Estimating Induced Travel from Capacity Expansions on Congested Corridors

Michael L. Anderson Lucas W. Davis Leila Safavi*

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Principal Investigators: Michael L. Anderson and Lucas W. Davis

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[*] This report was prepared for the California Air Resources Board and the California Environmental Protection Agency. (Anderson) University of California, Berkeley; *mlanderson@berkeley.edu* (Davis) University of California, Berkeley; *lwdavis@berkeley.edu*; (Safavi) University of California, Berkeley; *lsafavi@berkeley.edu*.

Disclaimer

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Abstract

This project uses Caltrans Performance Measurement System (PeMS) data from four study sites to estimate the effects of non-general purpose lane capacity expansions on traffic flows. These effects, often referred to as “induced travel,” are critical in determining the environmental impacts of transportation infrastructure projects and forecasting regional changes in vehicle miles traveled (VMT). While a number of studies estimate correlations between aggregate miles of roadways and total VMT, these results are not directly applicable to most current and future California roadway capacity projects, since non-general purpose lane expansions including high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes are becoming an increasingly common strategy for expanding capacity on congested freeways. The results indicate statistically significant increases in average speeds and traffic flows at all four study sites. The increases tend to be larger during peak hours, though increases are documented in most cases during both peak- and off-peak hours. The report also presents results from a set of “placebo tests” using data from locations without lane expansions for comparison purposes. These estimates reflect short-run local impacts and do not speak to medium- or long-run effects, spillovers to arterial street networks, regional impacts, or land use changes.

Executive Summary

Background

In California the transportation sector is the largest source of carbon dioxide emissions and criteria pollutants (California Air Resources Board, 2017). Reducing roadway travel is thus critical for the state's climate and air quality goals. These objectives potentially conflict, however, with ongoing efforts to reduce traffic congestion by expanding the roadway network. Economists and transportation engineers have long observed that roadway capacity creates its own demand, a phenomenon known as induced travel or the "Fundamental Law of Congestion" (Downs, 1962).

While existing scholarship on induced travel is robust (Deakin et al., 2020), few studies have examined non-general purpose lane capacity expansion projects, including high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes. This study helps to fill this gap in knowledge by measuring the effect of expanding roadway capacity via non-general purpose lanes on average speeds and traffic flows. This research is timely and topical because an increasing number of California's freeway expansion projects include HOV and HOT lanes.

Objectives and Method

This project uses data from the Caltrans Performance Measurement System (PeMS) to estimate the impacts of lane capacity expansions on speed and traffic flow (i.e. the number of vehicles per hour that pass a particular location). A significant advantage of this project is that it relies entirely on publicly-available, non-confidential data, and all of our data and code from the analyses will be posted publicly upon completion of the project.

Our analysis focuses on four prominent study sites, and induced travel is identified using regression analyses that control for seasonal, weekly, and daily traffic patterns. We hypothesize that lane expansions increase average speeds and traffic flows. These two outcomes are causally related. Higher speeds reduce the effective price of travel, leading drivers to take more trips. We expect induced travel to be especially pronounced during peak driving periods, when the reductions in traffic congestion are most significant. Accordingly, we report results both for peak and off-peak periods. We also report results from a set of "placebo tests" using data from locations without lane expansions for comparison purposes.

It is important to emphasize that our estimates are most credible for measuring short-run, highly-localized impacts. Making causal statements about medium- and long-run impacts, or about broader regional impacts, is much more challenging because of the difficulty in constructing a credible counterfactual. In the short run, outcomes prior to the expansion provide a highly credible counterfactual to outcomes after the expansion. However, in the long run it becomes much more difficult to disentangle the causal impact of the expansion from slowly-evolving demographic, employment, and economic factors.

Results

We find statistically significant increases in average speed at all four study sites. Average speed increases both during off-peak and peak periods, but the increases tend to be concentrated during peak periods. For example, with the I-580 Express Lanes project we find average speed increases of 6 mph during off-peak periods and 21 mph during the morning rush hour. These results for average speed confirm our hypotheses and provide an important "first-stage" for testing induced travel.

We find statistically significant increases in traffic flows at all four sites. As expected, the increases tend to be larger during peak hours, though we find increases in traffic flows both peak- and off-peak in most cases. For example, with the I-580 Express Lanes project we find 18% increases in traffic flows during off-peak periods, and 31% increases during the morning peak. While one might expect HOV and HOT lane expansions to *decrease* traffic flows via induced carpooling, we find no evidence of net declines in traffic flows at any of the four sites.

Conclusions

HOV and HOT lanes differ from general purpose lanes because they create an incentive for carpooling. This incentive potentially mitigates the traditional induced travel effect by increasing vehicle occupancy. Nevertheless, we find that induced travel is more than sufficient to offset increased vehicle occupancy, resulting in a net increase in traffic flows. In future work it would be interesting to learn more about how these projects change the carbon *intensity* of travel (i.e. CO2 per passenger-mile traveled). Another top priority for future research is to better understand congestion pricing strategies for HOT lanes.

Body of Report

Introduction

The transportation sector is the largest source of carbon dioxide emissions in the United States, contributing 1.9 billion metric tons of carbon dioxide emissions in 2019. This equates to 37% of all energy-related carbon dioxide emissions (U.S. Energy Information Administration, 2020). In California the transportation sector plays a similarly outsized role, again responsible for 37% of all emissions, and the largest source of criteria pollutants as well (California Air Resources Board, 2017). The overwhelming majority of sector emissions come from roadway vehicles. Reducing roadway travel is thus critical to reducing GHG emissions and local air pollution.

This goal is potentially in conflict, however, with ongoing efforts to reduce traffic congestion by expanding the roadway network. Researchers in the transportation, planning, and economic literatures have long pointed out that expanding the roadway network reduces travel times, potentially leading to an increase in vehicle use. A recent expert panel defines induced travel as follows: "A project that reduces user travel costs — reduces travel time, uncertainty, risks, or expenditures — can lead to changes in traveler behavior that can increase the overall amount of travel." (Deakin et al., 2020).

Empirical studies on induced travel extend back several decades. Early studies claimed that over time, the effects of induced travel would completely offset any reduction in congestion following capacity expansion (Downs, 1962; Smeed, 1968). Most subsequent studies find strong correlations between vehicle miles traveled (VMT) and total miles of roads, though the exact elasticity estimates vary widely. Short- and long-run elasticity estimates range from 0.19-1.34 and 0.53-1.03, respectively, using a wide variety of different methodologies and geographies. See, for example, Cervero (2002), Noland and Hanson (2013), and Handy and Boarnet (2014).

While existing scholarship on induced travel is robust, there has been relatively less focus on non-general purpose lane capacity expansion projects, including high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes. See Appendix A for our summary of the existing literature, with particular emphasis on available studies of HOV and HOT lanes.

This project complements recent work by Deakin et al. (2020) by measuring the effect of lane expansions on average speeds and traffic flows, with a particular emphasis on non-general purpose lanes, including both HOV and HOT.[1] Speed is measured in miles-per-hour and flows are measured as the number of vehicles per hour that pass a particular location. We focus on traffic flows because they are an easily available measure of induced travel. A more comprehensive measure of induced travel would include all forms of travel in all locations, and would typically be measured in VMT.

Our analysis focuses on four prominent study sites including three non-general purpose lane expansions and one general-purpose lane expansion project. To establish the robustness of our findings, we also compare our estimated changes in speeds and flows to analogous changes at four "control" sites that lie in the vicinity of our study sites but experienced no expansions.

This research is timely and topical because, though state and regional agencies have acknowledged the induced travel impacts of adding general-purpose lanes to congested freeways, an increasing number of freeway expansion projects include managed lanes, such as HOV and HOT lanes. Additionally, the Solutions for Congested Corridors Program (created by Senate Bill [SB] 1) explicitly states that, "program funds cannot be used to construct general purpose lanes on a state highway. Capacity increasing projects on the state highway system are restricted to high-occupancy vehicle lanes, managed lanes, and other non-general-purpose lane improvements for safety and/or operational improvements for all modes of travel. Examples are auxiliary lanes, trucks climbing lanes, or dedicated bicycle lanes." Going forward it is thus reasonable to expect that most state freeway expansion projects will involve HOV or HOT lanes.

Materials and Methods

Literature Review

We begin with a review of the existing literature. For this review we surveyed the relevant economic, transportation, and planning studies on induced travel and characterized their relevance for modern roadway capacity enhancement projects. We

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[1] Deakin et al. (2020) conclude, "In short, the panel's assessment was that special purpose lanes, including HOV and HOT lanes, add capacity, and this capacity increase has the potential to support additional travel. How much additional capacity is added is a function of how the lane is designed, managed, and used and the travel behaviors, particularly for HOV and for HOT lanes, and these factors are complex and not completely understood. The panel concluded that *more investigation of these issues is important to establish a strong evidentiary basis for estimating the induced travel effects of these lane types* [emphasis added]." (p. 19)

classified studies according to research design, geography, and time period, identifying those most relevant to current California policies. Particular attention was paid to capacity enhancement projects and to non general-purpose lane expansions. A reviewed and revised version of the literature review is included in the Appendix.

Site Selection

We next worked with the California Air Resources Board, other State agencies, and other key stakeholders to identify a set of lane capacity enhancement projects in California. We were particularly interested in identifying non-general-purpose lane expansion projects and projects that occurred in the last decade, for which data availability is better. We conducted preliminary assessments of data quality at about one dozen potential sites, before narrowing the set to four study sites with good data availability. For each of these four study sites, there is relatively good coverage in the PeMS data, including several continuously functioning loop detectors and time series coverage both before and after the capacity expansion.

Table 1 describes the four study sites. All four study sites are lane expansion projects in California, two in the San Francisco Bay Area and two in Southern California. Figure 1 and Figure 2 show the geographic locations of the Bay Area expansion sites and Southern California sites in red, respectively. All four expansions occurred between 2010 and 2016, and all were major projects with total project costs in excess of $200 million. To determine the exact opening dates we consulted news archives and other sources.

Table 1: Selected Study Sites

Name of Expansion Project	Highway	County	Year of Expansion	Project Cost (Millions)
Caldecott Tunnel Fourth Bore	SR 24	Alameda and Contra Costa	2013	$417
San Bernardino Widening Project	I-215	San Bernardino	2010	$723
I-580 Express Lanes	I-580	Alameda	2016	$345
West County Connectors	I-405	Orange	2014	$297

Based on helpful feedback from CARB, we also selected a nearby comparison site for each of the four study sites (see Table 2). The goal with these comparison sites is to provide a credible counterfactual for how outcomes would have evolved at the study site in the absence of the expansion project. The locations of the comparison sites are also shown in Figure 1 and Figure 2. We selected comparison sites in the same county as each of our study sites to capture changes in county-level employment and other county-level trends. In selecting comparison sites we attempted to select locations that were unlikely to be traversed by trips that also cross the study site of interest, so as to avoid capturing any direct impacts of the lane expansions.

Figure 1: Northern California Study Sites

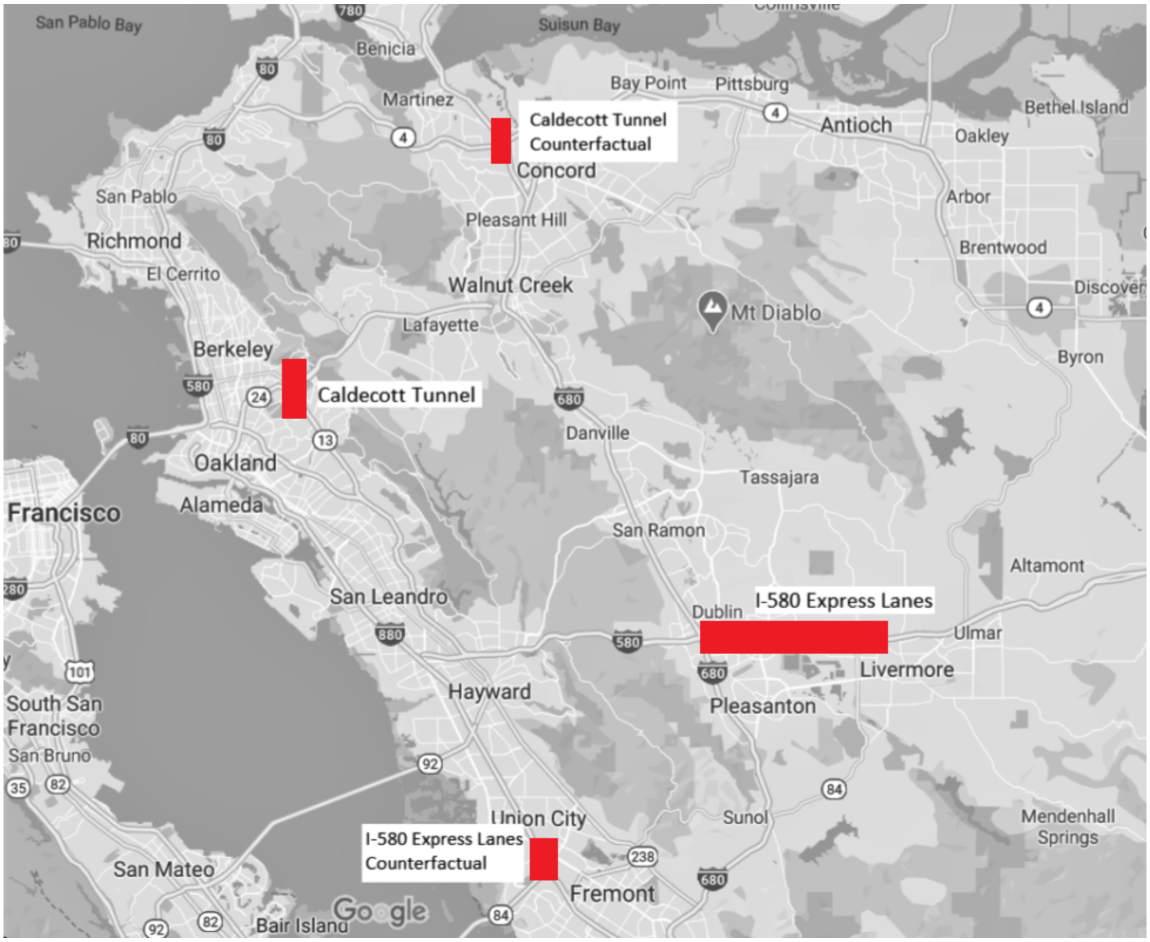


Figure 2: Southern California Study Sites

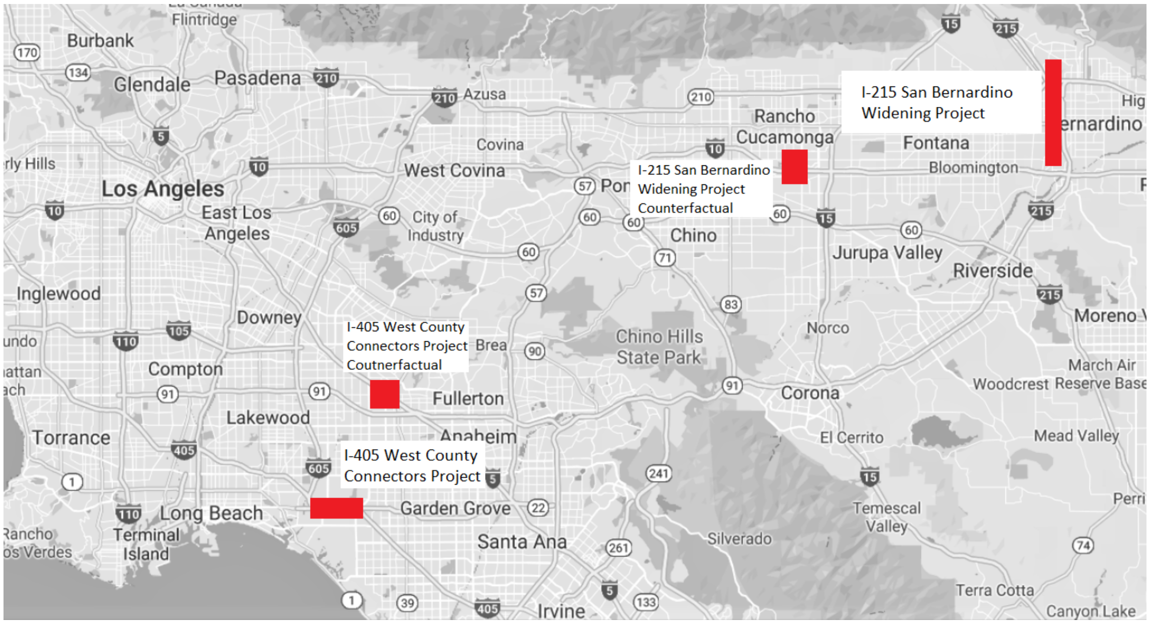


Table 2: Study and Comparison Sites

Study Site		Comparison Site	
Highway	County	Highway	County
SR 24	Alameda and Contra Costa	SR 4	Contra Costa
I-215	San Bernardino	I-10	San Bernardino
I-580	Alameda	I-880	Alameda
I-405	Orange	I-5	Orange

Detailed Description of Study Sites

Table 3 summarizes the context and lane expansion type for each project. Site 1 is California State Route 24 (SR-24) at the Caldecott Tunnel. SR-24 connects suburban Contra Costa County, to the east, with the cities of Oakland and San Francisco, to the west. Traffic flows at this location peaks Westbound in the morning and Eastbound in the afternoon, driven by commuters who live in suburban Contra Costa County travel and work in Oakland, San Francisco, and surrounding areas. The land use immediately around the location is suburban as well as park areas including the Claremont Canyon Regional Preserve, Sibley Volcanic Regional Preserve, and the Siesta Valley Recreation Area.

