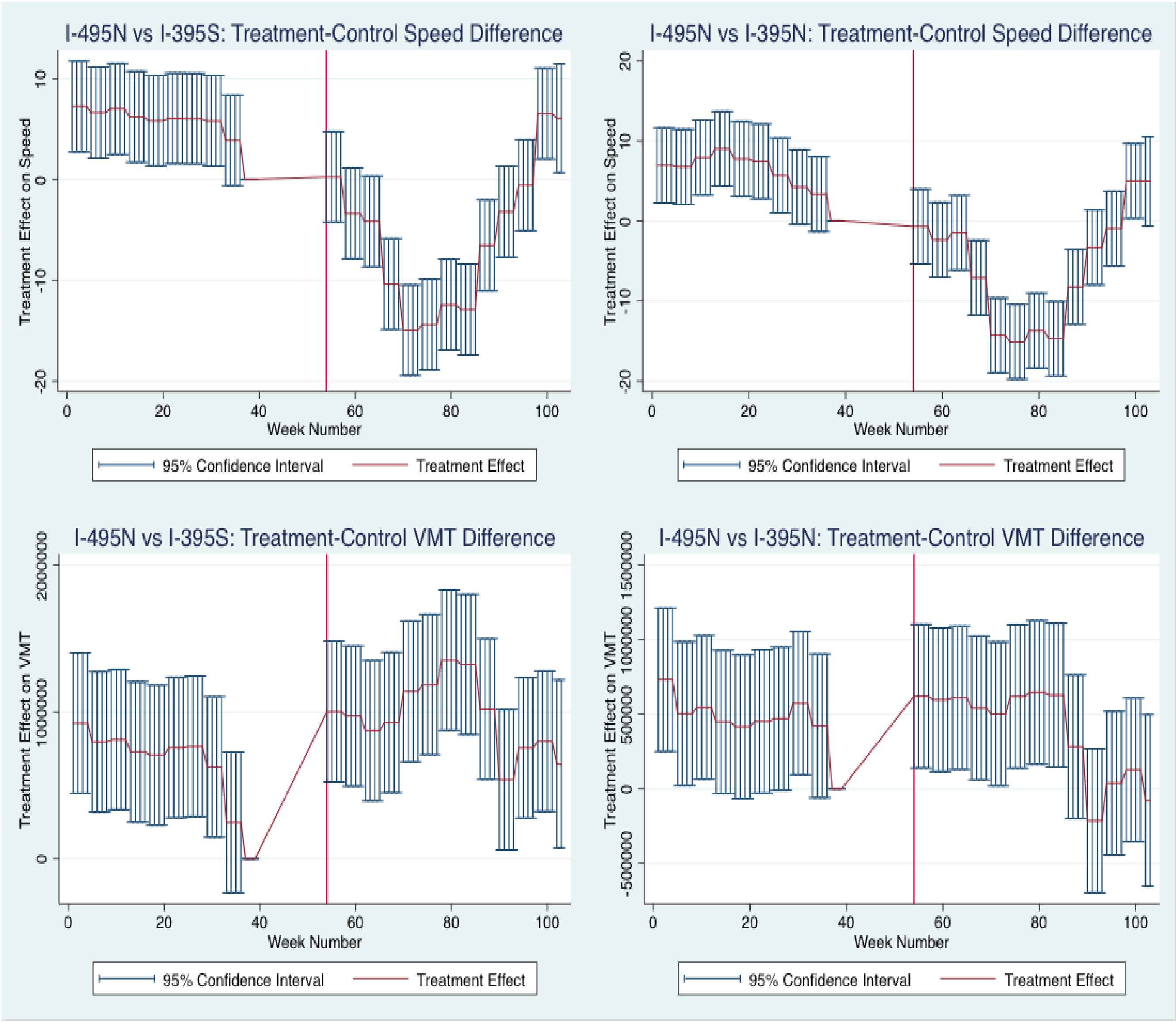
Again, we control for anticipation effects by dropping all observations 15 weeks prior to HOT lane implementation on I-66. This seems appropriate for this DD analysis, as parallel trends weaken between I-495 and I-395 about 15 weeks prior to implementation. As shown in the table below, after dropping these observations, the I-495N estimates for speed are robust, continuing to show a large decrease in average speed. Similarly, the estimated treatment effects for I-495N VMT are also robust, with the I-395S comparison still showing a statistically significant increase in VMT and the I-395N comparison still showing no significant effect. On the other hand, as shown in Appendix Figure 2, the I-495S estimates for VMT are not robust, showing inconsistent and varying results. While the I-495S estimates for speed are robust, continually showing no significant effect, we are still skeptical of the I-495S regressions, given the weak parallel trends and lack of robustness to the anticipation effects control for the VMT estimates.

