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Congestion Makes It Harder to Breathe: Do High-occupancy Toll Lanes Reduce Emissions?

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I. Introduction

In the past few decades, road congestion and carbon dioxide emissions have spiked in the United States. In 2012, commuters experienced 5.5 billion hours of additional travel time due to congestion, up from 2.5 billion hours in 1995. This additional travel time costs commuters approximately 2.9 billion gallons of wasted fuel and a total travel and fuel cost of $121 billion. Even more alarming, this congestion is occurring more frequently outside rush hour times, with around 40% of delays in the middle of the day and night. (Lomax et. al, 2005, 2013). With an increase in congestion, the U.S. has also seen an increase in carbon emissions from the transportation sector. From 1990-2009, carbon emissions from transportation have increased by 18%, and in 2013 transportation accounted for 35% of the total carbon dioxide released into the air (U.S. Department of Energy, 2013). This increase in carbon dioxide emissions has occurred even though engine efficiency and fuel standards have increased over time. In 1990, the average miles per gallon for a lightweight passenger vehicle was 18.8 MPG while in 2009, the average miles per gallon was 21.7 MPG (Bureau of Transportation Statistics). These efficiencies and standards have been extremely successful at reducing a variety of other emissions. Since 1970, particle matter 2.5 and carbon monoxide emissions are down 48 percent and 86 percent respectively. However even with this tremendous progress in curbing these types of emissions, the U.S. population has increased 56% and vehicle miles traveled, a metric that shows how much roads are utilized, has increased 166%. Because there are more Americans on the road and each American travels longer distances, carbon dioxide emissions have increased despite these automotive improvements. Additionally, research shows that automobiles emit more emissions during stop and go motions than holding a constant speed. The Environmental Protection Agency found through their motor vehicle emission simulator that cars have the highest emission rates between speeds of 0-20mph (2015). This evidence leads to the question, how can congestion be reduced in order to decrease the amount of carbon dioxide emitted from vehicles?

There are a variety of congestion reduction strategies that are discussed within the literature review; however, this paper will specifically focus on how high-occupancy toll lanes can be used to alleviate congestion and thus reduce carbon dioxide emissions. This congestion reduction method would not only help increase the efficiency of the U.S. economy but improve the overall health of its citizens by improving air quality.

II. Literature Review

Previous literature states that reducing congestion is an effective way to reduce emissions. In a paper by Janet and Walker (2011), they found that the introduction of the E-ZPass improved vehicle flow through tollbooths and reduced harmful emissions by 10-20%. Amazingly, this reduction in emissions resulted in increased infant health nearby the toll plaza. However, the fundamental law of road congestion makes congestion reduction a complex task. This theory states a positive interference between roadways expansion and users. As roadways expand, they are met with a directly proportional increase of drivers on the road (Downs, 1962). This result occurs because an expanded roadway increases the supply of roadway, reducing the transportation costs. However, this reduction in cost in turn shifts travel demand right encouraging more drivers on the road. Although the fundamental law of congestion does increase capacity of the road for a similar travel cost as before, it does little to alleviate congestion.

Federal and local governments have tried to combat congestion and emission issues through a variety of polices, such as subsidizing public transportation, expanding existing roadways, creating pay-to-use roads, implementing taxes and creating high-occupancy vehicle lanes (HOV). Unfortunately, many of these policies have seen little success at relieving congestion. In regards to public transportation, the lack of convenience and other personal factors has dissuaded many Americans from substituting public transportation for personal transportation. Thus increases in public transportation have done little to alleviate congestion (Duranton and Turner, 2011). Additionally, research states current bus public transportation is inefficient and recommends that it could be improved by using smaller buses operating at higher frequencies (Gronau, 2000). As previously mentioned, expanding roadways does little to solve congestion. This result is owed to the fundamental law of road congestion (Duranton and Turner, 2011). Economists frequently recommend pay-to-use roads as a method to reduce congestion and such roads are generally effective in doing so. This policy shifts costs from the government to the consumer while simultaneously reducing costs of congestion (Vickrey, 1969). However these policies were thought to be tough to implement because they are politically unfavorable, thus deterring politicians from backing these projects (Gronau, 2000). Taxes have also been used as a disincentive for automobile ownership. In 2003 researchers found that over the life of the vehicle, owners would pay up to 18% of the original price on the car in taxes (Parry et al., 2007). However, it is apparent that this disincentive has done little to deter car ownership.
Also, high-occupancy vehicle lanes (HOV) have historically been a popular way for the government to encourage carpooling, reducing the amount of cars on the road to decrease congestion. In theory HOV lanes seem like a successful method; nevertheless, empirical evidence says differently. A study performed in California found that HOV lanes are underutilized, leading to a 20% reduction of capacity of the highway. Additionally, HOV lanes did little to encourage carpooling as about 50% of carpoolers were from the same household (Kwon and Varaiya, 2008). Altogether, these ineffective policies have led to the consideration of a high-occupancy toll lane (HOT).