The study site is a classic bottleneck, with the number of lanes decreasing as traffic approaches the tunnel. The Caldecott Tunnel consists of multiple “bores,” each with two lanes. Prior to expansion there were three bores (six lanes total), with only one bore operating in the off-peak direction at any given time. We focus on the expansion, completed November 15, 2013, of the fourth bore, which took the total number of tunnel lanes from six to eight, relieving the bottleneck in the off-peak direction. Figure 3 presents before and after images from Google Earth. Today at the Caldecott Tunnel SR-24 continues to have four lanes in each direction (eight total).

Site 1 is the one general purpose lane expansion we consider in this project; the other three sites all include HOV or HOT lane expansions. At Site 1 we focus in particular

Figure 3: Fourth Bore Project at SR-24 Caldecott Tunnel


(a) 2008

(b) 2014

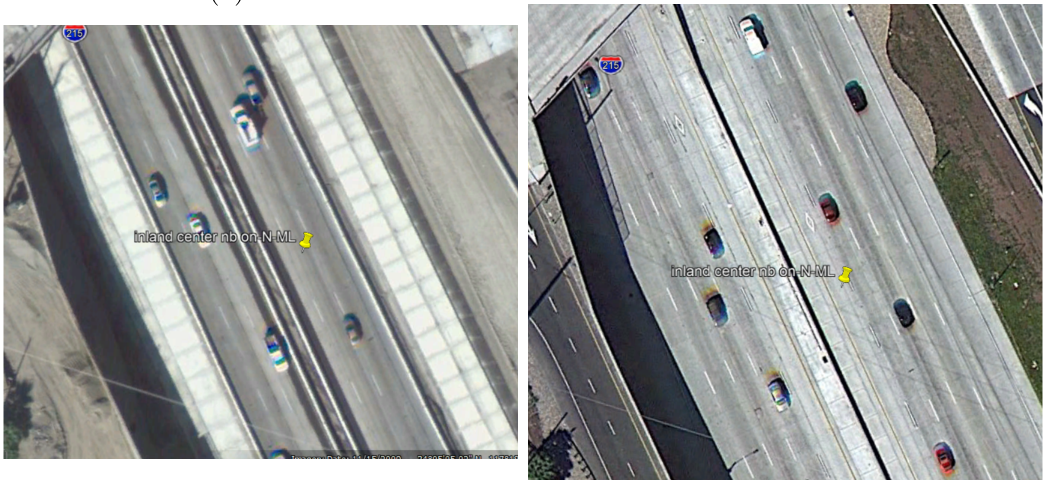
on data from two specific loop detectors: (1) Tunnel Road East and (2) Gateway Boulevard West. Both detectors have reasonably good coverage, though for the data from Tunnel Road East there are long stretches of missing data for Lane 1 at this location, including missing observations for all of 2014.

Site 2 is the San Bernardino Widening project on Interstate 215 (I-215) in San Bernardino County, 60 miles east of Los Angeles. The I-215 travels through the city limits of San Bernardino (population 215,000). To the North, the I-215 connects to I-15. To the South, the I-215 connects to CA-60, CA-91 and Riverside (population 330,000). Northbound traffic at this location peaks in both the morning and the afternoon. The land use immediately around the location is urban/suburban San Bernardino with a mix of residential and commercial and a broad network grid of surface streets.

We focus on Phase 2 of this multi-phase project, which widened I-215 between Orange Show Road and Rialto Avenue. Several bridges were reconstructed, new on- and off-ramps were constructed, and the freeway was widened from three to five lanes in each direction, with the addition of one general purpose lane and one HOV lane in each direction. Phase 2 was completed July 28, 2010. Figure 4 presents before and after images from Google Earth.

With Site 2 we focus on northbound traffic at the Orange Show and Mill loop detectors. Detector coverage in the southbound direction is insufficient during the sample period to support an empirical analysis. Moreover, in the northbound direction we observe speeds and flows from both the mainline and HOV lanes, whereas in the southbound direction data is available from the mainline lanes only.

Figure 4: Lane Expansion at I-215 San Bernardino Widening Project



(a) 2009

(b) 2011

Site 3 is the Interstate 580 (I-580) Express Lanes project in Alameda County, 26 miles southeast of Oakland. The express lanes span 10 miles in the eastbound direction and 12 miles in the westbound direction, traveling through Dublin (population 63,000), Pleasanton (population 82,000), and Livermore (population 90,000). Traffic at this location peaks Westbound in the morning and Eastbound in the afternoon, driven by commuters who live in Dublin, Pleasanton, Livermore, and surrounding areas and who work to the West in Hayward, Union City, Fremont, or in other parts of the Bay Area. The land use immediately around the location is suburban including a mix of residential, commercial, as well as park areas including Doolan Canyon Regional Preserve.

The Express Lanes project added two new lanes westbound throughout most of the broader project area, including one new HOT lane and one new general purpose lane. However, we focus on a specific location where just a single new HOT lane was added with no additional general purpose lane. Eastbound, one new HOT lane was added, and one HOV lane was converted to HOT. These new lanes opened February 19, 2016.

With Site 3 we focus on westbound traffic at the Isabel Avenue loop detector. A limitation with Site 3 is that we do not observe data in the HOT lane. Thus the speed and flow data that follow are measured in mainline lanes only. We focus on the westbound direction because detector coverage in the eastbound direction is

Figure 5: Lane Expansion at I-580 Express Lanes Project


(a) 2014

(b) 2017

insufficient during the relevant sample period to support an empirical analysis; in particular, there is no coverage of Lane 6 (the rightmost lane) after the expansion at Isabel. We explored the possibility of "splicing in" Lane 6 from a nearby detector (e.g. Airway) but we could not find a good match and had lingering concerns that Lane 6 at other locations could be a poor proxy for the missing coverage in Lane 6 at Isabel. Figure 5 presents before and after images from Google Earth.

Site 3 is the only one of the four sites with HOT lanes. Vehicles with 2+ individuals access the HOT lanes at this location for free. Solo drivers at this location can pay a toll to access the HOT lanes. Toll prices depend on congestion levels and are updated every 3 minutes and displayed to drivers on overhead signs. During the first year of operation tolls averaged \$1.62 and \$2.13 for travel westbound and eastbound, respectively, but reached as high as \$9.75 and \$9.00. Tolls for end-to-end travel are capped at \$13.00 and \$9.00 for westbound and eastbound travel, respectively. HOT lane users must have a FasTrak electronic toll tag and an active FasTrak account.[2] There are no tollbooths, and users can enter and exit the HOT lanes at most locations (see Alameda County Transportation Commission (2017, 2018) for details).

Finally, Site 4 is the West County Connectors project on Interstate 405 (I-405, or San Diego Freeway). This study site is at the western edge of Orange County, inside the greater Los Angeles metropolitan area, and passing through parts of Garden Grove (population 172,000), Westminster (population 90,000), and the edge of Long Beach

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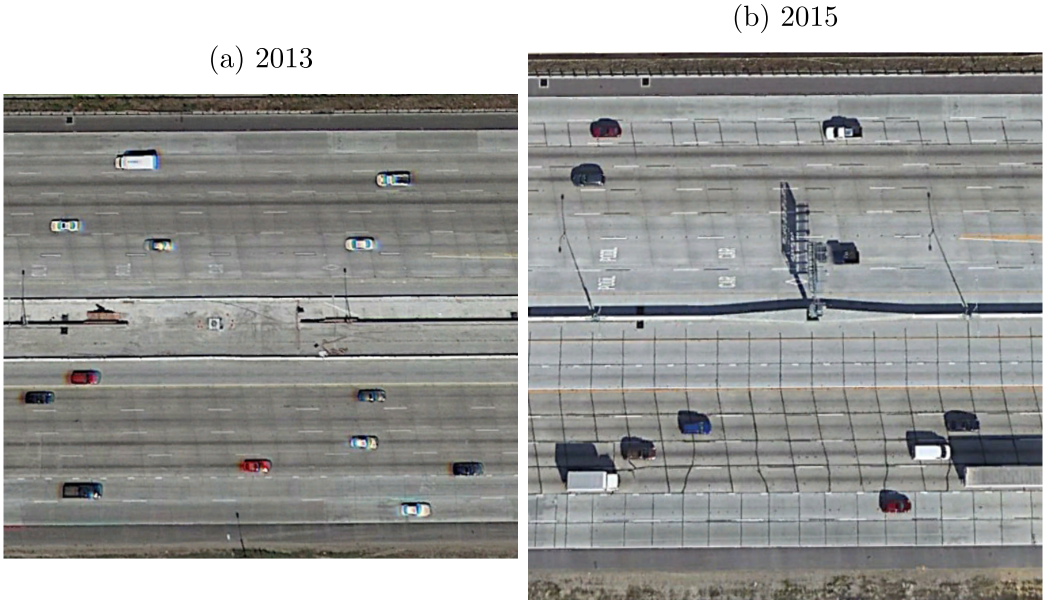
[2] The HOT lanes are free to carpools (2+), vanpools, motorcycles, buses, and eligible clean-air vehicles, as well as to all vehicles outside the hours of operation Monday through Friday 5am to 8pm. Carpoolers need the FasTrak Flex toll tag which has a switch allowing the user to indicate the number of riders (1, 2, or 3+) in the vehicle. During the first year of operation, 38% of HOT lane users accessed the lanes toll free.

Figure 6: Lane Expansion at I-405 West County Connectors Project


(a) 2013

(b) 2015

(population 460,000). Northbound traffic at this location is heavy from morning through evening. Compared to the other three study sites there is at this location less of a well-defined peak, consistent with a more varied composition of drivers. The land use immediately around the location is suburban including a mix of residential, commercial, as well as park areas including the Seal Beach National Wildlife Refuge.

West County Connectors was a 4-year project that added a second HOV lane in both north and south directions, as well as bridges to connect the HOV lanes on I-405 with SR-22 and I-605. The project was completed December 10, 2014.

With Site 4 we focus on northbound traffic. Detector coverage is insufficient in the southbound direction during the period prior to the capacity expansion to support an empirical analysis. Figure 6 shows before and after images from Google Earth. Northbound traffic (i.e. traveling from right to left) has 7 lanes in 2013 and 8 lanes in 2015, including two lanes clearly marked as HOV lanes.

Description of the Data

For each study site and comparison site we collected data on speeds and traffic flows from the California Department of Transportation (Caltrans). Our data come from the Performance Measurement System (PeMS) database, a publicly-available compendium of traffic-related information from the California freeway system. PeMS includes a wealth of historical and real-time information about traffic, lane closures, and incidents. The data for this analysis comes from PeMS' system of almost 40,000 loop detectors throughout the state.

Loop detectors are small insulated electric circuits installed in the middle of traffic lanes. As illustrated in Figure 7, loop detectors are typically installed in the same place across all lanes. Loop detectors measure the rate at which vehicles pass, measured in vehicles per five minutes period. In addition, loop detectors measure average vehicle speed by sensing how long it takes each vehicle to pass over the detector. Vehicle speed is measured in average vehicle speed in miles-per-hour during a five-minute period.[3]

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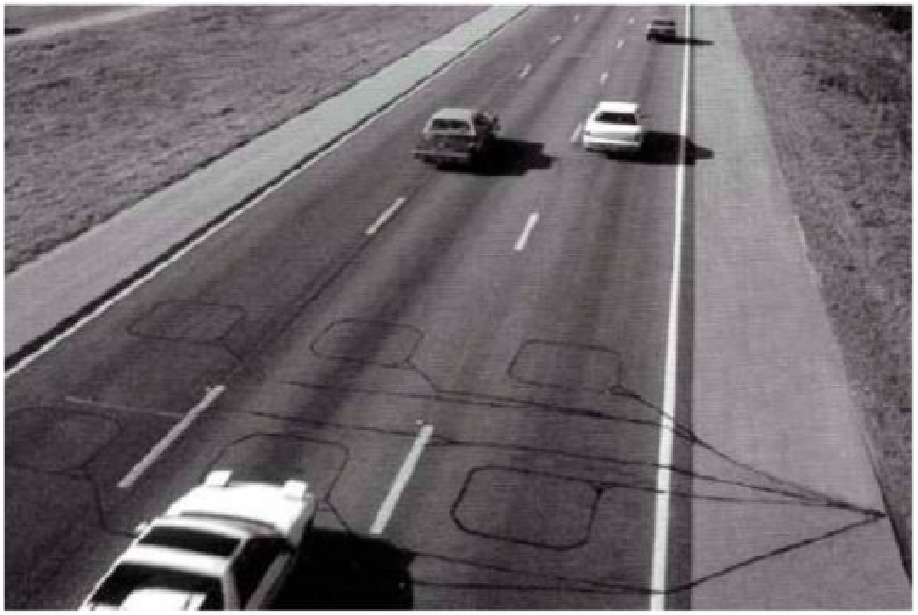
[3] We also explored the possibility of using a different kind of monitor, Traffic Census stations, to study traffic volume and speed for trucks. While all of our sites except I-405 had a census station directly on the expanded portion of the highway, none of these census stations were collecting data during the appropriate time frame for our research design, both before and after.

Table 3: Study-Site Context

Project	Site Context	Expansion Type
Caldecott	Commute route from Contra Costa County suburbs (east) to job centers in Oakland, Berkeley, and San Francisco (west)	Off-peak general-purpose lanes
San Bernardino	Commute route from San Bernardino and points north to Riverside and points south	General-purpose and HOV lanes
I-580 Express Lane	Commute route from Livermore/Central Valley exurbs (east) to job centers in Oakland, San Francisco, and San Jose (west)	General-purpose and HOT lanes
West County Connectors	Bidirectional route linking Los Angeles/Long Beach (north) and Santa Ana/Orange County (south)	HOV lanes

Figure 7: Typical Installation of Loop Detectors



Source: Sobanjo (2019).

While the PeMS database offers measurements at frequent intervals, the loop detector data is not always complete over large stretches of time. There are a variety of reasons a loop detector may be turned off and unable to collect data, such as incidental power outages and shut-downs due to roadway construction.

We make no attempt to address missing data on speeds. This choice reflects our expectation that lane arbitrage will tend to equalize average speeds across lanes. It would be unusual, for example, to see one lane consistently experiencing 40mph travel while another averaged 60mph, as one would expect drivers to substitute to the faster lane. This arbitrage is likely to be strongest during peak hours when all drivers are choosing lanes to minimize delays. Thus for speeds we simply use the average speed across all observed lanes, implicitly assuming that these lanes are representative.

Traffic flows are more problematic, however. Drivers tend to prefer some lanes more than others so missing data from, for example, the left-hand lane is different from missing data from the right-hand lane, and we do not want our estimates of induced travel to be biased by compositional changes over time in data availability.

Thus to address this missing data problem for traffic flows we use two different strategies – one strategy for our graphical analyses and then a different second strategy for the regression analyses. We describe the first strategy here, and then in the following section describe the second strategy once we have introduced the regression equation.

In particular, for our graphical analyses, we use a regression-based imputation process to fill-in missing values when loop detector data for vehicle flows is not available. Specifically, we regress five-minute vehicle flows F_{it} for monitor i at time t on an interaction of loop detector ID, month-of-year, day-of-week, hour-of-day, and post-expansion indicators. Formally, let i index monitors, m index month-of-year, d index day-of-week, h index hour-of-day, and $\mathbf{1}[Post\ Expansion]_t$ is equal to 1 if the five-minute interval occurs after the expansion has occurred. We estimate the equation,

$$F_{it} = \gamma^1_{imdh} + \gamma^2_{imdh} \cdot \mathbf{1}[Post\ Expansion]_t) + \varepsilon_{it}. \tag{1}$$

The parameters γ^1 and γ^2 are conditional means by i, m, d and h for before and after the lane expansion, and ε_{it} is the error term. In effect, this process imputes a missing 5-minute flow observation at a given loop detector using historical data from the same loop detector at roughly the same time (e.g. average traffic flows at location i at 2 pm on Wednesdays in March).[4] We interact all of these fixed effects with a post-expansion indicator, essentially performing this imputation process two times, once using the pre-expansion data and then another second time using the post-expansion data. This approach ensures that we do not impute pre-expansion traffic flows using data from after the expansion, which may be higher due to induced travel demand. Failing to interact the monitor by month-of-year by day-of-week by hour-of-day indicator variables with the post-expansion indicator would tend to attenuate pre-versus-post comparisons when there are missing data.

A nice feature of this project is that it relies entirely on publicly-available, non-confidential data. All of the data used for this project can be downloaded through the PeMS website at `http://pems.dot.ca.gov/`. Using publicly-available, non-confidential data means that future researchers can replicate and extend all of our

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[4] In some cases, only a proper subset of lanes at a given loop detector may be missing data. In these cases, we impute data for the missing lanes, and combine those imputations with observed flows for the non-missing lanes. For example, if there are four lanes, two of which are missing, we sum the two non-missing flow observations with two imputed flow observations to infer total 5-minute flows at that location and time.

analyses and results. To this end, we will publicly post all data and code generated during the project to make it available to CARB and future researchers, and we have taken steps throughout the project to carefully document all methods to assist replication and extension.