Effect of I-66 HOT Lane Implementation on I-495N Controlling for Anticipation Effects

	(1) Original DD	(2) Controlling for Anticipation Effects	(1) Original DD	(2) Controlling for Anticipation Effects
	Speed		*VMT*	
I-495N vs I-395S	-10.24* (1.13)	-11.47** (1.23)	429,446.60** (99,445.76)	324,898.90** (99,311.16)
I-495N vs I-395N	-10.21** (1.19)	-12.03** (1.30)	92,495.77 (95,426.33)	-71,487.78 (95,910.31)

*This table shows how controlling for anticipation effects changes the treatment effect estimate of HOT lane implementation on I-495N when compared to I-395N/S. Column (1) shows the original DD estimate, while column (2) shows the estimates after dropping observations 15 weeks or sooner than HOT lane implementation. A p-value < 0.05 is denoted by **.

Lastly, I once again utilize the event study approach to assess statistical differences between I-495 and I-395 at different month-level intervals. Unsurprisingly, even after controlling for anticipation effects, the I-495S event study plots show very weak parallel trends in the pre-period, confirming our doubts in the DD results produced by the I-495S comparisons (Appendix Figure 3). Furthermore, as shown in the plots below, while the I-495N event study results on speed reflect the DD results, showing a sharp decline in I-495N speed directly after implementation that gradually recovers over time, these results also show strong statistical differences between I-495N and I-395 before implementation. Thus, while we are confident that I-495N speeds decreased after I-66 HOT lanes were implemented, we cannot confidently say this change was caused by the HOT lanes, themselves. Similarly, the event study results on I-495N VMT also show weak parallel trends in the pre-period, with no substantial change in treatment effect in the post-period. Ultimately, it is clear from this event study that I-495 and I-395 are poor comparison interstates for a DD analysis. Thus, we are unable to assess whether I-66 and I-495 are, in fact, strong substitutes, and whether the I-66 HOT lanes produce spillover onto nearby substitute routes.


I-495N vs I-395S: Treatment-Control Speed Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-495N vs I-395N: Treatment-Control Speed Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-495N vs I-395S: Treatment-Control VMT Difference
Treatment Effect on VMT
Week Number
95% Confidence Interval
Treatment Effect
I-495N vs I-395N: Treatment-Control VMT Difference
Treatment Effect on VMT
Week Number
95% Confidence Interval
Treatment Effect

Conclusions from DD Results

Based on weekly traffic data, HOT lane implementation on I-66 produced relatively small, but statistically significant, decreases in average vehicle speed on I-66E, but much larger and statistically significant increases in VMT. While our DD analysis of I-66W fails to confirm that HOT lane implementation decreased average vehicle speed, it does show that it dramatically increased weekly VMT on I-66W. Thus, the overall commuting capacity of I-66 seems to have increased as a result of HOT lane implementation. Moreover, shortly after I-66 implemented HOT lanes, I-495N experienced a decrease in average vehicle speed and an increase in VMT, with these trends returning to pre-implementation levels over time. However, given that I-495 and I-395 lack strong parallel behavior in the pre-implementation period, we are unable to attribute these changes on I-495N to the implementation of the I-66 HOT lanes.

Limitations

It is important to highlight the methodological limitations of these DD results. First, as mentioned earlier, parallel trends were only held strongly for three interstate comparisons: I-66E vs I-395S, I-495N vs I-395N, and I-495N vs I-395S. Given that there were twelve possible DD comparisons between all of the interstates, we must at least question the actual strength of parallel behavior between these interstates, limiting the confidence with which we can make causal claims.

Similarly, there were no diagnostic checks to analyze whether I-66 and I-395 were appropriate complements and whether I-495 and I-66 were actually substitutes. Specifically, HOT lane implementation on I-66 may have actually had an impact on I-395, thereby undermining the validity of the DD comparison. Alternatively, even though I-495N and I-395 may have had similar pre-implementation trends, there is limited evidence outside of this DD analysis that I-495 acts as a viable substitute route for many I-66 drivers.

Furthermore, there is the possibility that other impactful events could have occurred around the time of I-66's HOT lane implementation that affected both the treatment and comparison interstates, meaning we would have misestimated the actual causal impact of the intervention. Lastly, there is also the possibility that there were post-implementation events that only affected one of the interstates, again meaning we would have attributed external impacts on traffic to the implementation of HOT lanes. In fact, both I-395 and I-66 experienced construction during parts of this DD analysis. Although this construction is often completed outside of peak hours, thereby minimizing its impact, it could still easily distort the estimated impact of HOT lane implementation.