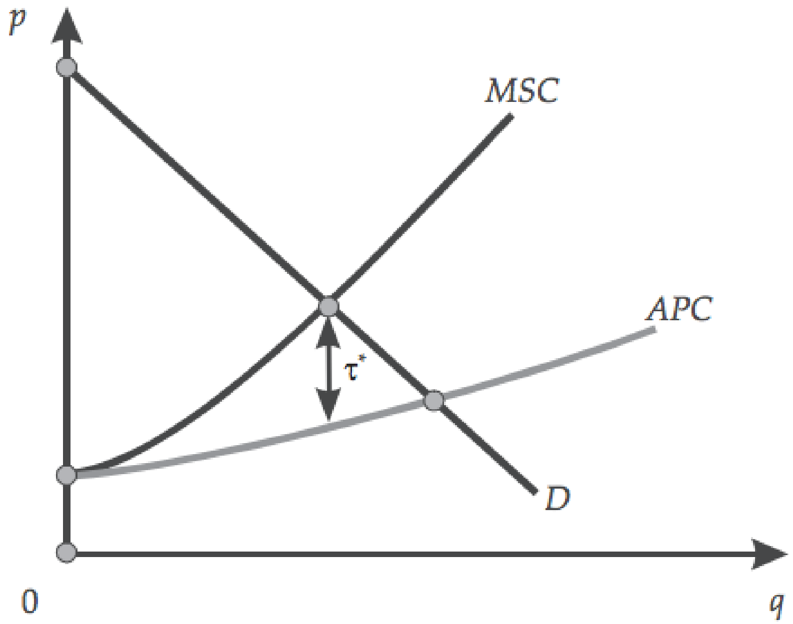
A HOT is a special lane similar to a HOV lane that requires cars to carry a certain amount of individuals in the car, normally three, in order to utilize the lane, encouraging car-pooling. However HOT lanes have another feature that HOV lanes do not. If the car owner does not have enough riders in the car, he/she can pay a toll based on the amount of congestion currently experienced on the highway. Gordon Fielding and Daniel Klein promoted the use of HOT lanes. They found similar findings to Kwon and Varaiya in their analysis in California almost 25 years before. They argued that HOV lanes were underutilized because 43% of carpoolers live in the same household. Thus, it is likely that those carpoolers would be traveling together regardless of the HOV lane. Therefore, a HOV lane could be slightly modified with new automated toll technologies in order for single riders to pay to use the lane. A HOT lane would be easy to implement since it only requires a slight modification to an existing HOV lane. This modification would allow the lane to be more utilized and reduce congestion (Fielding and

Klein, 1993). California introduced the first HOT in the United States in 1995 on Route 91 and saw tremendous congestion improvements. The introduction of the HOT lane reduced peak delays from 30-40 minutes to 12-13 minutes and brought the state millions in revenue (Sullivan, 1998). Compared to the results of the other ineffective policies, it seems that HOT lanes would be a more viable option to reduce congestion. They provide exclusivity from traditional lanes, creating a similar environment to the regular toll roads and HOV lanes. They also encourage carpooling with personal cars, which in theory provides a solution in line with smaller public transportation vehicles that travel at a higher frequency. Finally, the HOT is an improvement off of a regular HOV lane that may end up being underutilized during peak hours, which reduces HOV lane effectiveness. Therefore, does investment in HOT lanes reduce congestion and emissions?