Empirical Strategy

We measure the impact of lane expansions on average speed and vehicle flows by comparing outcomes before and after expansions. The following regression equation describes our approach:

$$Y_t = \beta_0 + \beta_1 \cdot \mathbf{1}[Post\ Expansion]_t + \theta_m + \alpha_d + \delta_h + \varepsilon_t. \tag{2}$$

We use a regression equation of this form for examining both speeds and flows. In both cases, the outcome variable is measured in five-minute periods, indexed by t. When we are examining speeds, Y_t denotes average vehicle speed, in miles-per hour, averaged across all lanes. When we are examining flows, Y_t denotes the natural log of total vehicle flows in all lanes. Using logs for the vehicle-flow regressions makes the estimated coefficients easier to interpret because they are approximately equal to percentage changes.[5]

The explanatory variable of interest, $\mathbf{1}[Post\ Expansion]_t$ is an indicator variable equal to one after the lane expansion and zero otherwise. We also include in all regressions a rich set of control variables, including month-of-year (θ_m), day-of-week (α_d), and hour-of-day (δ_h) indicator variables. We estimate Equation (2) separately by study site so these fixed effects control for site-specific seasonal, weekly, and daily patterns. These fixed effects also reduce the variance of the error term, ε_t, thus increasing the statistical precision of our estimates.

Unlike many previous analyses of induced travel, we report not only point estimates but also standard errors that can be used to construct 95% confidence intervals and p-values. These statistics are valuable because they allow readers to assess the reliability and precision of our results, as well as to perform hypotheses testing. In

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[5] We estimate proportional changes in flows for each expansion project, but we do not specifically estimate VMT figures because the expansion projects focus on relieving bottlenecks. Thus, while we know the roadway length of each project, we do not know the length of each trip that crosses the (relieved) bottleneck (to the best of our knowledge, these data do not exist). One can, however, make assumptions about average trip length at each study site and multiply the change in the number of vehicles crossing the bottleneck (flows) by the preferred estimate of trip length to compute VMT.

estimating standard errors and other statistics we cluster by calendar day to account for serial correlation in the error term ε_t.

The parameter of interest is β_1. This coefficient measures the impact of the lane expansion on the outcome of interest. That is, controlling for seasonal, weekly, and daily patterns, how does the outcome change after the lane expansion? Our hypothesis is that lane expansions will increase average speeds and vehicle flows. These two outcomes are causally related. Higher speeds reduce the effective price of travel, leading drivers to take more trips. We expect induced travel to be especially pronounced during peak driving periods when the reductions in traffic congestion are most significant. Accordingly, we report results both for peak and off-peak periods. We restrict the analysis throughout to include weekday observations only.

The identifying assumption for β_1 is that $\mathbf{1}[Post\ Expansion]_t$ is uncorrelated with ε_t. This is a reasonable assumption within a small time period around the lane expansion, but becomes a less reasonable assumption for a wider window due to broader trends and time-varying omitted variables. Over a longer time period, changes in population demographics, the distribution of employment, land use, and economic fundamentals will influence both average speeds and vehicle flows. Related, in all regressions we exclude data from after March 2020, corresponding to the onset of Covid-19. Our capacity expansion projects were all completed well before this period so this exclusion has little or no impact on our estimates.

As noted earlier, our data on traffic flows are not always complete; occasionally we are missing data at certain points in time. If all lanes are missing data during a given five-minute period t, then the observation gets dropped from the regression. However, if a proper subset of lanes are missing (i.e. less than 100% of lanes) during t, then the observation remains, and flows for the missing lanes are implicitly set to zero. These missing data may pose a problem for our estimates if data are missing during the hours of the day that we expect flow to be most affected by the expansion. In cases where the data are not missing at random, the β_1 coefficient in Equation (2) may not reflect the true impact of lane expansions on flows, as we do not directly observe the full traffic patterns. The coefficient could be biased upwards or downwards, depending on whether more data are missing from the pre- or post-expansion period, respectively.

To address the issue of missing data on traffic flows, we augment the regression described in Equation (2). In particular, we construct an additional variable, "% Missing," that equals the percent of 5-min observations missing at a monitor during a given hour. We include this variable and its interaction with the post-expansion indicator variable in the modified regression equation to control for the impact of missing observations on the observed traffic flows. The following regression captures this approach:

$$\begin{aligned} Y_t &= \beta_0 + \beta_1 \cdot \mathbf{1}[Post\ Expansion]_t + \beta_2 \cdot \%\ Missing_t \\ &\quad + \beta_3 \cdot \mathbf{1}[Post\ Expansion]_t \cdot \%\ Missing_t + \theta_m + \alpha_d + \delta_h + \varepsilon_t. \end{aligned} \tag{3}$$

In this modified regression, β_1 continues to remain the coefficient of interest. However, the regression now includes the β_2 coefficient as well, which controls for the impact of missing observations on the average traffic flow. Because we expect missing observations to lead to lower traffic flows on average (as the missing lane gets set to zero flows), we expect the β_2 coefficient to be negative. The interaction term, with coefficient β_3, controls for the fact that the impact of missing observations may differ in the pre- and post-expansion periods, as traffic flows change. The regression estimates for traffic flows presented throughout the rest of the paper use this augmented specification, described in Equation (3).

Before turning to the results, it is important for us to again emphasize that our estimates are most credible for measuring short-run, highly-localized impacts. Making causal statements about medium- and long-run impacts, or about broader regional impacts, is much more challenging due to the difficulty in constructing a credible counterfactual. In the short run, outcomes prior to the expansion provide a highly credible counterfactual to outcomes after the expansion. However, in the long run it becomes difficult to disentangle the causal impact of the expansion from slowly-evolving demographic, employment, and economic factors. For example, over a multi-year period, capacity expansions can lead to large-scale changes in land use. These impacts we cannot credibly measure with our approach.

Results

Evidence on Changes in Speeds After Lane Expansions

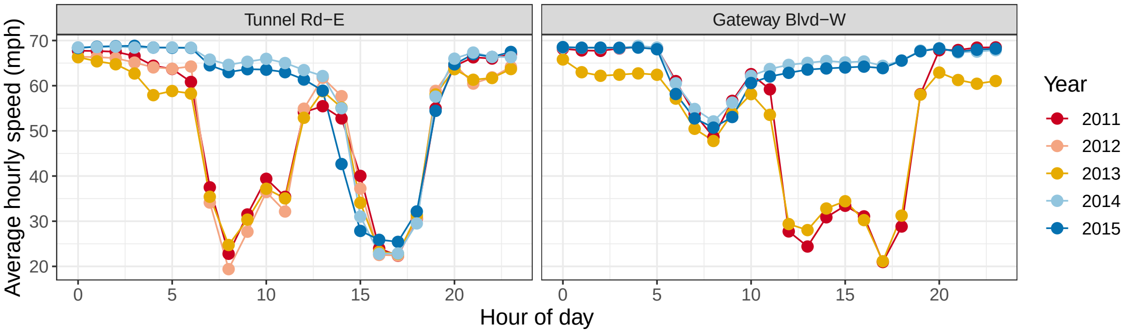
Figures 8, 9, 10, and 11 describe average speeds at the four study sites. For each site we present average speeds by hour-of-day in Panel (a), and then monthly average speeds by year in other other panel or panels. The hourly patterns are very interesting documenting traffic slowdowns during the morning commute, afternoon commute, or both, whereas the monthly averages are more useful for comparing changes across years.

The figures provide visual evidence of speed increases at all four lane expansion projects. For example, Figure 8 documents severe slowdowns at the Caldecott Tunnel prior to the lane expansion. Slowdowns are most severe eastbound in the morning and westbound in the afternoon. With the opening of the fourth bore in November 2013, the number of lanes serving traffic in those directions doubled from two to four, and average speeds increases dramatically, essentially reaching free-flow speeds. This pattern is similar in both the hour-of-day plots and the monthly average plots.

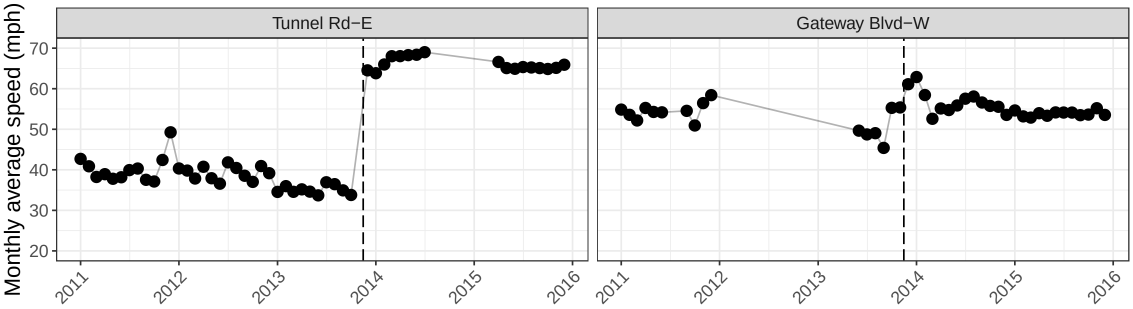
Speeds increase at the other sites as well. Figure 9 shows sharp speed increases at the Orange Show loop detector after the I-215 San Bernardino Widening Project is completed in 2010, with speeds during peak afternoon hours increasing from below 30 mph to above 50 mph. Similarly, Figures 10 and 11 show significant speed increases after 2016 and 2014 at I-580 and I-405, respectively. Overall, the visual evidence from all four sites is consistent with the lane expansions resulting in meaningful speed improvements.

Figure 8: Speeds at SR-24 Caldecott Tunnel Fourth Bore

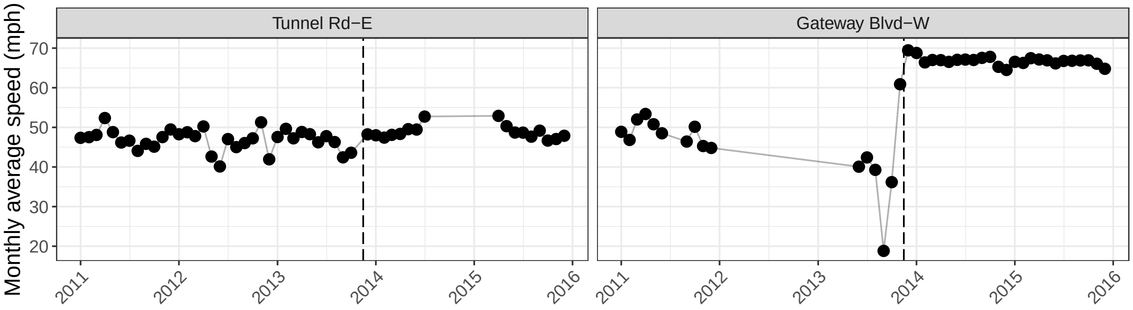
(a) All hours



(b) 6-8 AM



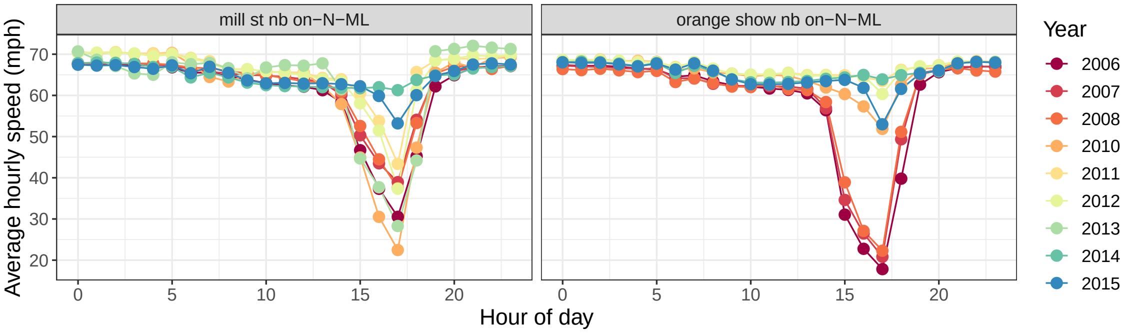
(c) 5-9 PM



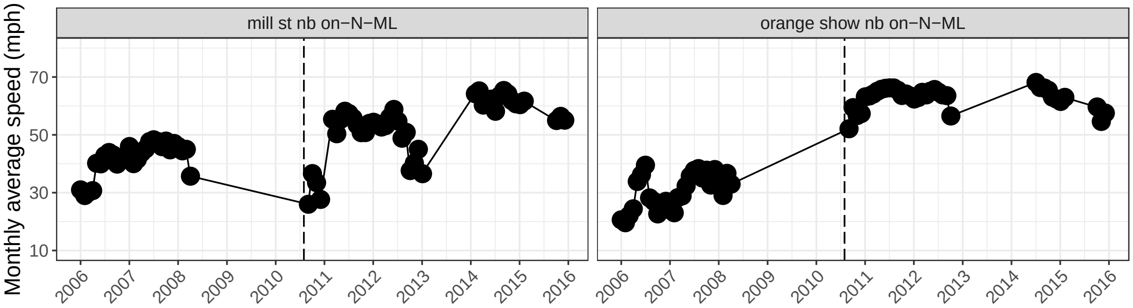
Note: These figures plot average vehicle speeds at two different loop detectors close to the Caldecott Tunnel on SR-24. Figures on the left describe eastbound traffic at a loop detector located at Tunnel Road. Figures on the right describe westbound traffic at a loop detector at Gateway Boulevard. The vertical dashed lines in panels (b) and (c) indicate the lane expansion.

Figure 9: Speeds at I-215 San Bernardino Widening Project

(a) All hours



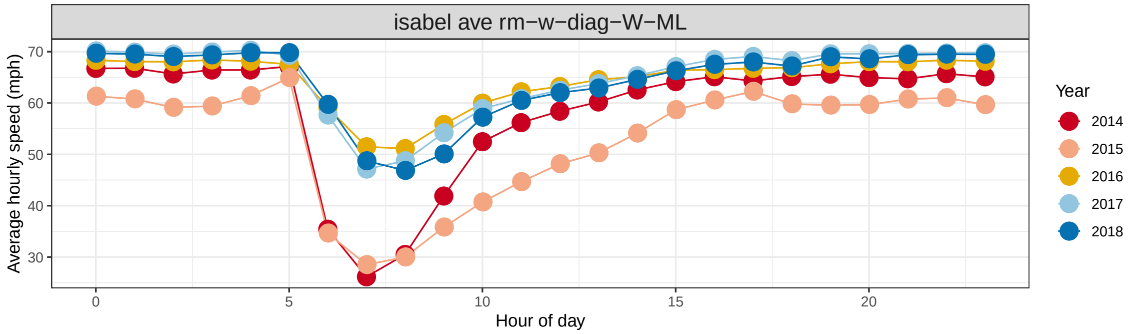
(b) 4-6 PM



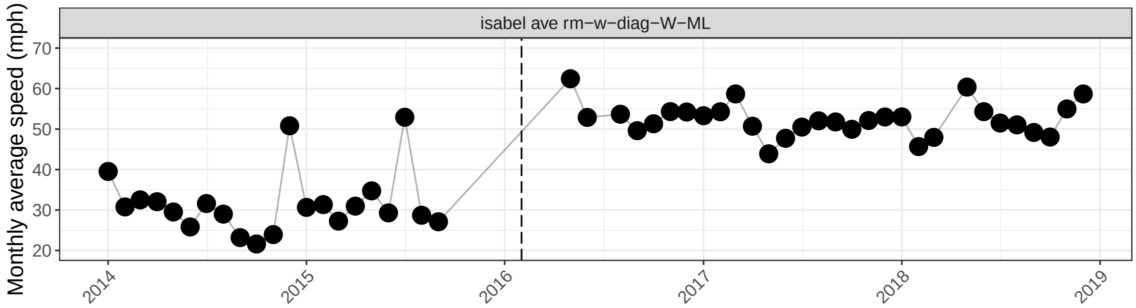
Note: These figures plot average vehicle speeds at two different loop detectors at the San Bernardino Widening Project. Figures on the left describe northbound traffic at a loop detector located at Mill Street. Figures on the right describe northbound traffic at a loop detector at Orange Show road. The vertical dashed lines in panel (b) indicate the lane expansion.

Figure 10: Speeds at I-580 Express Lanes Project

(a) All hours



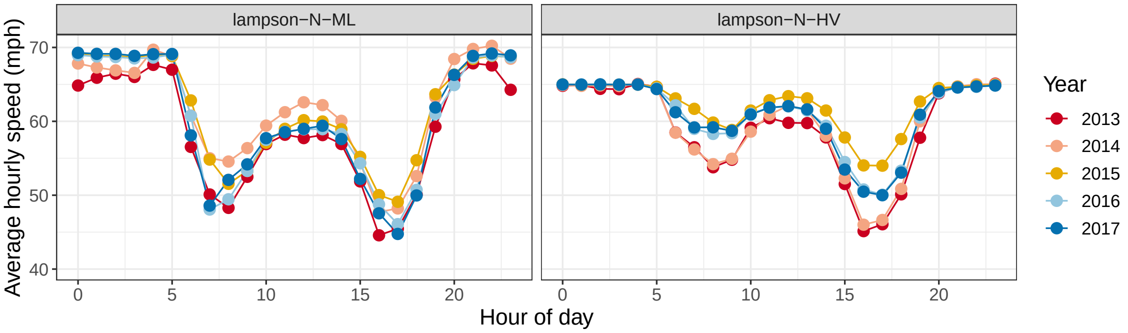
(b) 6-8 AM



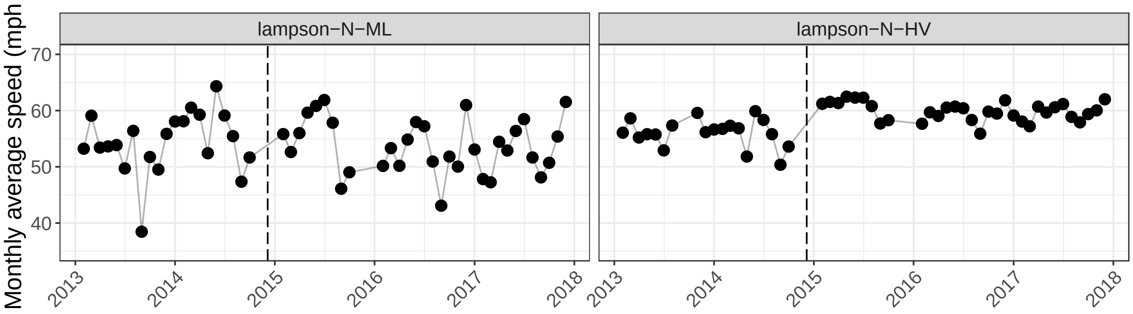
Note: These figures plot average vehicle speeds westbound at the Isabel Avenue loop detector at the I-580 Express Lanes Project. The vertical dashed line in panel (b) indicates the lane expansion.