Evaluating the Cost-Effectiveness of HOT Lanes

Calculating the Value of Time Savings of the I-66 HOT Lanes

In determining whether the HOT lanes are a worthwhile investment for managing congestion, I estimate the monetary value of time savings that the I-66 HOT lanes create using data from VDOT's PEMS database through the following steps:

1. I find the difference in pre and post-implementation average travel time on the I-66 HOV/T lanes during peak hours.
   a. Average pre-implementation travel time: 26.54 minutes vs average post-implementation travel time: 25.57 minutes[2]
      i. Average travel time savings = 0.97 minutes[3]
2. I then estimate the daily number of cars on the express lanes during peak hours in the post-period by dividing the total vehicle miles traveled by the length of the road.
   a. 89,792.38 / 9.3 = 9,655.09 vehicles during peak period
3. Next, I extrapolate the number of commuters from the number of vehicles based on data that roughly 65.3% of vehicles are HOV (Hedgpeth, 2020). Assuming a conservative estimate that HOV vehicles only have two passengers, I make the following calculation for total I-66 drivers:
   a. (9655.09*.347) + (9655.09*.653*2) = 15,959.86 commuters
4. I then multiply this quantity of commuters by the average minute savings to find the total amount of commuter-minutes saved during peak hours. I then convert this calculation to total daily hours saved during peak hours.
   a. 0.97 * 15,959.52 = 15,481.07 peak hour commuter-minutes → 15,481.07/60 = 258.02 commuter-hours saved per day during peak hours
5. Finally, I monetize the value of this time savings by multiplying the total number of daily commuter-hours saved by the median hourly wage in Washington, D.C. (U.S. Bureau of Labor Statistics, 2019).
   a. 258.02 * 34.46 = **$8,891.31 in time saved per day, or $3,245,326.70 saved per year**

Interpreting the Cost-Effectiveness of the I-66 HOT lanes

Given an estimate of over $3 million in time savings per year, limited direct project costs, and a constant stream of revenue for the state of Virginia, the I-66 HOT lanes are a highly cost-effective policy. In the first two fiscal years of operation, the I-66 HOT lanes collected roughly $35 million in toll revenue, funds that can be used for other transportation projects and have a multiplier effect in value ("Fiscal Year 2019," 2018). Moreover, my estimation of the value of time savings may actually be fairly conservative. First, I assume HOV vehicles only have two drivers, which is obviously a cautious approach given that many commuters ride in buses or cars with more than two passengers. Moreover, I assume that only drivers during the peak-period and on I-66 benefit from the HOT lane travel-time savings, even though the literature shows that some arterial routes experience decreased congestion and drivers often shift their commute to off-peak hours. Lastly, I do not consider time-savings from decreased commute volatility.

[2] The timeframe of the pre-implementation period is December 4, 2016-December 29, 2017, while the time frame of the post-implementation period is January 1, 2018-December 22, 2020.
[3] It is important to note that this is not a causal estimate of time savings, but rather a simple before-after comparison.

At the same time, there are certainly costs that need to be considered regarding the I-66 HOT lanes. First, the Virginia state government potentially invested time and resources researching the effectiveness and implementation process of HOT lane policies. Secondly, VDOT had to install the tolling signage and infrastructure needed for dynamically-priced tolling stations. Third, given reports of increased HOV violators, the state of Virginia potentially invested in greater police enforcement of HOV requirements (Lazo & Hardin, 2018). Lastly, HOT lanes could actually increase average travel time for former HOV drivers on I-66 who shifted to other transportation modes or commuters on nearby substitute routes who experienced increased congestion.

Interpreting the Cost-Effectiveness of the I-495 HOT Lanes

The I-495 HOT lanes have far different cost-effectiveness implications than the I-66 express lanes. While implementation on I-66 simply involved converting its HOV lanes to HOT lanes, the I-495 project required constructing an additional two express lanes in each direction. This cost approximately $2 billion in initial capital costs, with the state of Virginia paying over $400 million ("Innovative Finance in Action: Virginia I-495 HOT Lanes," 2009). Moreover, given that the project is fully owned and partly financed by private road operator companies, the state of Virginia does not collect toll revenue.

Assuming that the I-495 HOT lanes achieve a similar monetary value in time savings as the I-66 HOT lanes[4], and this yearly time-savings value of $3.247 million is achieved in perpetuity at a discount rate of 5%[5], commuters would only recoup $64.94 million in time-savings (3.247/0.05) in present-value terms relative to the $400 million in capital costs that taxpayers spent ("Market Activity," 2020). Of course, there are other potential benefits of the I-495 HOT lanes, as they could attract cars away from other roads, thereby saving the time of commuters from competing routes. Moreover, the estimate of the monetary value of time-savings on I-66 was overly conservative for the number of reasons previously explained. Ultimately, though, with its high up-front construction costs and lack of a revenue stream, the I-495 HOT lanes need to save substantially more time for commuters to compete with I-66 in terms of cost-effectiveness. Specifically, the state would need to earn $20 million-worth of time savings per year in perpetuity at a discount rate of 5% to break even with its initial $400 million investment. This would amount to roughly 580,000 hours saved for median-earning D.C. workers per year, or 1,600 hours saved per day.