III. Theory

Congestion reduction theories aim to reduce the volume of vehicles on a road and/or increase the frequency at which automobiles travel on the road. This research utilizes a congestion reduction theory to in turn argue a reduction in emissions. As previously stated by the Environmental Protection Agency, reducing the amount of vehicles on a road and maintaining uniform travel speeds reduces total emissions released by automobiles. With the reduction in emissions from automobiles, air quality will improve. Consider figure 1 below, a short-run model where road capacity is fixed. Transportation economic theory states that travel demand is a function of the quantity of trips demanded at a certain cost. There are two cost curves within the model. The average private cost curve, denoted APC, is the driver’s cost of using a road. This curve is upward sloping because as more people use the road congestion will occur. Congestion has the associated costs of fuel and time. Similarly, the marginal social cost curve, denoted MSC, is the social cost of using the road. This curve is also upward sloping and captures costs of time and pollution. Without any congestion reduction attempts from the government, the model equilibrium would occur at the intersection of the demand curve and the APC curve. This result occurs because drivers will only choose to drive until their own personal cost threshold is reached. However, applying a congestion reduction theory such as a HOT lane, the government could make individuals pay the social cost of using the road. If they decided to implement this strategy, the equilibrium occurs at the intersection of the demand curve and the MSC curve. The difference between the MSC curve and the APC curve represents the toll required to use the HOT lane. This toll increases the cost of the trip and, following the law of demand, reduces the amount of trips demanded. By reducing the amount of trips demanded, there will be a reduction in congestion. This toll can be set in order to maximize the social welfare on the road.

Figure 1



IV. Data

To determine if HOT implementations reduce congestion, data was pulled from the Texas A&M Transportation Institute and the National Highway Traffic Safety Administration. The Texas A&M Transportation Institute provides a dataset that analyzes 101 urbanized areas, categorized from small to very large, from 1982-2014. This dataset provides information on the urbanized areas population, number of auto commuters, freeway vehicle miles traveled, arterial vehicle miles traveled and a Travel Time Index. The paper manipulated this dataset to concentrate on the years 1994-2014 and focused on a combination of 43 large and very large urban areas with 903 total observations. This manipulation occurred since HOT lanes currently exist only in very large urban areas. In addition, the first HOT implementation in the United States did not happen until 1995. By focusing on very large and large urban areas, the analysis will reveal how successful an HOT lane is at reducing congestion compared to a large or very large urban area that did not implement an HOT lane. The paper measures congestion through the Texas A&M Transportation Institute Travel Time Index (TTI). This index is determined by the ratio of off-peak hours on a highway relative to peak hours on a highway. For example, a ratio of 1.00 means that it takes the same time to travel along a road during peak and off-peak hours. A ratio greater than 1.00 means it takes longer for someone to travel during peak hours than off-peak hours. To calculate the actual percent change in travel time, subtract 1.00 from the Travel Time Index values then apply the percent change equation. For example if in 1995 the Travel Time Index for an urban area were 1.25 and then 1.50 in 1996, this would represent a 100% increase in travel time (0.25 increased to 0.50).

The National Highway Traffic Safety Administration provides data on traffic fatalities at the county level from 1994-2014. Since counties have the potential to overlap in urban area classifications, if necessary, crash data was aggregated across multiple counties to best capture traffic fatalities in a specific urban area. For example, the dataset includes the urban area of

Atlanta, Georgia. However, the counties of DeKalb and Fulton encompass this urban area. Traffic fatalities between these two counties were aggregated to best capture the effect on the classified urban area. Note that traffic fatalities were used as a proxy for accident data due to data availability. Thus this proxy underestimates the effect on congestion since a fender bender would not be reported as a traffic fatality but would cause a travel delay. Additionally, due to the advancement of safety features within vehicles, traffic fatalities in each urban area are expected to decrease over time.

HOT implementation data was collected from local government websites that have opened an HOT lane. This data is used as a dummy variable. HOT implementation is marked as a “0” if it was not implemented yet and a “1” after the implementation date. Additionally, the analysis also takes into account if an urban area has opened a second HOT lane on another highway during the timeframe the data was collected. This additional lane opening is categorized by a dummy variable HOT2.