Figure 11: Speeds at I-405 West County Connectors Project

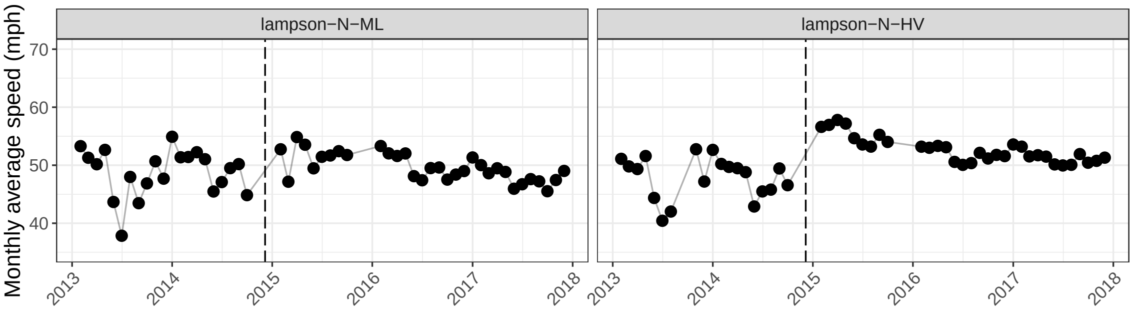
(a) All hours



(b) 6-8 AM



(c) 3-5 PM



Note: These figures plot average vehicle speeds at two different loop detectors at the I-405 West County Connectors Project. Figures on the left describe northbound traffic at a loop detector located on the mainline lanes at Lampson Avenue. Figures on the right describe northbound traffic at a loop detector located on the HOV lanes at Lampson Avenue. The vertical dashed lines in panels (b) and (c) indicate the lane expansion.

Regression Evidence on Changes in Speeds

Tables 4, 5, 6, and 7 present regression evidence on the change in speeds at our four project sites. These results quantify the visually apparent changes in speed in Figures 8 through 11 and test their statistical significance. Each column reports the estimate of β_1 from Equation (2) for a given site, direction, and time of day (defined as peak or off-peak).

Table 4 reveals that, following the completion of the fourth bore of the Caldecott Tunnel, speeds increase significantly in all hours and both directions. Speed increases are largest in the eastbound direction during the morning and in the westbound direction during the afternoon. The increases are highly statistically significant. Off-peak speeds also increase in both directions, particularly westbound. This increase is consistent with Figure 8, which reveals pre-expansion slowdowns throughout the afternoon on SR-24 westbound, even outside the 4-6 pm window (recall that prior to the expansion, the SR-24 bottleneck entailed four lanes of traffic merging down to two lanes).

Tables 5 and 6 reveal similarly large increases in speeds during peak times following the relevant expansions. For example, on I-215 average speeds increase 33 mph during the northbound afternoon peak at Orange Show Road, and they increase 21 mph during the westbound morning peak (towards Oakland and San Francisco) on I-580. The increases are again highly statistically significant.

Speed increases on I-405, reported in Table 7, are more modest. The HOV lanes experience average speed increases in the range of 4 to 5 mph during morning and afternoon peak hours. Those increases are statistically significant but smaller in magnitude than most of the estimates from the other three study sites. Mainline lanes, which were not expanded, experience changes in speed that are small and mostly statistically insignificant.

Table 4: Change in Speeds at SR-24 Caldecott Tunnel Fourth Bore Project

	East		West	
	Off-peak (1)	6-8 AM (2)	Off-peak (3)	4-6 PM (4)
Post	6.803***	26.670***	13.250***	19.480***
	(0.465)	(0.953)	(1.001)	(1.002)
Baseline speed (mph)	52	38	52	47
Observations	542,276	84,029	472,331	150,116
R^2	0.543	0.640	0.347	0.427

Notes: This table presents results from a regression of 5-min average vehicle speed on a post-expansion indicator. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated by peak-hours in Columns (2) and (4). Eastbound regressions use data from two monitors to extend coverage to 2015. Statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5: Change in speed at I-215 Widening Project

	North			
	Orange Show ML		Mill St ML	
	Off-peak (1)	4-6 PM (2)	Off-peak (3)	4-6 PM (4)
Post	3.696^{***}	33.298^{***}	1.774^{***}	12.754^{***}
	(0.224)	(0.988)	(0.284)	(1.392)
Baseline speed (mph)	63	30	65	42
Observations	1,069,512	153,098	1,077,048	153,894
R^2	0.188	0.589	0.182	0.241

Notes: This table presents results from a regression of 5-min vehicle speeds on a post-expansion indicator using data from the mainline monitor indicated in the heading (Orange Show or Mill St). All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2006-2015. Off-peak hours are all hours excluding the indicated peak-hours in Column (2). Baseline speed refers to the average speeds in the pre-expansion period. Statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6: Change in speeds at I-580 Express Lanes Project

	West		
	Off-peak (1)	6-8 AM (2)	4-6 PM (3)
Post	6.151***	20.980***	4.619***
	(0.515)	(1.377)	(0.447)
Baseline speed (mph)	59	31	62
Observations	646,748	132,759	263,300
R^2	0.267	0.343	0.081

Notes: This table presents results from a regression of 5-min vehicle speeds on a post-expansion indicator using data from the westbound Isabel monitor. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2014-2019. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (3). Baseline speed refers to the average 5-min speed in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Table 7: Change in speeds at the I-405 Connectors Project

	North					
	HOV lanes			HOV + ML lanes		
	Off-peak (1)	6-9 AM (2)	3-5 PM (3)	Off-peak (4)	6-9 AM (5)	3-5 PM (6)
Post	1.125*	4.082***	4.724***	0.529	0.868	1.966*
	(0.477)	(0.578)	(0.774)	(0.734)	(1.195)	(0.876)
Baseline speed (mph)	62	56	48	63	54	49
Observations	286,734	75,305	56,452	1,345,533	336,804	252,287
R^2	0.358	0.161	0.328	0.250	0.152	0.125

Notes: This table presents results from a regression of 5-min vehicle speeds on a post-expansion indicator using data from the Lampson North monitor. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2014-2019. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (3). Baseline speed refers to the average 5-min speed in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Placebo Tests on Changes in Speeds

Tables 8, 9, 10, and 11 present evidence on the changes in speeds at our four comparison sites, one for each project. As we explained earlier, the main purpose of these sites is to perform a set of "placebo tests" from sites without lane expansions. These sites lie in the same counties as the project sites, but far enough away that they should be unaffected by the expansions at the four study sites. Thus, if our research design is valid, we expect the changes in speeds at the comparison sites to be much smaller than the changes observed at the project sites.

The results at the comparison sites largely bear out these expectations. In Table 8, for example, the changes at the comparison site (SR-4 in Contra Costa County) are negative and many times smaller than the speed increases at the relieved bottleneck (Table 4). The I-215 and I-405 comparison sites both exhibit very small, and sometimes statistically insignificant, changes in speed, on the order of 2 mph or less (Tables 9 and 11). The I-580 comparison site exhibits somewhat larger changes in speed (–6 mph during the afternoon peak), but in all cases there are speed decreases, rather than speed increases (Table 10).

The evidence of near zero changes in speeds at the comparison sites provides reassurance that the observed speed increases at the project sites are in fact due to the projects. Decreases in speeds at comparison sites could suggest that traffic flows are broadly increasing in our study's counties. We examine this possibility in the next section.

Table 8: Placebo Test: Change in Speeds at the Comparison Site for the Caldecott Tunnel

	West		East	
	Off-peak (1)	6-8 AM (2)	Off-peak (3)	4-6 PM (4)
Post	-0.787^{***}	-1.825^{***}	-3.283^{***}	-5.296^{***}
	(0.094)	(0.192)	(0.125)	(0.235)
Baseline speed (mph)	66	65	64	61
Observations	448,486	85,890	448,108	140,763
R^2	0.249	0.218	0.391	0.592

Notes: This table presents results from a regression of 5-min average vehicle speed on a post-expansion indicator. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated by peak-hours in Columns (2) and (4). Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Table 9: Placebo Test: Change in Speeds at the Comparison Site for the I-215 San Bernardino Widening Project

	West		East	
	Off-peak (1)	4-6 PM (2)	Off-peak (3)	6-8 AM (4)
Post	1.954^{***}	2.676^{***}	-0.008	-1.715^{***}
	(0.248)	(0.298)	(0.166)	(0.506)
Baseline speed (mph)	64	62	64	58
Observations	1,041,447	177,199	1,051,833	175,428
R^2	0.109	0.058	0.154	0.053

Notes: This table presents results from a regression of 5-min average vehicle speed on a post-expansion indicator. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated by peak-hours in Columns (2) and (4). Statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 10: Placebo Test: Change in Speeds at the Comparison Site for the I-580 Express Lanes Project

	South		North	
	Off-peak (1)	6-8 AM (2)	Off-peak (3)	4-5 PM (4)
Post	-1.065^{***}	-3.386^{***}	-1.923^{***}	-6.072^{***}
	(0.281)	(0.714)	(0.180)	(0.854)
Baseline speed (mph)	64	40	60	34
Observations	843,160	138,588	920,026	99,444
R^2	0.314	0.267	0.625	0.102

Notes: This table presents results from a regression of 5-min average vehicle speed on a post-expansion indicator. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated by peak-hours in Columns (2) and (4). Statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 11: Placebo Test: Change in Speeds at the Comparison Site for the I-405 West County Connectors Project

	South		North	
	Off-peak (1)	6-9 AM (2)	Off-peak (3)	3-5 PM (4)
Post	−0.028	−0.013	0.686^{*}	0.078
	(0.232)	(0.180)	(0.282)	(0.624)
Baseline speed (mph)	64	60	63	59
Observations	770,601	184,499	785,866	138,810
R^2	0.200	0.020	0.192	0.051

Notes: This table presents results from a regression of 5-min average vehicle speed on a post-expansion indicator. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated by peak-hours in Columns (2) and (4). Eastbound regressions use data from two monitors to extend coverage to 2015. Statistical significance: * $p < 0.05$, ** p < 0.01, *** $p < 0.001$.

Evidence on Changes in Traffic Flows After Lane Expansions

We now turn to the evidence on traffic flows. In presenting the results, we follow the same overall approach as we used with speeds, first presenting graphical evidence followed by regression evidence.

Figures 12, 13, 14, 15 plot traffic flows at the four study sites. For each site the top panel shows average traffic flows by hour-of-day, and the bottom panel (or panels) shows monthly average flows, with a vertical line indicating the lane expansion.

For most sites we do see changes in traffic flows, though the changes in traffic flows tend to be smaller and less pronounced than the changes in average speeds documented in the previous section. Consider Figure 12, for example. At this site, SR-24, we observed large speed increases eastbound in the morning and westbound in the afternoon. Consistent with induced travel, we indeed see traffic flow increases eastbound in the morning, and westbound in the afternoon. The timing of the flow increases corresponds to the opening of the Caldecott fourth bore in November 2013, and the increases are substantial in magnitude.

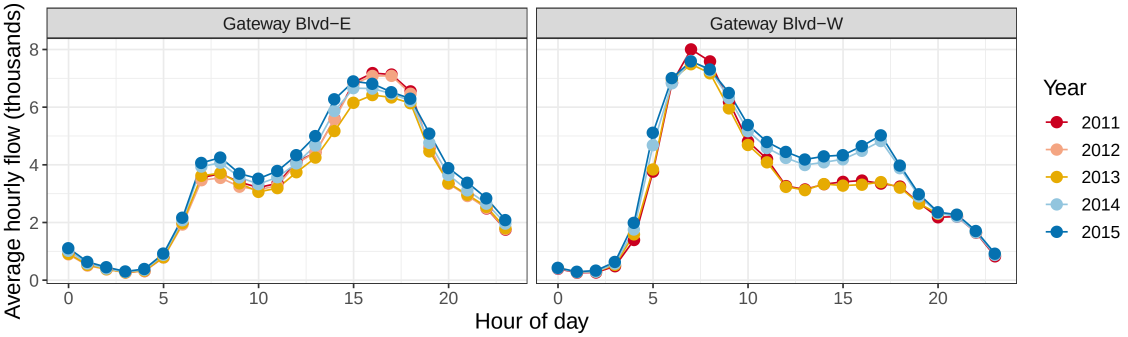
Consider also the pattern of traffic flows for the I-215 San Bernardino Widening project in Figure 13. Here we documented sharp speed increases in northbound travel during the afternoon peak following the expansion in 2010. Correspondingly, we observe traffic flow increases during northbound afternoon travel, particularly later in the sample. We conjecture that the traffic flow increases in 2014 and 2015 likely correspond to completion of additional phases of the widening project, completed downstream of the study site.

Traffic flows for the I-580 are plotted in Figure 14. Recall that we observed large speed increases in Westbound morning travel. Traffic flows increase steadily in 2016, 2017, and 2018. The morning increases are particularly large, but we see traffic flow increases during afternoon hours as well, potentially pointing to broader compositional changes at this site.

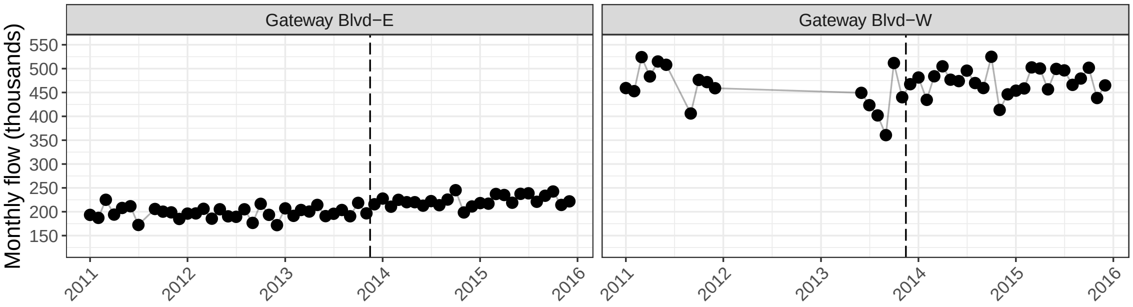
Finally, Figure 15 plots flows at the I-405 West County Connectors project. Here we observed speed increases in Northbound afternoon traffic. Traffic flows appear to increase significantly during these same afternoon hours. This is particularly true in the HOV lanes as is expected given that the number of HOV lanes increased from one to two.