[4] The PeMS database does not have travel time data for I-495. The I-66 and I-495 HOT lanes may actually produce vastly different time-savings amounts, since the I-495 HOT lanes operate for the entire day, not just during peak hours, and because the interstates have different average car volume. However, the comparison is made to show the vast differences in cost implications between the two types of projects.

[5] The median coupon rate for Virginia bonds issued towards road/highway projects is 5%.

Evaluating the Equity of HOT Lanes

Arguably the most prominent criticism of HOT lanes is that they disproportionately benefit affluent commuters, while pricing out low-income drivers with exclusionary toll prices. (Southern Environmental Law Center, 2013) (Ecola & Light, 2009) (Brownstone, et. al., 2003). To assess the level of equity surrounding HOT lanes, I will consider the following factors: the distributional effects of HOT lanes between express lanes and general purpose/substitute lanes, the price of Northern Virginia HOT lanes relative to their time savings, and the redistribution of HOT lane toll revenue. Ultimately, while I find that express lane toll prices may be exclusionary for many low-to-middle income commuters, I also conclude that HOT lanes create benefits for the entire commuting network, alleviating congestion on alternative routes and providing revenue for public transit projects.

Distributional Impacts of Congestion Pricing on Express Lanes vs GP/Substitute Lanes

One common critique of converting HOV lanes to HOT lanes is that they provide a reliable express route for those able to pay, but they do not benefit drivers on GP or substitute route and can even make these roadways more congested. To assess this claim, I cite a before-after study from Venkatanarayana, et. al., who analyze how volume and speed changed on GP lanes shortly after I-495 implemented HOT lanes (Venkatanarayana, et. al., 2014). As seen in the table below, both I-495N and I-495S GP lanes saw moderate increases in traffic volume, of 8% and 4% respectively, during the AM peak period, suggesting a slight spillover effect from the HOT lanes. However, speed largely remained unchanged during the AM peak period, leaving GP lane drivers unaffected by the addition of the toll lanes. Alternatively, speeds dramatically increased during the PM peak period on the I-495N/S GP lanes, by 15% and 30%, respectively. This suggests that the addition of express lanes actually alleviated traffic on the interstate's GP lanes during the PM peak period.

Percent Change in Volume and Speed after HOT Lane Implementation

	I -495N GP Lanes		I -495S GP Lanes	
	AM Peak	PM Peak	AM Peak	PM Peak
Traffic Volumes	8%	0%	4%	-2%
Traffic Speeds	-1%	15%	1%	30%

*This table shows the effect of I-495's HOT lane policies on the interstate's general purpose lanes. Specifically, it shows the percent change in average daily traffic volume and vehicle speed on the GP lanes of I-495N/S during its AM and PM peak periods after HOT lane implementation.

Source: Venkatanarayana, et. al. (2014), VDOT

Given that I-66 solely converted its HOV lanes to HOT lanes, as opposed to creating more driving space by constructing additional lanes, it is even more prone to the negative spillover concerns addressed above (Lazo, 2017). While the addition of HOT lanes may attract SOV drivers from arterial routes onto I-66, it could simultaneously force HOV drivers off of the interstate as it becomes more crowded, in addition to incentivizing drivers to convert from HOVs to SOVs, thereby increasing overall traffic volumes. Yet, these negative effects simply do not materialize in practice. Not only does average vehicle speed on I-66 increase during peak-hours, all four arterial routes in the vicinity of I-66 saw speed increases six months after HOT lanes were implemented, as shown in the table below ("Transform66: Inside the Beltway, 2018).

Effect of I-66 HOT Lane Implementation on the Average Speed of Arterial Routes

	Route 50	Route 29	Route 7	GW Parkway
Pre-toll Speed (mph)	26.1	19.6	18.8	32.9
Post-toll Speed (mph)	26.3	20.8	19.8	35
Percent Change in Speed	0.9%	6.2%	5.1%	6.3%

*This table shows the spillover effect of I-66's HOT lane implementation on nearby arterial routes. Specifically, the table displays the average vehicle speed of I-66's four main substitute routes before and after I-66 implemented HOT lanes, in addition the percent change in average speed.

Source: Office of the Secretary of Transportation (2017), VDOT.

Evaluating the Pricing of HOT Lane Tolls Relative to their Time-Savings

While HOT lanes may not be negatively affecting low-income drivers who cannot afford to use them, they may still be priced in an exclusionary manner, creating a commuting network where only wealthy drivers have the guarantee of a reliable express route. The basic concept of congestion pricing is that the tolls should be set at a rate where the marginal driver that would create a situation of gridlock is priced out of the market; yet, it is possible that this goal could be achieved at prices lower than what the I-66 HOT lanes are currently charging.