To determine if HOT implementations reduce emissions within an urban area, data was sourced from the Environmental Protection Agency, Federal Highway Administration and the U.S. Census Bureau from 1994-2014. The EPA provided data on carbon emissions while the Federal Highway Administration provided data on motor fuel use on highways and non-highways by all automobiles. Due to data availability, both carbon emissions and motor fuel use are estimated at the statewide level. Since this research focuses on congestion and carbon reduction within urban areas, these statewide measurements were altered to best represent the urban areas carbon emissions and motor fuel use. The data was altered by multiplying the ratio of the urban areas population relative to the statewide population. The Texas A&M Transportation Institute dataset provided the urban areas population while the U.S. Census provided the statewide population data. This altercation is justified since denser regions of states, such as urban areas, would use more energy, contributing to carbon emissions. Additionally, these urban areas have strong commuting patterns, resulting in higher motor fuel use relative to a rural area.

The U.S. Census Bureau also offers a County Business Patterns survey that provides information on number of establishments in a certain sector as well as total number of paid employees within that sector. This survey is conducted at the metropolitan statistical area level. This classification shares many of the same boundaries as an urban area classification since neither is bound to official cities and towns nor official counties. The variables of number of establishments and number of paid employees will be used as proxies to gauge the productivity of these sectors. The more establishments and employment within each sector, the more likely they are producing more carbon emissions within the area. The sectors included in the dataset are agriculture, construction, finance, manufacturing, mining, retail, transportation/utility and wholesale. Due to the U.S. Census data formatting, the transportation and utility sectors were combined into one sector. The summary statistics of the described data are provided below:

Table 1

Variable	Count	Mean	Std. Dev.	Min	Max
Agricultural Employment	903	1,204	2,581	0	17,841
Agricultural Establishments	903	265	449	0	2,936
Arterial Daily VMT (000)	903	25,435	23,300	4,800	126,010
Auto Commuters (000)	903	1,270	1,078	267	5,928
Carbon Emissions (million metric tons)	903	48	42	3	223
Construction Employment	903	69,999	54,291	0	369,991
Construction Establishments	903	7,328	6,178	1,568	49,188
Finance Employment	903	86,083	92,629	0	654,885
Finance Establishments	903	5,869	5,064	1,152	36,937
Freeway Daily VMT	903	26,290	24,352	4,095	139,275
HOT Implementation 1	903	0	0	0	1
HOT Implementation 2	903	0	0	0	1
Manufacturing Employment	903	131,757	127,115	0	698,121
Manufacturing Establishments	903	3,753	3,663	766	22,180
Mining Employment	903	1,773	5,390	0	62,927
Mining Establishments	903	139	254	8	1,509
Motor Fuel (000 gallons)	903	1,312,232	1,205,533	96,739	6,890,413
Population (000)	903	2,958	3,134	615	19,040
Retail Employment	903	174,748	136,108	0	935,456
Retail Establishments	903	12,167	10,993	3,481	79,502
Traffic Fatalities	892	191	239	23	1,796
Transportation/Utility Employment	903	55,496	55,635	0	340,763
Transportation/Utility Establishments	903	2,326	2,212	534	15,611
Travel Time Index	903	1	0	1	1
Wholesale Employment	903	77,362	80,108	0	514,766
Wholesale Establishments	903	5,787	6,303	1,382	41,678

In order to best fit the regression, many of these variables were transformed. To account for population differences across urban areas, auto commuters and traffic fatalities were altered into per capita estimates. Additionally, freeway daily and arterial street daily vehicle miles traveled were aggregated. After they were aggregated, total vehicle miles traveled were transformed into per capita estimates. Each per capita estimate was logged in order best capture a linear relationship between it and the Travel Time Index. All sector employment data was altered into per capita estimates. Finally, carbon emissions, motor fuel and all sector specific employment and establishment data were also logged to best fit a linear relationship over time.