Figure 12: Traffic Flows at the SR-24 Caldecott Tunnel Fourth Bore Project

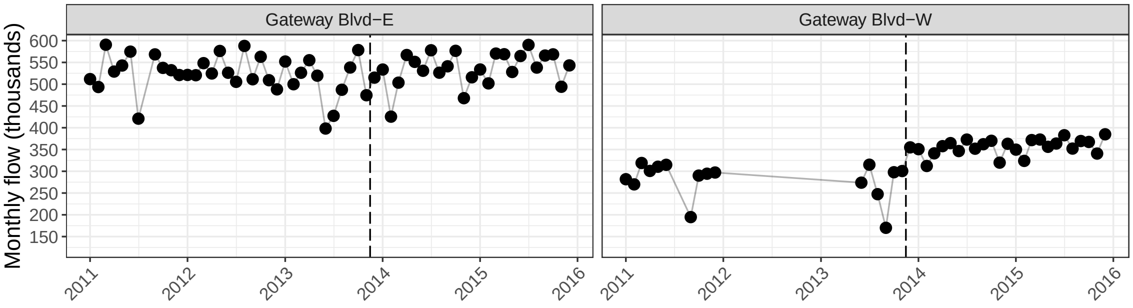
(a) All hours



(b) 6-8 AM



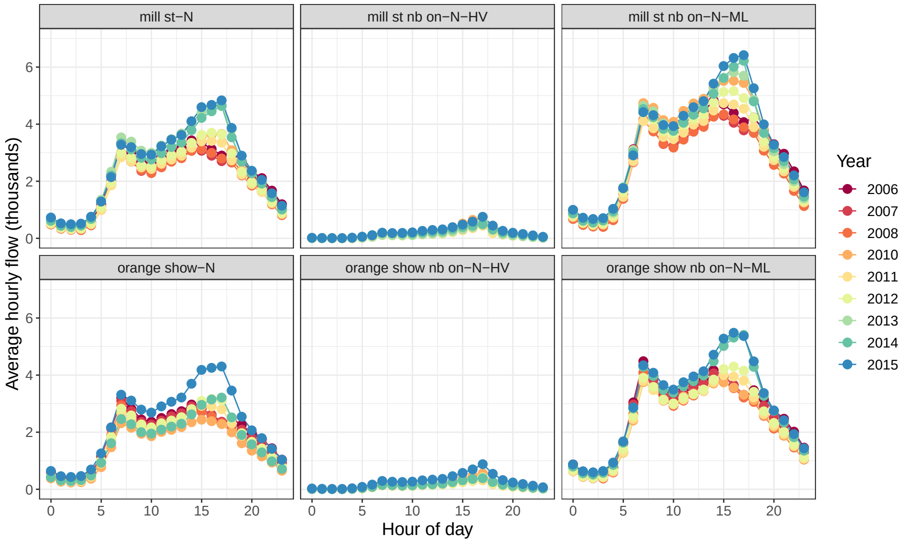
(c) 5-9 PM



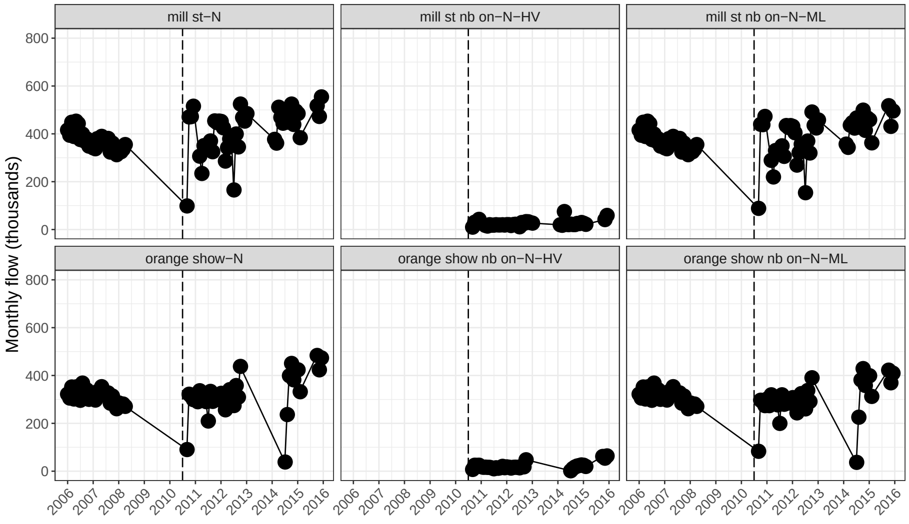
Note: These figures plot average traffic flows at two different loop detectors close to the Caldecott Tunnel on SR-24. Figures on the left describe eastbound traffic at a loop detector located at Gateway Boulevard. Figures on the right describe westbound traffic at the same loop detector at Gateway Boulevard. The vertical dashed lines in panels (b) and (c) indicate the lane expansion.

Figure 13: Traffic Flows at the I-215 San Bernardino Widening Project

(a) All hours



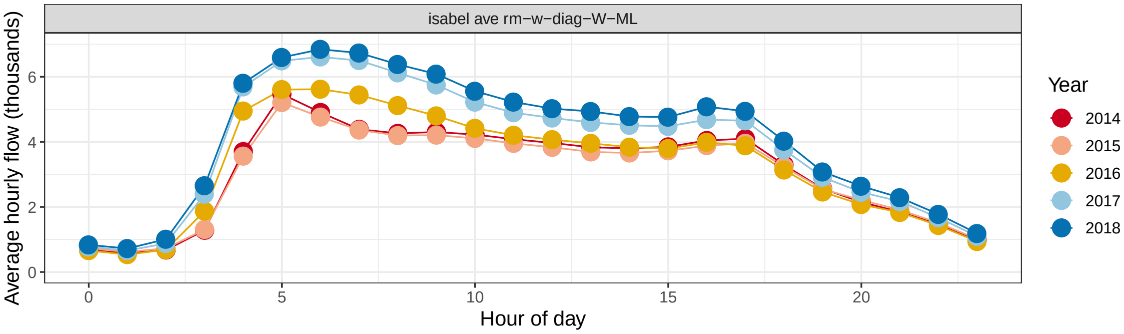
(b) 6-8 AM



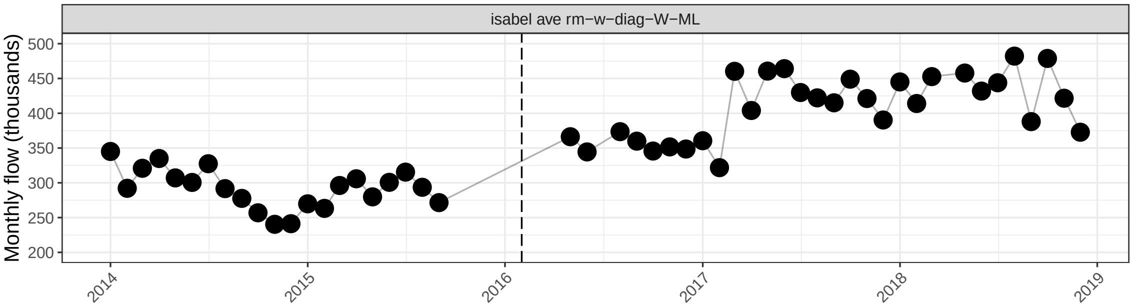
Note: These figures plot average traffic flows at two different loop detectors at the San Bernardino Widening Project. Figures indicated as "Mill Street" describe northbound traffic at a loop detector located at Mill Street. Figures indicated as "Orange Show" describe northbound traffic at a loop detector at Orange Show road. Total, HOV lanes ("HOV") and mainline lanes ("ML") are plotted for each loop detector. The vertical dashed lines in panel (b) indicate the lane expansion.

Figure 14: Traffic Flows at the I-580 Express Lanes Project

(a) All hours



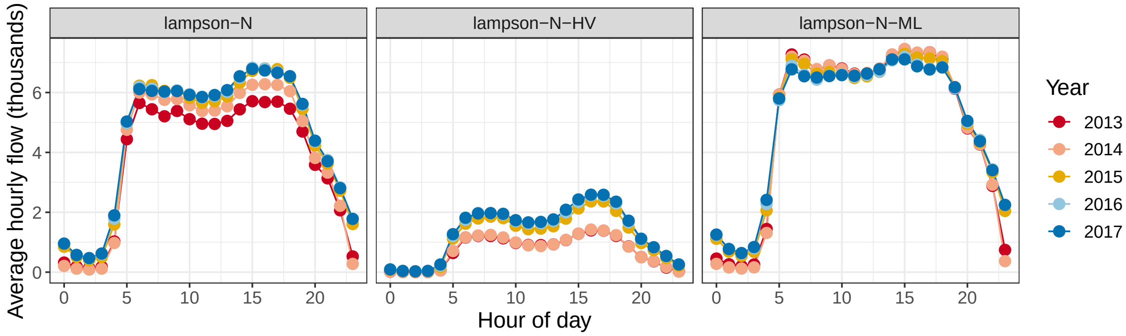
(b) 6-8 AM



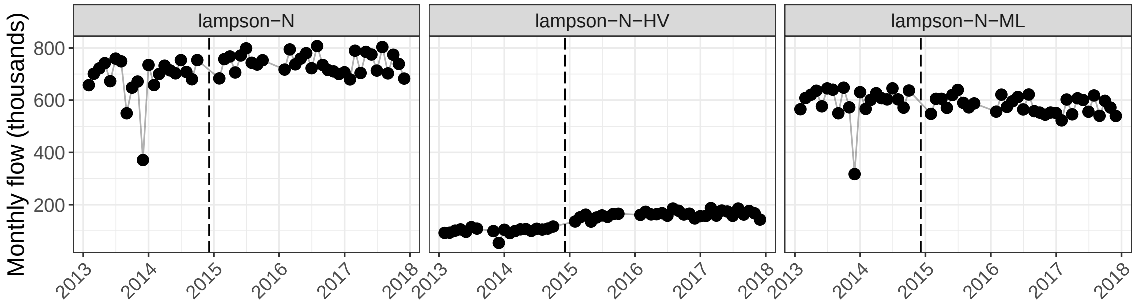
Note: These figures plot average traffic flows westbound at the Isabel Avenue loop detector at the I-580 Express Lanes Project. The vertical dashed line in panel (b) indicates the lane expansion.

Figure 15: Traffic Flows at the I-405 West County Connectors Project

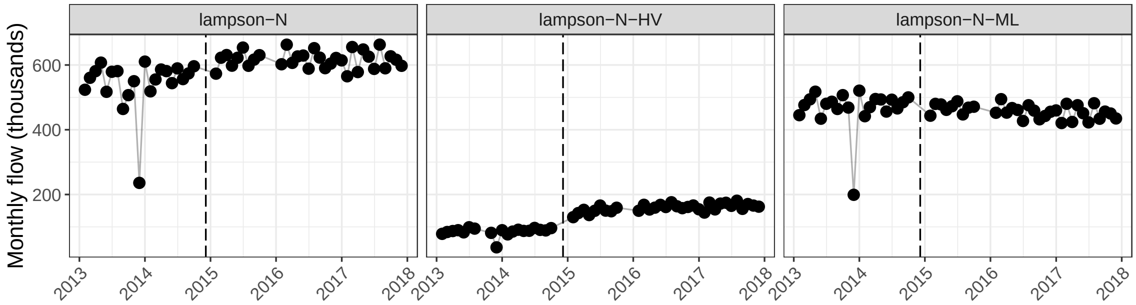
(a) All hours



(b) 6-9 AM



(c) 3-5 PM



Note: These figures plot average traffic flows at two different loop detectors at the I-405 West County Connectors Project. Figures on the left describe northbound traffic at all loop detectors at Lampson Avenue. Figures in the middle describe northbound traffic at a loop detector on the HOV lanes at Lampson Avenue. Figures on the right describe northbound traffic at a loop detector located on the mainline lanes at Lampson Avenue. The vertical dashed lines in panels (b) and (c) indicate the lane expansion.

Regression Evidence on Changes in Traffic Flows

Tables 12, 13, 14, and 15 present regression evidence on the change in flows at the four project sites. These results quantify the changes in traffic flows observed in Figures 12 through 15, and test for statistical significance. Each column in these tables reports the estimate of β_1 from Equation (3) for a given site, direction, and time of day (defined as peak or off-peak).

Table 12 reveals that, following the rise in speeds resulting from the lane expansion, traffic flows increase approximately 10% in the eastbound direction (morning) and 24% in the westbound direction (afternoon). The increases are highly statistically significant. Off-peak flows also increase in both directions, particularly westbound. While the off-peak westbound increase may appear surprising, prior to the fourth bore's completion, lane reversals occurred between 2:00 am and 5:00 am (switching west to east) and 11:30 am and 12:00 pm (switching east to west). In practice this means that westbound speeds also increased at various times outside the 1:00 pm to 7:00 pm window we consider in Table 12. The flow increases are of notable magnitude, but nevertheless substantially below the 100% theoretical maximum flow increase that could occur as the freeway goes from two lanes to four lanes in the relevant direction. Thus, in the short-run, we do not observe a level of induced travel that is equal to the capacity expansion for this project.

Tables 13 and 14 reveal similarly large increases in flows during peak times following the relevant expansions. For example, flows increase approximately 36% during the northbound afternoon peak near Orange Show Road on I-215 in mainline lanes, and over 42% in mainline and HOV lanes combined. On I-580, flows increase approximately 31% westbound during the morning peak. The increases at both sites are highly statistically significant. The lane expansions at these sites could theoretically increase capacity by up to 66% and 50% respectively. Thus, the ratio of induced travel to capacity expansion appears larger than at the SR-24 site.

Flow increases on I-405, reported in Table 15, are large in the HOV lanes. Morning peak-hour HOV flows increase over 45%, and afternoon peak-hour HOV flows increase approximately 58%. Flow increases in all lanes combined are more modest, in the range of 11% to 13% during peak hours. These estimates suggest that the majority of the induced travel is occurring in the HOV lanes; indeed, these were the only lanes that were expanded. Finally, there appear to be large increases in off-peak demand in Columns (1) and (4). These increases are driven by large proportional increases in traffic flows during late-night and early-morning hours. We investigated this anomaly and determined that nighttime lane closures during the construction period artificially depressed late-night traffic flows prior to the project's completion. Thus we do not interpret the off-peak changes in I-405 traffic flows as representing induced travel.

Table 12: Change in Traffic Flows after SR 24 Caldecott Tunnel Fourth Bore Project

	East		West	
	Off-peak (1)	6-11 AM (2)	Off-peak (3)	1-7 PM (4)
Post-expansion	0.091^{***}	0.103^{***}	0.181^{***}	0.239^{***}
	(0.006)	(0.009)	(0.004)	(0.005)
Baseline hourly flow	2001	2285	2038	3148
Observations	155,039	72,633	98,279	54,910
R^2	0.915	0.667	0.932	0.542

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from the Gateway East and Gateway West monitors. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (4). Baseline hourly flow refers to the average total hourly flow in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$

Table 13: Change in Traffic Flows after I-215 San Bernardino Widening Project

Panel A: Mill St - North

	ML lanes		HOV + ML lanes	
	Off-peak (1)	4-6 PM (2)	Off-peak (3)	4-6 PM (4)
Post-expansion	0.130^{***}	0.347^{***}	0.160^{***}	0.409^{***}
	(0.013)	(0.023)	(0.014)	(0.023)
Baseline hourly flow (count)	2604	4234	2662	4452
Observations	342,955	48,924	342,955	48,924
R^2	0.919	0.429	0.919	0.407

Panel B: Orange Show - North

	ML lanes		HOV + ML lanes	
	Off-peak (5)	4-6 PM (6)	Off-peak (7)	4-6 PM (8)
Post-expansion	0.172^{***}	0.358^{***}	0.202^{***}	0.422^{***}
	(0.010)	(0.017)	(0.010)	(0.016)
Baseline hourly flow (count)	2287	3473	2331	3610
Observations	313,328	44,778	313,331	44,778
R^2	0.920	0.578	0.923	0.613

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from mainline and HOV monitors at Mill St North and Orange Show North. All regressions include calendar month, day of week and hour fixed effects,and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2006-2015. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (3). Baseline hourly flow refers to the average hourly flow in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Table 14: Change in Traffic Flows after I-580 Express Lanes Project

	West		
	Off-peak (1)	6-8 AM (2)	2-7 PM (3)
Post-expansion	0.182***	0.310***	0.078***
	(0.008)	(0.017)	(0.009)
Baseline hourly flow (count)	1970	3383	2701
Observations	166,032	33,817	66,930
R^2	0.872	0.714	0.802

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from the mainline monitor at Isabel West. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2014-2019. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (3). Baseline hourly flow refers to the average hourly vehicle count in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Table 15: Change in Traffic Flows at I-405 West County Connectors Project

	North					
	HOV lanes			HOV + ML lanes		
	Off-peak (1)	6-9 AM (2)	3-5 PM (3)	Off-peak (4)	6-9 AM (5)	3-5 PM (6)
Post-expansion	0.759***	0.454***	0.584***	0.337***	0.107***	0.131***
	(0.008)	(0.012)	(0.006)	(0.046)	(0.021)	(0.012)
Baseline hourly flow (count)	548	1170	1343	4381	7880	8361
Observations	170,802	44,376	33,181	195,273	47,581	35,598
R^2	0.907	0.440	0.817	0.745	0.110	0.296

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from the mainline and HOV monitors at Lampson North. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures from 2013-2017. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (3). Baseline hourly flow refers to the average hourly vehicle count in the pre-expansion period. Statistical significance: * p < 0.05, ** $p < 0.01$, *** $p < 0.001$.

Placebo Tests on Changes in Traffic Flows

Tables 16, 17, 18, and 19 present evidence on the changes in flows at our four comparison sites. In evaluating these results, the important question is whether there are substantial increases in flows at the comparison sites. If these sites experience positive changes in flows that are of similar magnitude to our project sites, then we cannot rule out the possibility that the project sites would have experienced large changes in flows even absent the capacity expansions.

This evidence from the comparison sites suggests that our results are not driven by county-level trends. In Table 16 the evening changes at the SR-24 comparison site are negative and many times smaller than the afternoon flow increases at the relieved bottleneck (Table 12). The morning flow increases are larger (on the order of 6%), but they are still only half the magnitude of the observed morning flow increases at the Caldecott Tunnel. The I-215 comparison site (located on I-10 in San Bernardino County) exhibits slight decreases in flows (Table 17), strongly implying that the observed induced travel on I-215 is not driven by secular trends.

The I-580 comparison site exhibits somewhat larger changes in flows (Table 18), but only during off-peak hours. During peak hours the estimates are close to zero and much smaller than the estimates for I-580, providing evidence that our main results are not driven by county-level trends. Finally, the I-405 comparison site experiences flow increases on the order of 3% to 5% during the study period (Table 19). These trends are sufficient to explain the modest increases in mainline-lane flows at the I-405 project site, but far too small to explain the large increases in HOV-lane flows (Table 15).

Overall the evidence from the comparison sites suggests that unobservable factors are unlikely to explain more than a small fraction of the observed increases in traffic flows at our project sites during the expansion periods. This evidence lends support to the interpretation of our flow estimates as reflecting induced travel.

Table 16: Placebo Test: Change in Vehicle Flows at the Comparison Site for the Caldecott Tunnel

	West Off-peak (1)	West 6-8 AM (2)	East Off-peak (3)	East 5-9 PM (4)
Post-expansion	0.076^{***}	0.061^{***}	0.056^{***}	-0.017^{***}
	(0.003)	(0.016)	(0.003)	(0.004)
Baseline hourly flow	1312	2316	1398	1781
Observations	225,383	42,954	225,172	70,422
R^2	0.936	0.337	0.941	0.793

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from a mainline monitor on SR-4. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (4). Baseline hourly flow refers to the average total hourly flow in the pre-expansion period. Statistical significance: * $p < 0.05$, ** p < 0.01, *** $p < 0.001$.