To better understand the price of the I-66 HOT lanes, I calculate the average price per hour saved. Specifically, a VDOT study found that drivers saved 1.5-2 minutes per mile on the I-66 HOT lanes compared to using Route 29, and 0.5-1.5 minute per mile compared to using Route 50 (Office of the Secretary, 2017). Moreover, at the time of the study, the average toll price was approximately $12.72 ("Average Round Trip, 2018). Thus, as seen in the table below, depending on how many miles a commuter drives on the express lanes and what substitute route they would have used, they are paying anywhere from $47 to $164 per hour saved to use I-66.

Cost of Time Savings based on Average Toll Price and Distance Traveled				
	Distance Traveled on I-66 Express Lanes			
	Entire Route (9.3 miles)		Half of Route (4.65 miles)	
	Route 29	Route 50	Route 29	Route 50
Minutes Saved vs Substitute Route	16.28	9.3	8.14	4.65
Price per Hour Saved ($)	46.88	82.06	93.76	164.13

*This table shows the cost of time-savings on the I-66 express lanes based on the commuter's alternative route and distance traveled on I-66. Specifically, the first row shows the number of minutes saved based on whether a driver would have used Route 29 or Route 50 and whether they drive the entire length or half of the length of the I-66 express lanes. The second row shows the price per hour saved of using the I-66 express lanes, calculated based on the number of minutes saved and the average toll price on I-66.

Source: Office of the Secretary of Transportation (2017), VDOT.

These prices seem incredibly high, especially given that the median hourly wage of a D.C. worker is about $34. To put these prices into context, I compare them to a median willingness-to-pay estimate that Brownstowne et. al. calculate using a revealed preferences model from San Diego's I-15 HOT lanes (Brownstowne et. al., 2003). The study, which was conducted in 2003, found that San Diego commuters were willing to pay roughly $30 per commute-hour saved. After adjusting for inflation, the WTP estimate is about $42 per hour saved, which is lower than my most conservative estimate of the I-66 HOT lane price per hour saved. It is unclear if these high toll prices are a result of the extremely high demand for I-66 or the large number of high-earning commuters in the Northern Virginia area who are willing and able to pay prices above the market equilibrium. Moreover, HOT lanes do not just save time in the form of congestion reduction, but also by making commutes more reliable and less volatile. Regardless, current toll prices are undoubtedly out of the price range for many low and middle-income drivers.

Redistribution of HOT Lane Toll Revenue

Lastly, one pro-equity feature of HOT lanes is that, while low and median-income drivers may not be able to enjoy the direct benefits of the express lanes, they benefit in the long-term from toll revenue that is disproportionately funded by high-income drivers. Schweitzer and Taylor explain how, even though tolls are regressive in nature, they at least internalize the costs of using the roads on the drivers, themselves, granting toll avoidance options to low-income drivers that do not exist in transportation systems funded by sales taxes. Specifically, they estimate that if Orange Country's Route 91 converted its funding from value pricing to a completely sales tax-funded system, it would redistribute approximately $26 million from low-income residents to the more affluent (Schweitzer, L. & Taylor, B., 2008).

In the context of the Northern Virginia HOT lanes, revenue from the I-66 HOT lanes has already been allocated to major transit projects. Specifically, in April of 2019, the Northern Virginia Transportation Commission used I-66 toll revenue to approve $20 million-worth of transit improvement projects, most of which were related to public transit (Repetski, S., 2019). Additionally, Virginia officials and the NVTC are in negotiations to use I-66 toll revenue to fund the construction of a new metro station/tunnel near Rosslyn and a new bridge connecting D.C. and Virginia that would be used by freight/commuter trains and bikers (Smith, M., 2019). These are massive, state-funded capital investment projects that would most likely be impossible without I-66 HOT lane toll revenue.

Yet, even when considering all of these transportation projects supported by toll revenue, some would still argue that HOT lanes are inequitable, as wealthy drivers are essentially subsidizing less desirable transit options for low-income drivers so that they have the luxury of reliable automobility. By dominating the express lane market, wealthy drivers have greater job security, as they are less prone to being late to work, and they have considerably more leisure time (and therefore better quality of life and health). Moreover, revenue from the I-495 HOT lanes is not even collected by the state of Virginia, meaning non-express lane drivers may hardly benefit from these HOT lanes, which cost the state over $400 million to construct. At the end of the day, though, life with HOT lanes is still considerably better than the status quo for most D.C.-area commuters.

Conclusions for Implementation

Commuting in the D.C.-area has improved as a result of the Northern Virginia HOT lanes. According to annual congestion reports produced by INRIX, the number of hours wasted in traffic for the average D.C.-area driver decreased by 11% from 2018 to 2019, as D.C.'s congestion ranking continues to improve each year (Reed, 2020). Evaluations have consistently shown that HOT lanes provide drivers with reliable peak-hour express routes, while either increasing or not affecting travel speeds on nearby substitute routes. Below, I highlight the differing implications of implementing the I-66 and I-495 HOT lane models.