V. Model

In order to test if high-occupancy toll lanes have an effect on emissions, a two-stage least square fixed effects model was run. This model controls for unobserved differences across each urban area. This control reduces the likelihood of unobserved variables resulting in biased estimates. This model also allows the variable HOT Implementation 2 to be used as an instrumental variable in order to determine its effects on carbon emissions. This instrumental variable was lagged by two years to help address a simultaneity issue since urban areas that implement HOT lanes are likely the ones suffering from the most congestion. Therefore, the lag allows for the local population to adjust their commuting behavior to this new roadway and captures the implementation effects on congestion once commuting patterns have changed. HOT implementation 2 was selected as an instrument due to running a separate fixed effects model on the determinates of congestion seen in table 4 found in the appendix. This model showed urban areas that opened one HOT lane did not experience a reduction in traffic. However, the model did find if urban areas implemented a second HOT lane, on average they would experience a reduction in their Travel Time Index by about 7.5% in two years. Please refer to the appendix for a discussion regarding the defense of the instrumental variable.

The final two stage least square fixed effects model controls for carbon emissions released in agriculture, construction, finance, manufacturing, mining, retail, transportation/utility and wholesale sectors. The model controls for population as well as motor fuel used on highways and non-highways. Additionally, a year ID was included in the model to capture any year-to-year differences experienced over the time period. In preliminary models, manufacturing, wholesale and agriculture sectors were insignificant and therefore omitted in the final model. These sectors may be insignificant since the research specifically looks at urban areas. Manufacturing, wholesale and agriculture require space in order to operate effectively and urban areas typically have higher land prices than rural areas. Therefore, it is likely these sectors have a greater presence on the extremities or outside the classified urban areas, leading to their insignificance. Additionally, number of establishments and number of employees within each sector have an endogeneity problem. A high number of establishments will likely mean a high number of people are employed and vice versa, especially in urban centers. The number of establishments better captured a relationship with carbon emissions released rather than number of people employed within each sector. Thus, the final model includes only sector variables relating to number of establishments. Find the final model below where *ln(carbon)* is logged carbon dioxide, *TTI* is the Travel Time Index, *l2. HOT2* is the opening of a second HOT lane, *ln(commutecap)* is logged commuters per capita, *ln(pop)* is logged population, *ln(fuel)* is logged motor fuel, *ln(tu)* is logged number of transportation/utility establishments, *ln(mining)* is logged number of mining establishments, *ln(construct)* is logged number of construction establishments, *ln(retail)* is logged number of retail establishments, *ln(finance)* is logged number of finance establishments and *yr** is year id:

$$\ln(carbon) = \beta_0 + \beta_1(TTI = l2.HOT2) + \beta_2 \ln(commutecap) + \beta_3 \ln(pop) + \beta_4 \ln(fuel) + \beta_5 \ln(tu) + \beta_6 \ln(mining) + \beta_7 \ln(construct) + \beta_8 \ln(retail) + \beta_9 \ln(finance) + yr^* + \varepsilon$$

If the hypothesis is correct, implementing a second HOT lane will reduce congestion in the urban area. This reduction in congestion will then in turn reduce the amount of carbon dioxide outputted into the atmosphere, thus improving the health of citizens and the environment in the surrounding area.

VI. Results

The results from the first stage and second stage are seen in table 2 below:

Table 2

First stage			**Second Stage**		
TTI	**Coef.**	**Robust Std. Err.**	**ln(carbon)**	**Coef.**	**Robust Std. Err.**
L2. HOT2	-0.02014***	0.00432	**TTI**	-0.92123	0.70237
ln(commutecap)	-0.07479***	0.02753	**ln(commutecap)**	0.46921***	0.12068
ln(pop)	0.05529***	0.01083	**log(pop)**	0.48391***	0.06284
ln(fuel)	-0.0159**	0.00806	**log(fuel)**	0.42899***	0.03408
ln(tu)	0.00413	0.00863	**ln(tu)**	0.26389***	0.03266
ln(mining)	0.00519	0.00339	**ln(mining)**	0.03178**	0.01276
ln(construct)	0.04421***	0.00674	**ln(construct)**	0.24346***	0.03725
ln(retail)	-0.0454***	0.01226	**ln(retail)**	-0.66415***	0.05894
ln(finance)	-0.00935	0.00763	**ln(finance)**	0.08246***	0.02821