Table 17: Placebo Test: Change in Vehicle Flows at the Comparison Site for the I-215 Widening Project

	West Off-peak (1)	West 5-9 PM (2)	East Off-peak (3)	East 6-8 AM (4)
Post-expansion	-0.045^{***}	-0.030^{***}	-0.025^{***}	-0.014
	(0.002)	(0.004)	(0.002)	(0.010)
Baseline hourly flow	3013	4436	4465	6970
Observations	236,027	73,776	235,938	44,226
R^2	0.944	0.713	0.942	0.148

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from loop detectors on I-10. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (4). Baseline hourly flow refers to the average total hourly flow in the pre-expansion period. Statistical significance: * $p < 0.05$, ** p < 0.01, *** $p < 0.001$.

Table 18: Placebo Test: Change in Vehicle Flows at the Comparison Site for the I-580 Express Lanes Project

	South Off-peak (1)	South 6-8 AM (2)	North Off-peak (3)	North 2-7 PM (4)
Post-expansion	0.102^{***}	0.016	0.089^{***}	-0.044^{***}
	(0.006)	(0.014)	(0.005)	(0.006)
Baseline hourly flow	3404	5552	3271	5984
Observations	179,820	37,358	183,457	74,933
R^2	0.877	0.526	0.913	0.284

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from loop detectors on I-880. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (4). Baseline hourly flow refers to the average total hourly flow in the pre-expansion period. Statistical significance: * $p < 0.05$, ** p < 0.01, *** $p < 0.001$.

Table 19: Placebo Test: Change in Vehicle Flows at the Comparison Site for the I-405 West County Connectors Project

	South Off-peak (1)	South 6-9 AM (2)	North Off-peak (3)	North 3-5 PM (4)
Post-expansion	0.027^{***}	0.053^{***}	0.050^{***}	0.036^{***}
	(0.005)	(0.007)	(0.004)	(0.003)
Baseline hourly flow	2846	4274	2618	3690
Observations	193,195	46,127	196,489	34,723
R^2	0.862	0.131	0.888	0.078

Notes: This table presents results from Equation (3), where hourly log vehicle flows are regressed on a post-expansion indicator, a % missing variable and their interaction. Coefficients from the latter two variables are omitted for clarity. Data is collected from loop detectors on I-5. All regressions include calendar month, day of week and hour fixed effects, and standard errors are clustered at the calendar day level. Data is restricted to observed, weekday observations outside of highway closures. Off-peak hours are all hours excluding the indicated peak-hours in Columns (2) and (4). Baseline hourly flow refers to the average total hourly flow in the pre-expansion period. Statistical significance: * $p < 0.05$, ** p < 0.01, *** $p < 0.001$.

Discussion

In this section we put our results in context for CARB. We aim to describe how CARB may use the results from our analyses to aid in the assessment of Sustainable Communities Strategies (SCSs), per the agency's role in implementing California Senate Bill No. 375 (SB 375). In doing so we emphasize the limitations of our analyses and are explicit about what can and cannot be learned from them.

California Senate Bill No. 375

California SB 375 is known as the "Sustainable Communities and Climate Protection Act of 2008".[6] SB 375 was approved by Governor Arnold Schwarzenegger in September 2008 and went into effect in January 2009. SB 375 sets statewide goals for reducing carbon dioxide emissions. In particular, SB 375 tasks CARB with setting regional emissions reductions targets from passenger vehicles. To that end, the Metropolitan Planning Organizations (MPOs) from each California region must develop a "Sustainable Communities Strategy".

A SCS is one of the elements in a MPO's Regional Transportation Plan (RTP); a detailed planning document required to be prepared at least every 5 years but most MPOs prepare a plan every 4 years. The SCS must explain how a region will meet its emissions reductions targets. CARB assesses each region's SCS, provides feedback to the MPOs, and must either accept or reject the MPOs determination (see California Air Resources Board (2020a) and California Air Resources Board (2020b) for details).

Our four study sites correspond to two MPOs: (1) Association of Bay Area Governments (ABAG) and Metropolitan Transportation Commission (MTC); and (2) the Southern California Association of Governments (SCAG). The 2035 emissions reductions targets for MTC and SCAG are both 19%.[7]

The following two subsections describe the highway expansion plans for ABAG/MTC and SCAG. It is important to emphasize that these highway expansion plans are only one part of the much broader regional transportation plans. For example, both plans additionally include: (1) policies aimed at increasing carpooling, vanpooling, group ridesharing, and otherwise increasing the number of passengers per vehicle; (2)

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[6] The full name of SB 375 is "Transportation Planning: Travel Demand Models: Sustainable Communities Strategy: Environmental Review". See `https://leginfo.legislature.ca.gov/`.

[7] See `https://ww2.arb.ca.gov/our-work/programs/sustainable-communities-program/regional-plan-targets`.

policies aimed at increasing transit ridership, as well as bicycling and walking; and (3) longer-run policies aimed at increasing urban density and decreasing the overall demand for commuting. Combining the effects of all these strategies, ABAG/MTC and SCAG predict reductions in VMT per capita by 2040 relative to baseline of 7.4% and 12.0%, respectively (see Southern California Association of Governments (2016), p. 153 and California Air Resources Board (2018), Figure 10).

Plan Bay Area

In this subsections we briefly describe the highway expansion plans for the Bay Area MPO. ABAG/MTC are jointly responsible for regional planning for nine counties in the San Francisco Bay Area. ABAG/MTC jointly adopted its second RTP/SCS, known as Plan Bay Area 2040, in 2017. In Plan Bay Area 2040, 90%+ of investments are directed at existing infrastructure rather than expansion projects. Of the remaining approximate 10% targeted for expansion projects, about two-thirds are directed at public transportation investments rather than roadway expansions.[8]

As a result Plan Bay Area 2040 allocates only $10 billion out of a total budget of $300 billion to roadway expansion projects. The plan mentions that this category includes "select roadway expansions along highways and arterial roads throughout the region, the largest being new express lanes along U.S. 101 from San Francisco to Morgan Hill in the South Bay." (p. 67). Map 4.7 in the plan highlights new HOV and HOT lanes throughout the Bay Area region, particularly along the U.S. 101 corridor. See Figure 16.

The emphasis on express lanes is interesting because, unlike HOV lanes, HOT lanes generate revenue. At least in in theory, this means that an express lane expansion could yield a net reduction in carbon dioxide emissions, even while total VMT increases. For example, suppose the generated revenues were used to fund public transportation. This approach could potentially yield a "win-win", relieving traffic congestion at critical choke points for some drivers while also leading other drivers to substitute to lower-carbon transportation. But, of course, the actual effectiveness of public transportation expenditures depends on how and where these expenditures are applied and goes beyond the scope of this report.

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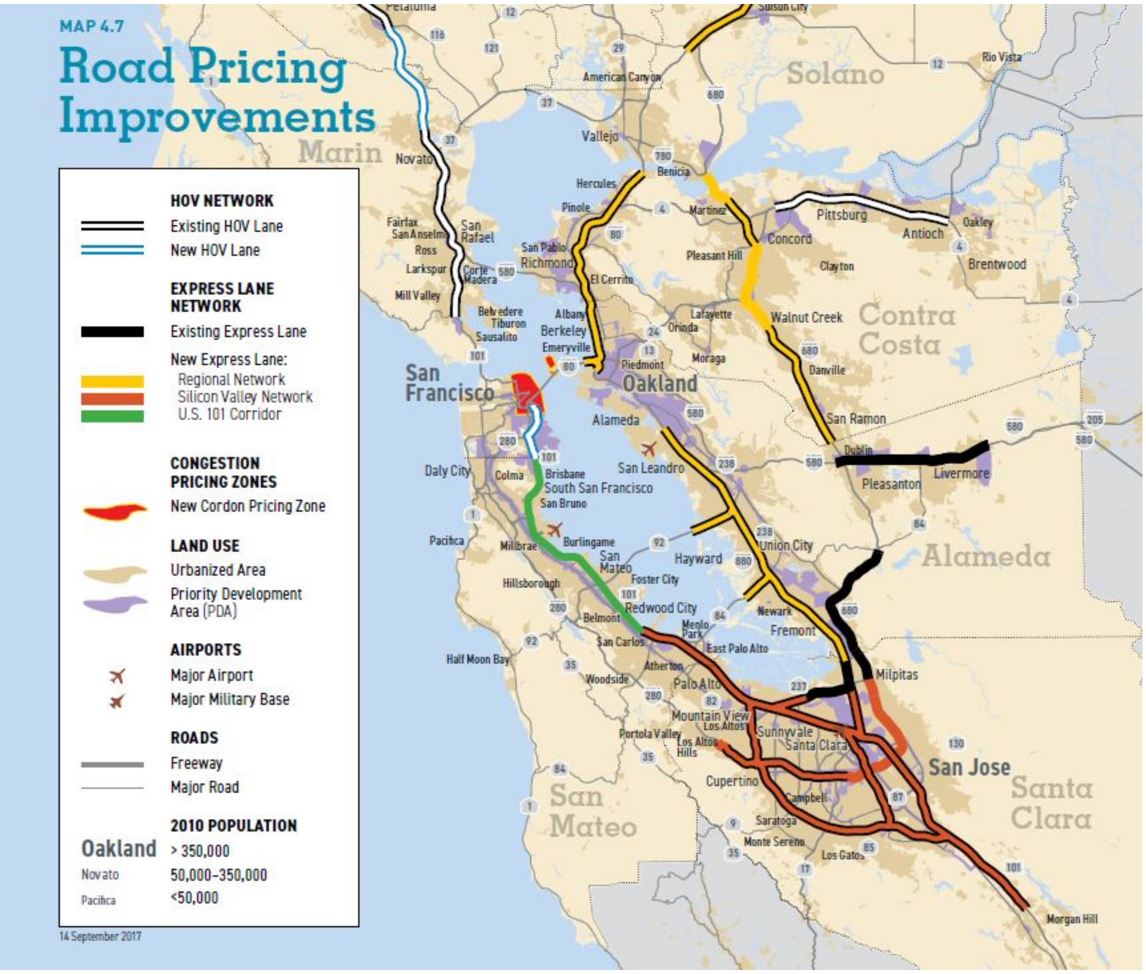
[8] See Table 4.4 in Metropolitan Transportation Commission and Association of Bay Area Governments (2017).

Figure 16: Road Pricing Improvements in Plan Bay Area 2040



Source: Metropolitan Transportation Commission and Association of Bay Area Governments (2017).

Connect SoCal

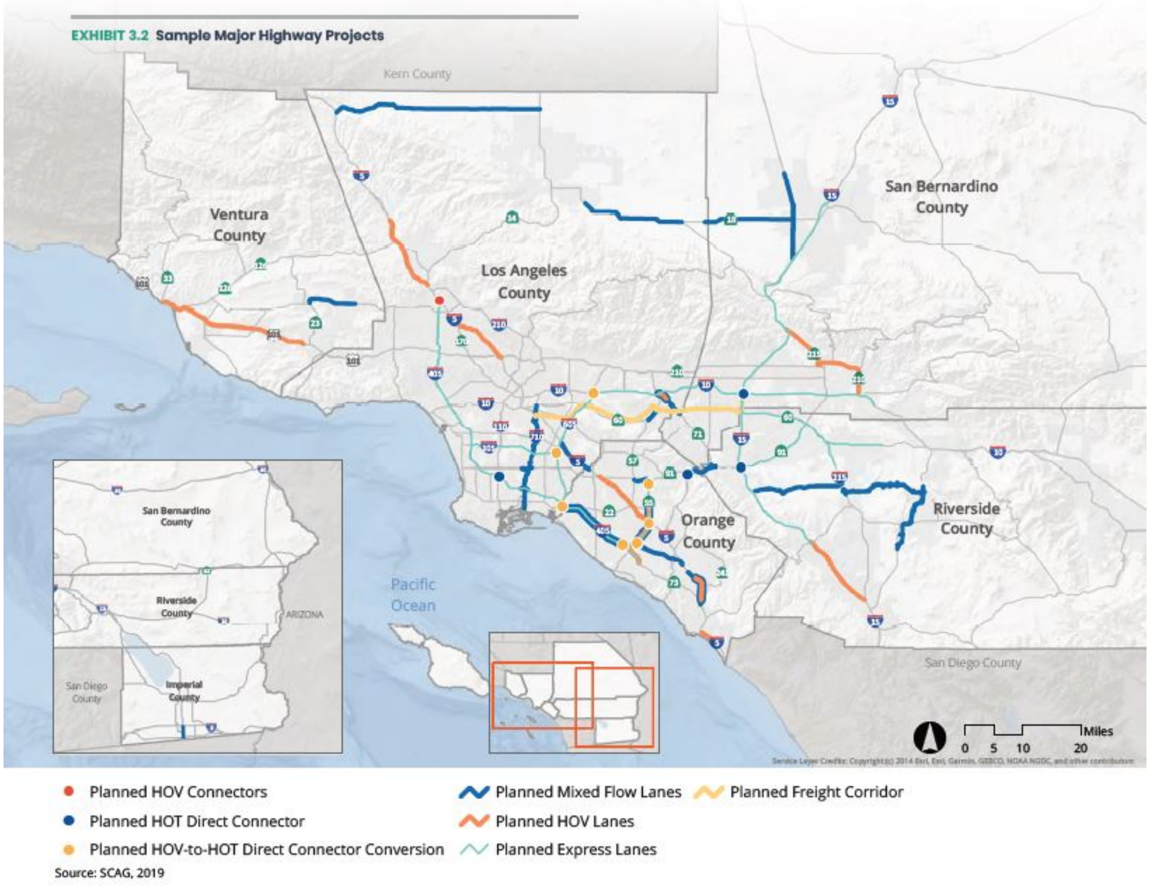
In this subsections we briefly describe the highway expansion plans for Southern California. Southern California Association of Governments (SCAG) is the largest MPO in California, by area and population, covering six counties in Southern California. SCAG adopted its third RTP/SCS in September 2020. The plan directs transportation investments within existing urbanized areas, prioritizes transit investments, and expands bicycling and pedestrian infrastructure. See Southern California Association of Governments (2020) for details.

With regard to highways, SCAG emphasizes preserving the existing transportation networks rather than new investments, "Yet, expansion of our highways and and arterials has slowed down over the past decade. Building new roads is no longer accepted as the only solution to our congestion challenges, partly due to lack of funding and challenging environmental and community concerns. However, given that critical gaps and congestion choke points still exist in the system, improvements beyond those that are operational in nature still need to be considered. Connect SoCal includes capital improvements that will address the choke points and gaps in the system, to ensure the system is operating optimally and provides adequate and equitable access to opportunities." (Southern California Association of Governments, 2020, p.72).

Southern California has one of the most comprehensive HOV lane networks in the nation, and SCAG has plans for several HOV expansion projects, including HOV gap closures, highway-to-highway HOV connectors, and HOV direct access ramps (see Figure 17). New HOV projects between now and 2040 would add lanes in parts of I-15, I-215, and SR-71 (Southern California Association of Governments, 2020, Table 3.2).

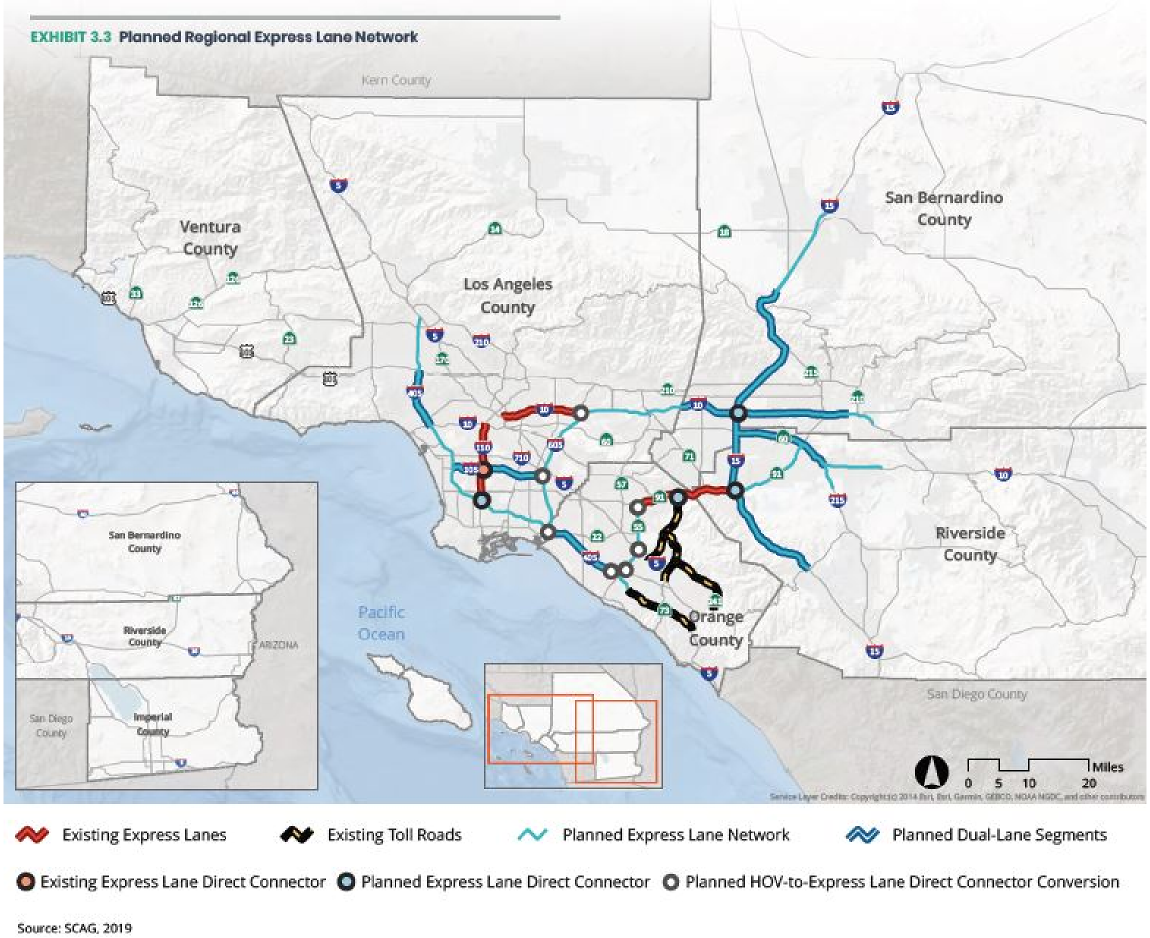
SCAG also envisions a large scale up of the region's express lane network (see Figure 18). SCAG argues that appropriately priced HOT lanes can outperform general purpose lanes in terms of throughput, especially during congested periods, and that HOT lanes deliver revenue that can be used to deliver the capacity expansions sooner and to support transit and other complementary objectives. See Southern California Association of Governments (2016) and Southern California Association of Governments (2020).