Converting Under-utilized HOV Lanes to HOT Lanes (the I-66 model)

As displayed from the previous analyses, transforming previously under-utilized HOV lanes to HOT lanes is the most cost-effective form of congestion pricing. My DD analysis found that the I-66 HOT lanes allow for a greater capacity of cars to be handled without substantially reducing speeds. Alternatively, a literature review of the I-66 HOT lanes found that they produce higher speeds at lower volumes *during peak hours*. Thus, taking these findings together, we can conclude that the I-66 HOT lanes cause drivers to adapt their commuting behavior to optimize the interstate's overall commuting capacity. The result is a reliable express lane during peak hours for drivers that are willing and able to pay, higher transit ridership and carpool volumes during peak hours, and greater utilization of the interstate during off-peak hours for drivers who can afford to delay their commute. Moreover, while I-66 HOT lane prices may be too expensive for middle and low-income drivers, they produce time-savings and transit improvement benefits for all commuters, not just express lane drivers.

With that being said, DOT planners face potential risks when converting HOV lanes to HOT lanes. Given that HOT lanes optimize the traffic flow of interstates, they may dramatically increase the total number of vehicles in the commuting network. While this may be desirable from an efficiency standpoint, this could obviously produce negative consequences. First, by increasing the total number of vehicles in the commuting network, greenhouse gas emissions from vehicles may increase, despite there being less per-vehicle emissions by having less stop-and-go traffic. Secondly, public transit maintenance and funding could be negatively impacted by HOT lanes if a significant number of transit riders choose to convert to SOV commuting when HOT lanes are opened. Lastly, while there are a number of viable substitutes to the HOT lanes in the Northern Virginia area, HOV drivers who are displaced by increased express lane traffic in other localities may face a greater burden when adjusting to HOT lane policies.

Furthermore, there is often a steep learning curve for DOT planners in understanding how commuters respond to newly added HOT lanes, making it difficult to set appropriate toll prices. As seen in the case of I-66, there was a sharp spillover effect from the introduction of HOT lanes after commuters were shocked by high prices. Thus, DOT planners must be flexible in the early stages of HOT lane price-setting and prepared to manage negative reactions from both high toll prices and increased traffic volumes on formerly HOV lanes. To alleviate these implementation concerns, DOT planners should leverage pricing data, tolling algorithm models, and lessons learned from localities that have implemented HOT lanes; however, it is important to note that no two HOT lane projects will garner the exact same reaction from drivers.

Adding HOT Lanes to Congested Interstates (the I-495 model)

As mentioned earlier, HOT lanes that require lane expansion and involve revenue/cost-sharing with private road operators have an inherently different economic justification and produce different cost-effectiveness and equity implications than the I-66 model. DOT planners should consider adding HOT lanes to an interstate to achieve two primary purposes: (1) to provide a reliable express route to drivers and (2) to increase the supply of roads in an under-supplied market. Compared to the I-66 model, which has the primary goal of more efficiently *distributing* drivers within a baseline commuting network, the I-495 model attempts to *expand* the scope of a commuting network to allow for more efficient traffic flow.

Thus, before adding HOT lanes to an interstate, planners must analyze whether such a policy would bring the supply of roads within a network in line with the market demand, or whether it would largely induce greater demand, thereby maintaining congestion on the GP lanes. By inducing greater demand, HOT lane implementation runs the risk of increasing the overall traffic volume of an interstate, while only increasing commuting efficiency for express lane users. As mentioned earlier, one study found that the I-495 HOT lanes produced both speed and volume increases, suggesting that any induced demand for I-495 did not offset the benefits of time-savings from the increased lane space. With that being said, more analysis needs to be conducted to estimate the amount of time-savings that lane-expansion projects like I-495 produce, given the high up-front costs that construction entails.

Another risk of the I-495 model is receiving strong public backlash for being inequitable, since some of its construction costs are shared by taxpayers, while revenue is fully collected by the private toll operators. Therefore, to achieve better political and public reception, states should require that some of the revenue from privately operated toll roads be allocated to public transit projects, even if this increases express lane toll prices.

Steps CEI can take to advocate for HOT lane implementation

In advocating for HOT lane implementation, CEI can take the following steps to be more convincing and memorable to both policymakers and the public:

- Quantify time and cost savings per commuter on both HOT lane interstates and arterial roads, so the audience can more personally relate to the benefits of HOT lanes.
    - To further contextualize these benefits, CEI could compare the yearly cost savings of HOT lanes to tangible goods, like the average amount of money a household spends on groceries or gas.
- Emphasize that HOT lanes grant drivers with more autonomy and flexibility—every day, drivers have the opportunity to choose whether or not paying for an expedited commute best fits their current needs.
- Reiterate that HOT lanes, when implemented effectively, benefit all drivers, not just express lane drivers.
    - CEI should constantly publicize both the time-savings produced by HOT lanes on substitute routes and the public transit projects that have been and will be funded by HOT lane revenue.
- Cite public opinion surveys of previously implemented HOT lane projects and emphasize that public support of HOT lanes tends to grow over time.
- Identify interstates throughout the country that are well-suited for HOT lane implementation (i.e. under-utilized HOV lanes or commuting networks where the demand for roads far exceeds the supply).
    - CEI should then leverage its legislative partnerships to motivate state DOTs to consider adopting HOT lanes.