After running the first stage regression, an F-test was ran to determine if *l2.HOT2* is a strong instrument. With an F-statistic of 21.73, the null hypothesis was rejected. Therefore, *l2.HOT2* is a strong instrument. Since the model incorporated only one instrument, the Sargen-Hansen test cannot be performed to prove validity. However, the instruments validity is proved in the appendix through multiple separate fixed effects regressions showing the significance of *l2.HOT2* in reducing the Travel Time Index. This significance shows that *l2.HOT2* is acceptable to use as a proxy for the Travel Time Index within the main two stage least squares regression. With a p-value of 0.000, the opening of a second HOT lane is significant in reducing the Travel Time Index by 0.020 in two years. This reduction in the Travel Time Index is equivalent to a 9.5% drop in peak travel time relative to off-peak travel time. This result is within 15% of the findings found in the defense of the instrument in the appendix. With a strong, valid and significant instrument, the second stage regression was run to see if the opening of a second HOT lane reduced carbon emissions in urban areas.

The results from the second stage show that a reduction in congestion due to the second HOT implementation is insignificant at reducing carbon emissions within an urban area. These results go against the initial hypothesis and provide an interesting point of analysis to why carbon emissions are not decreasing. Reviewing the data, urban areas that opened a second HOT lane did so in 2012. The dataset used for this research extended only until 2014. Therefore, it could be the case that HOT lanes only reduce congestion in the short term. The theory used to justify a HOT lane as the correct road infrastructure investment was a short term economic model. Thus, once people adjust their behavior to utilize these lanes, the lanes could follow the same fundamental law of congestion that other forms of road infrastructure investment follow, even with a toll disincentive. People that used alternative forms of transportation before the second HOT lane opened could change their behavior once they learned congestion was reduced slightly and start commuting to work via personal transportation. This analysis would imply that congestion would eventually return back to its original levels after the two year lag. However, further examination would be required to validate this hypothesis.

Another potential reason the opening of a second HOT lane does not reduce carbon emissions could be the macroeconomic climate at the time they opened. As previously mentioned, all urban areas that opened a second HOT lane did so in 2012. Following the finance crisis in 2008, a period of low interest rates began as well as a falling gasoline prices. Coupled with low interest rates and falling gasoline prices, U.S. citizens in the market for a new car could have purchased a car with a worse fuel economy than previously owned due to the current gas prices, with the assumption the gas prices will stay low. With more of these less efficient cars on the road, more carbon dioxide would be emitted into the atmosphere even with reduced congestion. Although opening an HOT lane may successfully reduce congestion, carbon emissions from automobiles are truly a function of vehicle characteristics and driver behavior. Thus, congestion was successfully reduced but macroeconomic factors potentially encouraged a change in vehicles and driver behavior on the road; therefore, unsuccessfully reducing carbon emissions in the urban area.

Finally, the data used within the regressions suffers from measurement error. Due to the spreading nature of gas particles, they could be moving across urban area lines. Thus, carbon dioxide coming from other areas may wash out any potential reduction in carbon dioxide due to traffic alleviation. The Travel Time Index itself suffers from measurement error since it estimates the peak travel time relative to off-peak travel time. This estimation may be over or underestimated, thus altering the true relationship between HOT implementations and congestion reduction. Additionally due to data availability, the scaling of statewide data to best represent the urban area may be biasing estimates. This measurement error could all contribute to the insignificance of the opening of a second HOT lane at reducing carbon dioxide emissions within urban areas.

VII. Robustness

In order to reinforce the validity of the main regression, a robustness test was performed. In the test, sector data that accounted for number of establishments in each urban area was changed to number of employees within each sector. The number of employees was transformed into per capita terms by dividing each sector employment by the urban area population. These per capita sector employment numbers were then logged to best fit the model. The results of the first stage and second stage are seen in table 3 below where *ln(tuempcap)* is logged number of employees per capita within the transportation/utility sector, *ln(constructcap)* is logged employees per capita in the construction sector, *ln(retailempcap)* is logged employees per capita in the retail sector, *ln(miningempcap)* is logged employees per capita in the mining sector and *ln(financeempcap)* is logged employees per capita in the finance sector:

Table 3

First Stage			**Second Stage**		
TTI	**Coef.**	**Robust Std. Err.**	**ln(carbon)**	**Coef.**	**Robust Std. Err.**
L2. HOT2	-0.01421***	0.0039	**TTI**	-1.23958	1.19986
ln(commutecap)	-0.04319	0.03323	**ln(commutecap)**	0.33855*	0.18179
ln(pop)	0.02978*	0.017	**ln(pop)**	0.27437***	0.09833
ln(fuel)	-0.01171	0.01337	**ln(fuel)**	0.47249***	0.05402
ln(tuempcap)	0.00115	0.00254	**ln(tuempcap)**	0.00997	0.00967
ln(constructcap)	0.02328***	0.00715	**ln(constructcap)**	0.09283**	0.04362
ln(retailempcap)	-0.00704	0.00922	**ln(retailempcap)**	-0.12929***	0.04495
ln(miningempcap)	0.00298	0.00235	**ln(miningempcap)**	0.00832	0.00928
ln(financeempcap)	-0.01613**	0.00728	**ln(financeempcap)**	-0.01779	0.03417

After running an F-test on *l2. HOT2,* with an F-statistic of 13.25, the instrument is strong. Additionally, as mentioned in the main regression, the instrument is valid. The instrument is still significant at the 0.01 level and will reduce the Travel Time Index by 0.014. The second stage of this robustness test reinforces the results of the main regression. With a p-value of 0.30, any effect of congestion alleviation a second HOT lane has on the Travel Time Index has no effect on carbon emissions. Thus, opening a second HOT lane in an urban area is insignificant at reducing carbon emissions.

VIII. Conclusion

This paper discussed the effect of road infrastructure investment on congestion and in turn its effect on emissions. Although a first HOT lane is insignificant at reducing congestion, the opening of a second HOT lane has potential to reduce peak travel times relative to off-peak travel times within an urban area by about 9.5%. These results aligned with the short term theoretical model of congestion pricing as well as previous empirical results discussed in the literature review. However, the opening of a second HOT lane does not reduce carbon emissions in the local urban area. This insignificance could be attributed to HOT lanes following the fundamental law of congestion in the long term, the macroeconomic climate during the analysis and/or measurement error within the data. Nevertheless, the findings have important implications for local governments trying to address a growing congestion issue. As mentioned in the literature review, congestion can be a tough problem to alleviate due to supply and demand factors of road use, personal transportation preferences and the cost of infrastructure investment. However, the congestion pricing tactic seems to be a plausible solution to date by offering governments a cost effective alteration to an existing HOV lane, encouraging carpooling outside households or by compelling users to make a time use decision. As discussed in the results section, although this congestion reduction may only last in the short-term, it offers local governments opportunity for increased revenue in the long term. In the future, further research should take place as more data is collected on HOT lanes. Six out of the twelve urban areas implemented an HOT lane in 2012 and the data collected in this paper only extended to 2014. A dataset that extends closer to present time will offer more insight on effectiveness of this road infrastructure investment and its impact on congestion and carbon emissions. If HOT lanes are found to reduce carbon emissions in the surrounding area in the future, they could provide an even more attractive investment with their positive externalities. With a reduction in congestion and carbon dioxide levels, HOT lanes could be the road to improve the happiness and overall wellbeing of the residents in the immediate area. However, if you are concerned about your impact on the environment, for now it is best to buy a Totoya Prius.

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X. Appendix

Please see below a discussion of the fixed effects model ran to determine the best instrumental variable used in the main regression:

10.A. Model

The model includes a variety of controls to capture other determinates of congestion such as logged population, logged total vehicle miles traveled per capita, logged automobile commuters per capita and logged traffic fatalities per capita. In preliminary models, logged traffic fatalities were insignificant and removed from the final model. See the final fixed effects model below where *TTI* is the Travel Time Index, *L2. HOT1* and *L2. HOT2* are dummy variables for lane opening dates, *ln(TotVMTCap)* is logged total daily vehicle miles traveled per capita, *ln(CommCap)* is logged automobile commuters per capita and *ln(pop)* is logged population:

$$TTI = \beta_0 - \beta_1 L2.HOT1 - \beta_2 L2.HOT2 + \beta_3 \ln(TotVMTCap) + \beta_4 \ln(CommCap) + \beta_5 \ln(Pop) + \varepsilon$$

This fixed effects model is not controlled for year effects since most year to year changes will be captured by per capita variables as well as the population variable. Additionally, both HOT1 and HOT2 are lagged by two years. These variables are lagged to help take care of a simultaneity issue since urban areas that implement HOT lanes are likely the ones suffering from the most congestion. Thus, the lag allows for the local population to adjust their commuting behavior to this new roadway and will capture the implementation effects on congestion once commuting patterns have changed. This model also uses robust standard errors to account for heteroscedasticity.