Figure 17: Major Highway Projects in Southern California 2040 Plan



Source: Southern California Association of Governments (2020).

Figure 18: Regional Express Lane Network in Southern California 2040 Plan



Source: Southern California Association of Governments (2020).

Implications of Our Research for RTP/SCSs

Table 20 summarizes the elasticity estimates for all four study sites. We first briefly describe each expansion in words and report the percentage of new lanes that are non-general purpose and the percentage change in total lanes. We then report the percentage change in flows and implied elasticities. The flow estimates summarize the results previously reported in Tables 12, 13, 14, and 15.

Across the four study sites, the average short-run increase in traffic flows ranged from 11.8% to 22.4%. The percentage change in total flows was broadly similar across different types of expansions, ranging from SR-24 which was a pure general purpose lane expansion project, to I-215 which is a mixed general purpose and non-general purpose lane expansion project, to I-580 and I-405 which were pure non-general purpose lane expansion projects.

These flow increases imply elasticities ranging from .152 to 0.843. For I-215, for example, the implied elasticity is 0.334, implying that a 10% increase in freeway expansion is associated with a 3.3% increase in total traffic flows. The smallest elasticity estimate comes from SR-24 and the largest elasticity estimate comes from I-405.

It is worth noting that the I-405 project included, in addition to the lane expansion, several additional connectors aimed at improving flow at nearby merges between I-405 and intersecting freeways. These new connectors mean that the true effective increase in capacity for the I-405 project was likely considerably larger than 14%, implying that the elasticity estimate of 0.843 reported in Table 20 is somewhat overstated. For this reason, we would suggest that the elasticity estimates from the other three study sites are likely more representative of the behavioral response one would expect to see in response to a typical lane expansion.

These elasticity estimates are within the range of estimates of induced travel in the previous literature. Whereas most previous studies focus on general-purpose lanes, our estimates are some of the first evidence from non general-purpose lane expansions. Overall, we find that the implied elasticities are similar across different types of lane expansions, and in all cases within the range of estimates from previous studies.

Induced travel will make it harder for MPOs to meet their carbon dioxide emission reduction goals. Both ABAG/MTC and SCAG envision significant increases in HOV and HOT highway lanes. Although both regions plan to spend a relatively small fraction of their total budgets on these expansion projects, these lanes nonetheless

Table 20: Elasticity Estimates for all Four Sites

SR-24 (1)	I-215 (2)	I-580 (3)	I-405 (4)
	A. Type of Expansion		
Two new general purpose lanes	*One new general purpose lane and one new HOV lane*	*One new HOT lane*	*One new HOV lane and new connectors*
	B. Percentage Non-General Purpose Lanes		
0%	50%	100%	100%
	C. Percentage Change in Total Lanes		
+100% (2 to 4)	+67% (3 to 5)	+25% (4 to 5)	+14% (7 to 8)
	D. Percentage Change in Total Flows		
+15.2%	+22.4%	+17.5%	+11.8%
	E. Implied Elasticity		
0.152	0.334	0.700	0.843

Notes: This table reports the elasticities implied by the results in Tables 12, 13, 14, and 15. The percentage change in total flows in panel D is calculated by taking a weighted average of the post-expansion regression coefficients, where the weights are the estimated vehicle flows during the indicated time period. Estimated flows are calculated by multiplying the baseline hourly flow by the number of hours in the period. In cases where results are presented separately for HOV lanes and all lanes, we only use estimates from regressions using all lanes. We use both off-peak and peak estimates, except in the case of I-405 where we use on-peak estimates only due to concerns that the off-peak flow estimates are biased due to nightly closures during the construction period. Finally, the implied elasticities are calculated as the ratio of the percentage change in total flows to the percentage change in total lanes.

represent a sizeable expansion in overall highway capacity. Our research implies that these non general-purpose lane expansion projects will lead to induced travel.

Limitations of Our Methodology

Our results imply significant short-run induced travel from HOV and HOT lane expansions. It is important to emphasize several limitations of the analyses, however.

First, while the PeMS data offer a wealth of detailed information, an inherent challenge with this information is missing data. Loop detector data is frequently missing for weeks or even months at a time. As we explain in Section , our methodology imputes for missing observations. We have documented our assumptions as carefully as possible and will be posting all data and code upon completion of the project. Nevertheless, it is important to point out that these imputation procedures are imperfect and can introduce bias into our estimates.

Second, these are short-run estimates. In essence, our approach measures induced travel by comparing average speeds and traffic flows before and after lane expansion projects. Thus, our estimates should be thought of as capturing the immediate impact of lane expansions over a one- or two-year time horizon. While a valuable starting point, there is reason to believe that this short-run impact may be very different from longer-run impacts. Over the medium- and long-run, there may be additional ways that drivers adapt to lane expansions; for example, they may take new jobs farther from their homes. Our estimates do not capture these longer-run adaptations.

The longer-run impacts are likely to be *larger* than the short-run impacts measured here. In the long-run, households and firms have more margins of adjustment. Workers can take new jobs farther from their homes, and firms can locate job sites farther away from where workers live. In addition, households can engage in additional discretionary travel, e.g. more recreational activities farther from their homes, and firms can increase their VMT associated with core functions (e.g. more Amazon deliveries). The vast majority of existing studies of induced travel find larger long-run elasticities than short-run elasticities (Deakin et al., 2020).

Third, these are localized estimates. Our approach examines average speeds and traffic flows at the specific congested locations where lane expansion projects occurred. However, relieving congestion can also affect driving behavior in adjoining highways and arterial street networks, as drivers change their transportation patterns to adjust to the new and lower overall time required to complete certain trips. To the extent that new HOV/HOT lane traffic was drawn from alternative routes off the freeway, our estimates would overstate total induced travel. At the same time, a reduction of travel on these alternative routes could itself generate some additional induced travel. Our estimates do not capture these broader spatial and regional impacts.

Fourth, our analysis does not capture land-use changes. Particularly over the long run, we should expect households and businesses to respond to these lane expansions by moving to new locations. Indeed, the entire pattern of new home and business construction is determined in response to available transportation infrastructure and patterns of congestion. Smart companies create new campuses in easily-accessible locations, for example. Anticipating and shaping these broader land use changes are one of the most important broader objectives in a SCS, but our results are short-run and thus provide no insight into this important longer-run margin.

Fifth, as with any empirical analysis there are limits to external validity. Driving behavior in these four locations may not be representative of driving behavior in other locations. In addition, there are serious questions about whether historical driving behavior is representative of future driving behavior. Many of the capacity expansions considered by MPOs will not occur until 2030 and beyond. But by 2030 the entire fleet of vehicles in California will be different, as will the available transit alternatives, not to mention evolving norms about telecommuting and other factors. Quite simply, what happened in the past may not be an accurate estimate about what will happen in the future.

These limitations of the analysis should be kept in mind when using our estimates to predict induced travel from non-general purpose highway lane expansion projects. Our results are a reminder that when the price of transportation declines, people use more transportation. While this was previously well established for general purpose lanes, our analyses confirm that this same behavior occurs with non-general purpose lanes as well. In addition to using our estimates, we would recommend planners consider a range of both higher and lower elasticities, as well as alternative assumptions about land use and other longer-run impacts.

Summary and Conclusions

This project measures induced travel from non-general purpose lane expansions. We collected data on speeds and traffic flows from four study sites, all of which experienced multi-hundred million dollar lane expansion projects during the 2010s. We found that all four projects relieved existing bottlenecks, resulting in increased average vehicle speeds. In addition, at all four sites we found evidence of induced travel, with statistically significant increases in traffic flows after lane expansions.

Across the four study sites, the average short-run increase in total traffic flows ranged from 12% to 22%. Results were similar across sites, including three non-general purpose HOV/HOT expansion projects, and one general-purpose lane expansion. These flow increases imply elasticities ranging from 0.15 to 0.84. These estimates of induced travel are within the range of estimates from the previous literature.

In addition to the specific policy implications discussed above, we drew some more general inferences from the patterns in our results. One conclusion that stood out to us is the critical role of unfilled latent travel demand. For example, on SR-24, the observed degree of induced travel (10% to 24% flow increases) was substantially less than the theoretical capacity expansion (a 100% increase). In contrast, the observed degree of induced travel at the I-215, I-580, and I-405 projects generally corresponded to over half the theoretical capacity expansion. We hypothesize that because the SR-24 expansion, the fourth bore of the Caldecott Tunnel, only changed capacity in the reverse-commute direction, the unfilled latent travel demand was too modest to generate a large induced travel effect. In contrast, all other projects increased capacity in both the commute and reverse-commute directions.

The asymmetric capacity enhancement on SR-24 also revealed an interesting pattern around discretionary travel. In the mornings, the reverse-commute capacity enhancement affected primarily reverse commuters (i.e. those living in the urban core and working in the suburbs) — few individuals take recreational trips on weekday mornings. In the afternoons, the reverse-commute capacity enhancement affected both reverse commuters (returning home from work) and traveling to the urban core for dining, entertainment, or social activities during the evening. While employment decisions typically represent significant commitments, recreational trips do not. Thus we should expect induced travel to be stronger in the afternoon, when individuals are traveling for both employment and recreational purposes, than in the morning. Indeed, the afternoon induced travel is approximately 2.5 times as large as the morning induced travel. This distinction between discretionary and non-discretionary travel is relatively understudied in the broader induced travel literature but our results suggest it is empirically relevant.

Finally, our results highlight the distinction between overall carbon emissions and the carbon intensity of travel. *Ex ante*, it is ambiguous whether additional HOV and HOT lanes should increase carbon emissions. On the one hand, an additional lane — even a restricted one — lowers the cost of travel and thus should increase the total amount of travel. On the other hand, by their nature HOV and HOT lanes incentivize carpooling, which should decrease the number of vehicles per passenger trip. Which of these effects dominates is an empirical question. At our study sites, it appears that the travel demand effect outweighs the carpooling effect; total vehicle flows generally increase. Nevertheless, the carbon intensity of travel — i.e. the amount of carbon dioxide per passenger-mile traveled — may have fallen. Our data do not allow us to definitively measure the carbon intensity of travel, but future research might explore this.

Recommendations

Our empirical methodology provides a roadmap for future projects aimed at measuring short-run project-level outcomes. Our methodology exploits the unusually rich PeMS data, and shows how analyses can be run to compare study site vs comparison site, peak vs off-peak, and weekday vs weekend. Examining these data along multiple dimensions adds credibility to the analysis as well as additional insights about driver behavior.

We put particular emphasis on graphical evidence. While we also report traditional regression tables and aggregate statistics, we found that the figures describing average speeds and traffic flows were a powerful way to summarize large amounts of data and to communicate complex findings to a broader audience. The patterns across hour-of-day, for example, helped us and others understand the timing of morning and afternoon peaks, and how this changed after lane expansions.

We found evidence of induced travel at all four study sites. However, the limitations of our analyses with regard to short-run vs long-run, local vs regional, land-use impacts, and external validity mean that our estimates capture only some of the behavioral responses to lane expansions. Consequently we recommend that our estimates be used with caution for predicting induced travel from non-general purpose lane expansion projects, and that planners consider a range of both higher and lower elasticities, as well as alternative assumptions about land use and other longer-run impacts.

We recommend that future similar analyses consider complementing PeMS data with "probe" data from smartphones and other GPS-enabled devices. A number of proprietary data vendors, including the company TomTom, produce data products based on high-frequency, high-resolution probe data. Whereas the PeMS data suffer from a large number of missing observations, data based on GPS-enabled devices to be more complete. Moreover, as impressive as California's PeMS system is, with over

40,000 total loop detectors, the probe data approach offers the possibility to more completely measure trip times for entire travel segments, rather than instantaneous speeds and flows at specific locations. In essence, probe data allow measurement of speeds along all major routes. They can thus complement the PeMS flow data, which can only be accurately collected by stationary sensors like the PeMS detectors.

Another priority for future work is to better understand the effect of congestion pricing. California is rapidly scaling up the use of express lanes, but there is still relatively little evidence on how drivers respond to price, let alone the broader efficiency and equity impacts of alternative approaches to HOT pricing. We could envision both experimental- style projects, in which researchers would pair with HOT operators to test particular pricing interventions, as well as observational studies based on historic variation in pricing. Economists are accustomed to estimating demand elasticities in other contexts and could be a valuable resource in such work.

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List of Inventions, Reports, and Copyrighted Materials Produced

Not Applicable

Glossary of Terms, Abbreviations, and Symbols

Table 21: Glossary of Terms, Abbreviations, and Symbols

ABAG	Association of Bay Area Governments
CARB	California Air Resources Board
EPA	Environmental Protection Agency
GHG	greenhouse gas
HOT	high occupancy toll
HOV	high occupancy vehicle
MTC	Metropolitan Transportation Commission
MPO	metropolitan planning organization
PeMS	performance measurement system
RTP	regional transportation plans
SB	state bill
SCAG	Southern California Association of Governments
SCS	sustainable communities strategies
SR	State Route
VMT	vehicle miles traveled
α_d	Fixed effects for day-of-week
β_0	Intercept in the regression equation
β_1	Effect of the lane expansion
β_2	Effect of % Missing in the augmented regression
β_3	Effect of % Missing interaction in augmented regression
δ_h	Fixed effects for hour-of-day
ε_t	Error term in the regression equation
γ^1_{imdh}	Conditional mean of traffic flows
γ^2_{imdh}	Conditional mean in traffic flows after expansion
θ_m	Fixed effects for month-of-year
F_{it}	Vehicle flows for monitor i during five-minute period t
$\mathbf{1}[Post\ Expansion]_t$	Indicator variable equal to one after the lane expansion
Y_t	Speeds (or flows) measured during five-minute period t
$\%Missing_t$	Percent of observations missing in period t

Appendix A: Literature Review

Scope

Researchers in the transportation, planning and economic literatures have long studied whether expanding roadways leads to an increase in vehicle use. This phenomenon, known as induced travel, is popularly summarized by the quote "if you build it, they will come." Empirical studies on induced travel extend back several decades with the earliest authors claiming that over time, the effects of induced travel would completely offset any reduction in congestion following capacity expansion (Downs, 1962; Smeed, 1968). While research since then has generally found support for induced travel, there exists substantial variation in the magnitude of the effect, both within and across studies.

This report reviews the existing literature on induced travel with particular emphasis on non-general purpose and HOV lanes. Due to the breadth of work on travel demand, we focus our approach in three ways. First, we emphasize studies which credibly disentangle the effect of induced travel from other relationships between roadway capacity and vehicle travel. This excludes some earlier literature which does not account for the fact that roadway expansions may occur precisely in areas where planners expect upticks in demand. Second, we focus our review on studies which measure the impact of road expansion on vehicle-miles traveled (VMT). This focus is in line with the majority of the literature which measures induced travel through the elasticity of VMT with respect to road expansion. Sometimes studies look at other outcomes such as the change in travel time or in average vehicle occupancy; however, it is difficult to convert these metrics into travel demand. Finally, we exclude studies that do not directly estimate the relationship between VMT and capacity expansion. A number of studies use engineering models of transportation demand to predict how drivers will respond to roadway changes, taking outside estimates of induced travel as given. Since these studies do not directly estimate induced travel itself, we focus our attention to direct measures of the phenomenon.

Evidence on Induced Travel

The existing empirical results regarding the impact of capacity expansion on VMT are shown in Table 22. While the results vary in methodology, geography, and findings, studies consistently find some evidence of induced travel. Short- and long-run elasticity estimates range from 0.19-1.34 and 0.53-1.03, respectively, which match the large ranges found in previous literature reviews (Handy and Boarnet, 2014;

Noland and Hanson, 2013; Cervero, 2002). The magnitude of induced travel may vary on a number of dimensions; for example, later studies tends to find larger results than earlier work. We discuss major factors impacting the size of measured effects in the sections below.