Appendix

Figure 1

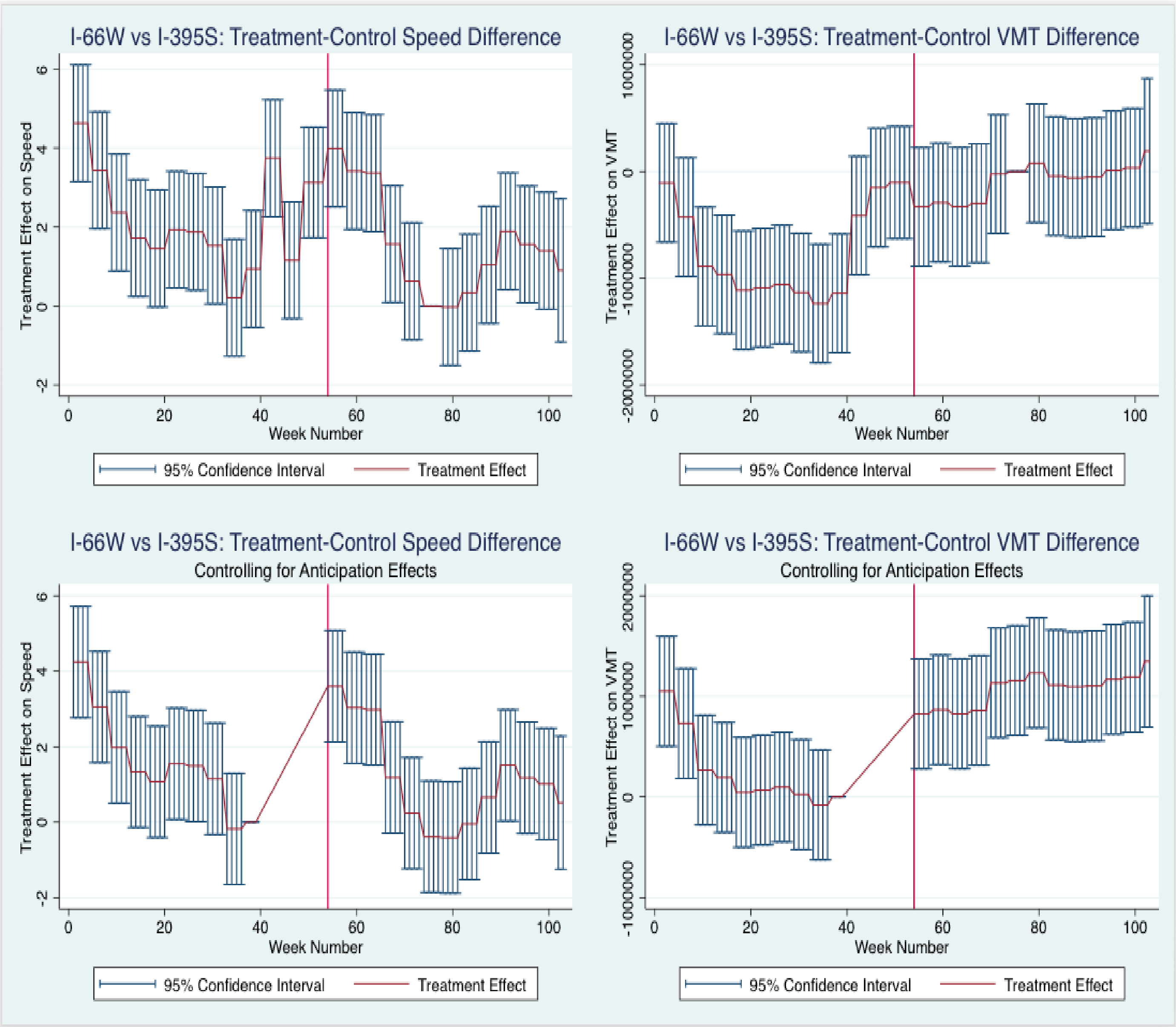
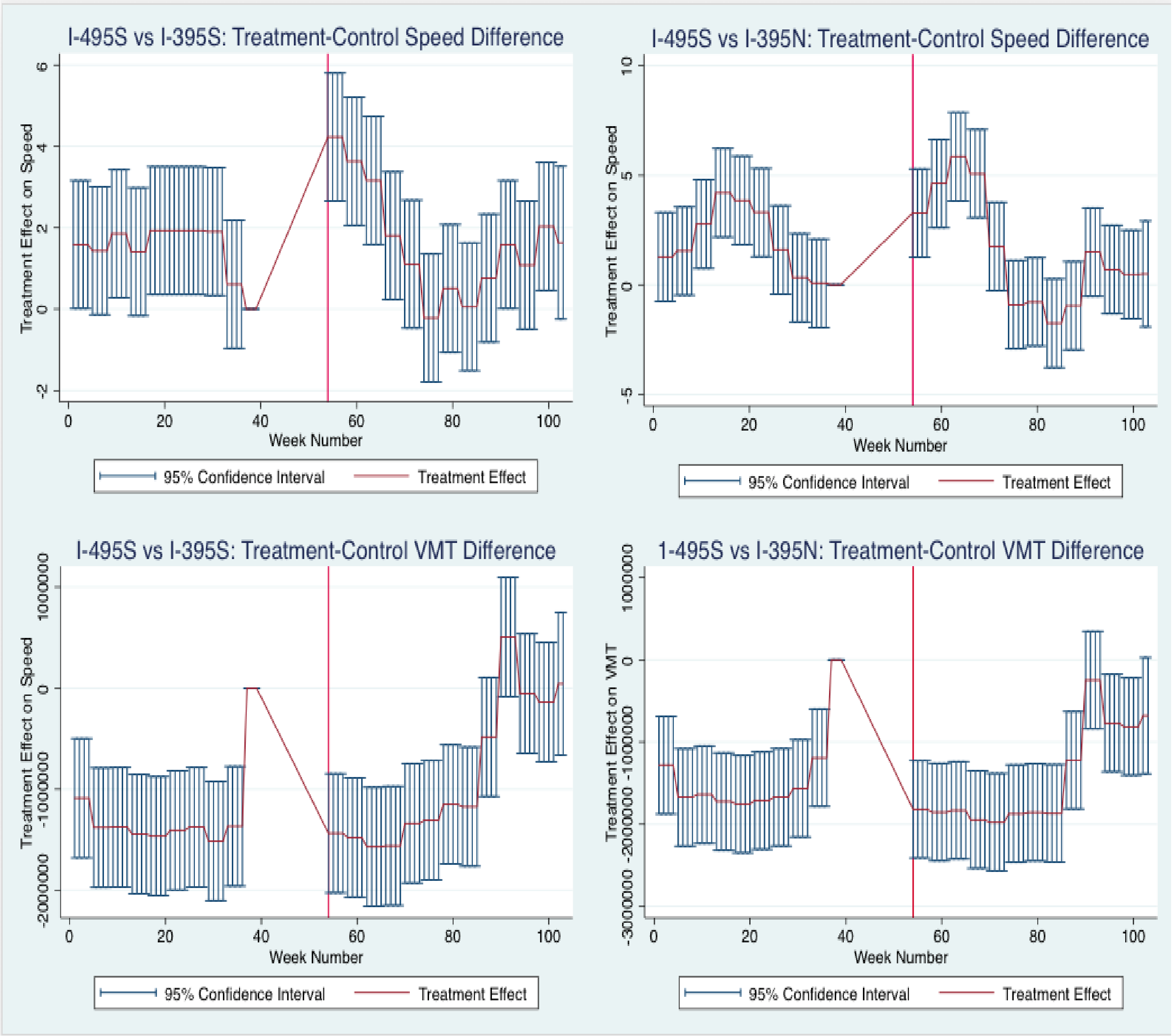