10.B. Results

The results are seen in table 4 below:

Table 4

TTI	Coef.	Robust Std. Err.
L2. HOT1	0.00683	0.00562
L2. HOT2	-0.01741**	0.00843
ln(commutecap)	0.12852**	0.05955
ln(totVMTcap)	0.08431***	0.03017
ln(pop)	0.09234***	0.02553

After running a fixed effects model, the analysis shows that if an urban area implemented a single HOT lane, *L2. HOT1,* it is insignificant in reducing congestion. This variable is insignificant with a p-value of 0.23. At first this result was disappointing; however, upon further analysis the insignificance makes sense. The Travel Time Index is measured by urban area. Therefore, this metric takes into account traffic on all roads with or without a HOT lane. Since a HOT lane normally does not extend the full length of a roadway, one HOT lane would not have a significant impact on the total urban area's traffic. However, it may potentially have an impact on the travel times on the specific roadway it was opened on. The results found that *L2. HOT2* is significant with a p-value of 0.044. Thus if an urban area opened a second HOT lane, on average two years later the implementations were able to reduce the congestion index in the urban area by 0.017. To provide context to this output, let the Travel Time Index for an arbitrary urban area with one existing HOT lane be 1.23 in 2014, which the mean of the Travel Time Index from 1994-2014 across all urban areas. If this urban area opened up a second HOT lane in 2014, by 2016 the Travel Time Index would have a value of 1.213. Using the same methodology from the data section of the paper, the second HOT lane opening would decrease peak travel time relative to off-peak travel time by in the urban area by 7.6% in two years. This decrease in the congestion has economic implications beyond time savings. By reducing congestion, the urban area becomes more productive while simultaneously reducing costs.

10.C. Robustness

In order to defend the results of the fixed effects regression, several robustness tests were performed. In particular, a random effects model and a fixed effects model with a year ID were run. The first robustness tests ran a random effects model, including regional dummy variables to capture the differences across urban areas located in different regions of the United States. These regional dummy variables are based off of the U.S. Census Bureau classifications. The results are seen in table 5 below:

Table 5

TTI	**Coef.**	**Robust Std.Err.**
L2. HOT1	0.00698	0.00057
L2. HOT2	-0.01712**	0.00823
ln(commutecap)	0.13422***	0.04082
ln(totVMTcap)	0.07887***	0.02611
ln(pop)	0.08611***	0.01306
NE	-0.0653***	0.02137
SE	-0.05884***	0.01952
MW	-0.104***	0.01856
W	0	(omitted)

This output reveals that the west has the most congestion when compared to every region, which is to be expected. More importantly, the output of HOT1 and HOT2 mirror the results of the main regression. *L2. HOT1* is still insignificant while *L2. HOT2* becomes slightly more significant with a p-value of 0.038 and a nearly identical coefficient of -0.017.

The second robustness test ran a fixed effects model that included a year ID, which captures any year-to-year changes over the time period the data was collected. The results are seen in table 6 below:

Table 6

TTI	**Coef.**	**Robust Std. Err.**
L2. HOT1	0.00465	0.00487
L2. HOT2	-0.0148**	0.0059
ln(commutecap)	-0.10957	0.06888
ln(totVMTcap)	0.04016*	0.02304
ln(pop)	0.04098*	0.02115

The results from this regression further reinforce the validity of the main regression. Although including the year ID causes some of the control variables to be insignificant, the outputs for HOT1 and HOT2 are once again repeated. In this regression, *L2. HOT1* is still insignificant at reducing congestion while *L2. HOT2* is significant at reducing congestion after two years. In fact, it will reduce the Travel Time Index by about 0.015, which is within 10% of the main regression's results.

Since these robustness tests help validate that a second HOT implementation is successful in reducing congestion in two years, HOT Implementation 2 is, therefore, a valid instrumental variable.