Figure 2

Effect of HOT Lane Implementation on I-495S Controlling for Anticipation Effects				
	(1) Original DD	(2) Controlling for Anticipation Effects	(1) Original DD	(2) Controlling for Anticipation Effects
	Speed		*VMT*	
I-495S vs I-395S	-0.22 (0.30)	0.15 (0.32)	37,667.62 (142,39.60)	380,783.30** (136,751.90)
I-495S vs I-395N	-0.19 (0.48)	-0.41 (0.53)	-299,283.20** (139,618.20)	-15,603.34 (134,302.50)

*This table shows how controlling for anticipation effects changes the treatment effect estimate of HOT lane implementation on I-495S when compared to I-395N/S. The (1) columns show the original DD estimate, while the (2) columns show the estimates after dropping observations 14 weeks or sooner than HOT lane implementation. A p-value < 0.05 is denoted by **, while a p-value less than 0.10 is denoted by *.

Figure 3


I-495S vs I-395S: Treatment-Control Speed Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-495S vs I-395N: Treatment-Control Speed Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
I-495S vs I-395S: Treatment-Control VMT Difference
Treatment Effect on Speed
Week Number
95% Confidence Interval
Treatment Effect
1-495S vs I-395N: Treatment-Control VMT Difference
Treatment Effect on VMT
Week Number
95% Confidence Interval
Treatment Effect

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