Time Horizons

In addition to sample and estimation strategy, induced travel estimates are sensitive to time horizons. The summarized results suggest that there is evidence for limited induced travel in the short-run, but significant evidence for the phenomenon in years following a capacity expansion. However, even the significant evidence for induced travel in the long-run is complicated by the fact that authors consider the effects of highway expansion over different time frames. Although half of the studies estimate that congestion returns to near pre-expansion levels in the long-run, the amount of time it takes for convergence to occur lies between 5 years, in the case of Cervero and Hansen (2002), and 10 years, in the study by Duranton and Turner (2011). The hetereogeneity in time-frames underscores the difficulty in relying on any one study for forecasting changes in VMT.

The difference in magnitude between short and long-run effects stems from the distinct ways that drivers respond to capacity expansion over time. In the short term, an increase in roadways leads to an immediate reduction in congestion, which spurs drivers to make a number of changes. These changes are summarized by Downs' theory of triple convergence: drivers may choose to reschedule routes from off-peak to peak travel times, switch routes to include the now expanded roadway, or change to driving alone from other modes of travel such as transit, walking, or carpooling (Downs, 1962). Some of these changes may not result in new trips, but may alter the route or time of existing travel. For example, commuters who change their driving commute to take advantage of a highway expansion are not undertaking travel that they wouldn't before the expansion; however, the length of the trip and its location in the roadway network may change. Freed-up capacity that exists after the resulting mode and route shifts may also increase total travel within a region if drivers are induced to undertake new trips.

In the long-run, other factors in response to the expansion may induce new travel. For example, expansions may result in a change in land-use for the surrounding areas, such as urban sprawl and workers who move to take advantage of the shorter commute afforded by new roadways. While components of long-run changes may occur shortly after the expansion, long-run changes are distinct from short-run in that they are not solely caused by driving choices. Location choices made by firms, housing decisions made by commuters and new buildings built by developers all affect long-run changes in VMT.

Route Switching

Few studies attempt to distinguish new trips induced by capacity expansions from mode and route switching. If drivers are simply changing their commutes to include travel on the new roadway, increases in highway demand should be offset by decreases in demand for neighboring roads. Hansen and Huang (1997) find that an increase in state-highway lane miles does not affect VMT on off-state highways and conclude that the total increase in VMT outweighs any substitution effect from traffic diversion. Duranton and Turner (2011) find similarly weak results on reductions in off-highway traffic. They show that a 10% increase interstate lane kilometers diverts 0.52% of traffic from major urban roads. The remaining studies are unable to answer how expansions in highways divert traffic from other roads because they do not compare changes in VMT across different types of roads. Instead they estimate net changes in VMT either on highways (Noland and Cowart, 2000; Hymel, 2019; Hansen and Huang, 1997; Hsu and Zhang, 2014) or across all major roads (Fulton et al., 2002; Graham et al., 2014; Cervero and Hansen, 2002). Listed reasons to not disaggregate data by road type include lack of existing data, unreliability of data for non-major roads, and experimental design. Studies with limited data may also have been statistically under powered to study VMT with further granularity.

Mode Switching

A shift away from public transit, biking and other forms of travel may be another major driver of increased vehicle travel on expanded roads. For example, increasing highway capacity may cause commuters who previously used public transit to drive cars instead, similar to the diversion of traffic from non-major roads to highways. Anderson (2014) developed a model in which driving times are a major determinant of public transit ridership and showed that outages in transit services led to a 47% increase in highway delays. While this study looks at decreased transit capacity instead of increased roadway capacity, the findings suggest that increasing freeway capacity could draw some riders off of public transit, as driving times fall.

A number of studies have looked at whether drivers respond to disruptions in the road network by changing their mode of travel or their route (Goodwin et al., 1998; Hunt et al., 2002; Ye et al., 2012; Zhu et al., 2010). Evidence that drivers switch from driving to alternate modes of travel during a roadway closure indicates some degree of flexibility in mode of transport. In these studies, authors identify bridges, highways, and other roadways that have been closed for repairs and study whether commuters switch their mode of travel or divert to alternate routes. Zhu et al. (2010) study traffic patterns after the collapse of the I-35W bridge over the Mississippi River in Minneapolis and find significant evidence of route shifting to the nearby I-94 bridge and a modest (6%) increase in transit ridership. They find no net decease in VMT, although they note that the lack of impact may be due to the fact that an additional lane was added to each direction of the I-94 bridge. Hunt et al. (2002) study the impact of the closure of the Centre Street Bridge, a major roadway in Calgary which provides access to the city's downtown. They find a 4.4% net reduction in VMT and a 9% increase in traffic on roadways and transit lines servicing the downtown area, although they note that they find similar trends for areas that were not affected by the bridge closure.

Overall, the disruption strain of research suggests that drivers may be flexible in how they travel. It is important to note that because this literature studies road network disruptions, it answers whether drivers can be transit users. It does not study the inverse case that is relevant to capacity expansions, namely, whether transit users will start becoming drivers. In general, more work is needed on mode shifting between transit and driving, particularly using actual travel data.

Geography

Studies that do not adopt a site-specific analysis look at changes in VMT on roads within a relevant geographic unit, most commonly counties or metropolitan statistical areas (MSA). Studying roads at the county or MSA level allows researchers to capture network effects of road expansions, such as increased access to unimproved roads. However researchers have taken different approaches to defining the relevant network. Cervero and Hansen (2002) argue that the county is the appropriate unit to study area-wide effects as larger regions may "overly dilute" the analysis by considering changes in VMT that are unrelated to the capacity expansion. On the other hand, Duranton and Turner (2011) claim that understanding traffic patterns at the larger MSA level is more relevant to national transportation policy. The sensitivity of the induced travel elasticities to the geographic unit of study is well documented by Hansen and Huang (1997) who conduct their analysis separately for counties and MSAs and find different results. While the short-run results are roughly the same, the long-run elasticity across MSAs is almost 30 percentage points higher than the county level elasticity (0.94 vs 0.62). The authors attribute this finding to cross-

Table 22: Elasticity Estimates from Induced Travel Regression Models

		Estimation strategy		*Elasticities*	
Study	Sample	Identification	Estimator	Short-run	Long-run
Hansen and Huang (1997)	CA counties (1975-1990)	Lagged lane-miles	FE	0.21	0.62
	CA MSA (1977-1990)	Lagged lane-miles	FE	0.19	0.94
Fulton et al. (2002)	Mid-Atlantic counties (1969-1996)	Lagged growth in lane-miles	FE	0.56-0.59	-
			2SLS	0.46-0.51	-
Noland and Cowart (2000)	US MSA (1982-1996)	Urbanized land area	FE	0.28	0.90
			2SLS	0.28	-
Cervero and Hansen (2002)	CA counties (1976-1997)	Measures of geography, politics, and air quality	2SLS	0.59	0.79
Duranton and Turner (2011)	US MSA (1983-2003)	1947 Interstate Highway Plan, 1898 railroad routes, mapped exploration routes from 1835-50	FE	-	0.82
			2SLS	-	1.03
Hsu and Zhang (2014)	Japan MSA (1990-2005)	1987 National Expressway Network Plan	FE	1.13-1.15	-
			2SLS	1.24–1.34	-
Graham et al. (2014)	US urbanized areas (1985-2010)	Lagged levels and differences of the dependent & independent variables	FE	-	0.53
			LMGPS	-	0.77
Hymel (2019)	US states (1981-2015)	Number of years representative in related House and Senate committees	FE	0.74	0.70
			2SLS	0.64-0.66	0.89-1.1

This table summarizes the results of induced travel studies for general purpose lanes. FE refers to a fixed-effects regression model, 2SLS refers to two-stage least squares regression, and LMGPS describes a linear mixed general propensity score model. The identification column lists the instrument used in the instrumental variables regression.

county induced travel over time; namely that expanding highways in a given county may eventually induce commuters to drive from surrounding areas. Studies that focus on MSAs typically find larger results than those observing county-level traffic, which supports the idea that roadway expansions may have far reaching network effects.

Not all areas experience the same level of induced travel over the same period of time. The elasticity reported in Table 22 under Fulton et al. (2002) is the result of combining data from three states: Maryland, Virginia and North Carolina. The authors also estimate their results separately for each state to find a wider range of elasticities. Their preferred model finds that on aggregate, a 10% growth in lane miles corresponds to a 4.6% growth in VMT over 3 years. Running their model separately for each state, the authors find that VMT growth is is 65% larger in North Carolina (0.48) as it is in Maryland (0.29). The authors do not consider a time horizon longer than three years to see if effects on VMT in the three states become closer over time. Several earlier studies including Hansen and Huang (1997) and Cervero and Hansen (2002) focus on California and generally find smaller elasticities than nationwide estimates. Nevertheless, it is difficult to attribute this difference to California alone given that studies have generally found larger results over time. Finally, Noland and Cowart (2000) use their regression results to forecast induced travel over a 15-year period for all major metropolitan areas in the United States. They find induced travel estimates ranging from 0.06 for Fresno to 0.34 for Louisville. They do not find significant differences in forecasted demand between high and low-urbanised areas or between high and low-congestion areas, suggesting more complicated factors may determine the magnitude of induced travel. In general, existing studies have not tried to answer why different areas experience different levels of induced travel. Given the interplay between different land-use factors, such as density, regional accessibility, and roadway mix, in determining congestion, site-specific studies may be better able to recover answers to this question.

Methodology

As discussed above, the majority of empirical studies run multivariate regression analyses using aggregated VMT data at the county or MSA level. Researchers have long been aware that the endogeneity of traffic growth may bias results from a simple regression of roadway capacity on VMT and have adopted empirical strategies largely in response to this potential bias Cervero (2003). The endogeneity problem arises because the relationship between VMT and roadway expansions runs both ways; while VMT may increase after adding a new lane to a highway due to induced travel, planners may decide to add a new lane to a highway precisely because they expect travel to increase. Under these conditions, the researcher is unable to determine whether the observed increase in VMT is a result of induced travel or the demand-generating event that precipitated the planner's decision.

Instrumental Variables

Most studies have attempted to overcome the endogeneity problem through an instrumental variables (IV) strategy. In this empirical design, researchers attempt to find a variable that is highly correlated with the supply of roads in given area, but uncorrelated with the demand for roads there. Researchers then follow a two-step procedure where they first model the assignment of roads to cities using the instrument and then model the effect of roads on traffic using predicted roadways from the first equation as a stand-in for actual roads. The first step is achieved through a regression of the instrument on the road supply variable, for example log annual lane kilometers in an MSA. The second then regresses the predicted annual lane kilometers from the first stage on log VMT. The regression coefficient in on log lane kilometers in the second step is the induced travel estimate. Researchers have experimented with a large number of instruments, summarized in the third column of Table 22.

The earliest studies used a variety of instruments. Fulton et al. (2002) use lagged growth in lane miles as an instrument for roadway growth, Noland and Cowart (2000) instrument lane miles with land area and population density, and Cervero and Hansen (2002) use a large number of variables describing area politics and physical geography as instruments for lane miles of highways. These instruments have come under scrutiny because they may be related to demand for travel in these areas, as well as the supply of roads, leading to a violation of the exclusion restriction (Duranton and Turner, 2011; Hymel, 2019). For example, in the case of the instruments used by Noland and Cowart (2000), travel demand is generally higher in more populous areas.

A number of recent studies, such as Duranton and Turner (2011) and Hsu and Zhang (2014), have adopted instruments related to historical transportation plans. These authors argue that these early proposed maps are correlated with actual highway routes, but that the span of time separating the plans from any contemporaneous demand shocks is sufficiently long for the two to be unrelated. Map-based instruments have also been used as an instrument in related studies on the effects of highway expansion and congestion on suburbanization (Baum-Snow et al., 2007), trade barriers and labor market outcomes (Michaels, 2008), and employment growth (Hymel, 2009). Studies with map-based instruments note that initial stock of roads are more likely to have been allocated to larger cities or easier geographies, which, in a similar vein to earlier instruments, may be associated with greater current travel demand. As a result, authors stress that "the exogeneity of this instrument hinges on having an appropriate set of controls" (Duranton and Turner, 2011). As we discuss below, the inclusion of various controls may affect the estimates of induced travel.

Outside of map-based and location characteristic instruments, Hymel (2019) has proposed using the power of a state's representative in the US House and Senate committees which make transportation related grants. The author argues that these representatives leverage their committee seniority to acquire grants for highway development regardless of unmet travel demand in their state. He finds long-run elasticity estimates between 0.89 and 1.1, in line with previous studies.

Other Methods

Empirical approaches other than IV are less commonly taken in the induced travel literature, a notable exception being Graham et al. (2014), who use a mixed model generalized propensity score. The authors argue they can address the endogeneity of roadway expansions by controlling for roadway characteristics that cause the planner to expand capacity. The likelihood that a roadway is a target for expansion is controlled for through a propensity score, a value assigned to each unit that is constructed from the set of predictive variables listed in data. Despite the method's popularity, propensity score matching has faced criticism from econometricians (King and Nielsen, 2019). While full discussion of these criticisms is beyond the scope of this report, a basic shortcoming is that propensity scores are constructed from the available covariates in the data, and thus any factors (e.g. stated factory openings) that are not captured in the data will not be controlled for with the propensity score.

Results are sensitive to model specification, both across and within studies. Authors who use IV models also report results from baseline regressions which do not control for endogeneity in traffic growth for comparison. We include both IV and baseline results in Table 22. Within each study, the IV models tend to find higher elasticities than the corresponding fixed-effect models, although Fulton et al. (2002) stands out as an exception. In three of the studies, IV results in the long-run are over 20 percentage points higher than their fixed-effect counterparts. Estimates may also be highly sensitive to inclusion of control variables. Hymel et al. (2010) replicate results from Noland (2001) and find that deflating the income control variable by the consumer price index (CPI) instead of the GDP deflator causes the short-run elasticity estimate to drop from 0.138 to 0.086. The sensitivity of results to different model specifications and variable measurements underscores the need for additional work on induced travel.

HOV and Non-General Purpose Lanes

While the results summarized above focus on the expansion of general-purpose lanes, researchers have increasingly become interested in non-general purpose lanes. Non-general purpose lanes include, but are not limited to, high-occupancy vehicle lanes (HOV), high-occupancy toll lanes (HOT), dedicated transit lanes and express tollways. Each type of lane places a different set of restrictions on users, but lanes may have some overlapping restrictions. For example, HOT lanes are available to high-occupancy vehicles free of charge, however single-occupancy vehicles may also "buy in" to the lane by paying a toll. HOT lanes therefore blend aspects of HOV lanes and express tollways.

Proponents have argued that in comparison to general purpose lanes, HOV lanes place "restrictions on use to encourage ridesharing and can reduce vehicle miles traveled" (*High-Occupancy Vehicle Lanes*, 2020). However, researchers have also found reasons as to why HOV lanes may have limited effectiveness. Shewmake (2012) suggests that carpooling incentives are highest when there is a large difference in speeds between HOV and the adjacent general occupancy lane, but these incentives may shrink as the number of drivers choosing to carpool increases and the difference in speeds diminishes. The author also notes that the proposed benefits of HOV lanes may also be diminished by induced travel. As with general-purpose lanes, reduced congestion on HOV and non-HOV lanes may induce drivers to change routes or switch transit modes. The question of whether subsequent induced travel outweighs short-term relief in congestion is not addressed in the literature, and the study of non-general purpose lanes is an important priority for future work.

Existing Literature

Despite the prevalence of HOV lanes on major roadways, there exists little literature that measures the impact of HOV lane construction on VMT. Instead, the "success" of HOV lanes has typically been evaluated by other metrics, including average vehicle occupancy, rates of utilization, average time savings, and number of passengers per lane (Kwon and Varaiya, 2008; Schofer and Czepiel, 2000). These studies typically find that HOV lanes are underused given their estimated capacity. Studies that do describe a relationship between HOV lanes and VMT often do not directly study the impact of opening an HOV lane on observed changes in VMT. Rather, they rely on transportation models to simulate responses to changes in roadway usage (Johnston and Ceerla, 1996; Rodier and Johnston, 1997) or discrete choice models to capture carpooling preferences (Small et al., 2005; Dahlgren, 1998). Results from these studies are mixed; just over half find that VMT decreases in response to HOV lanes.

Hanna et al. (2017) offer one of the few studies to examine how non-general purpose lanes affect traffic congestion. They study the removal of the "three-in-one" policy in Jakarta, the world's second largest metro area, whose roads rank globally amongst the highest in congestion. The "three-in-one" policy required all vehicles on major roads in the city's central business district to carry at least three individuals during peak hours and was in effect from 1992 to its unexpected discontinuation in 2016. Hanna et al. (2017) exploit the sudden removal of HOV restrictions to estimate the impact of HOV lanes on delays, defined as the number of minutes a car takes to move one kilometer. Using a regression discontinuity strategy, they study traffic immediately before and after the policy removal and find that vehicle flows on former HOV roads increased by 46% in the morning rush hour and 87% in the evening rush hour after the policy was lifted. The authors also find increases in traffic delays on former HOV roads during off-peak hours when restrictions did not apply and on roads that were not previously affected by the policy. Furthermore, they find that the increase in traffic persisted after the initial removal of the policy. Using counterfactual data on travel times generated by Google Maps, they continue to find increased traffic relative to the counterfactual on main and alternative routes two months after restrictions were lifted. While Hanna et al. (2017) present strong evidence that HOV restrictions reduce traffic, results from Jakarta may not be applicable to less dense cities or to areas where there is less familiarity with non-general-purpose lanes. They are also unable to determine whether the removal of HOV lanes induced travel, or whether HOV lanes prevented hypercongestion.

Open Questions

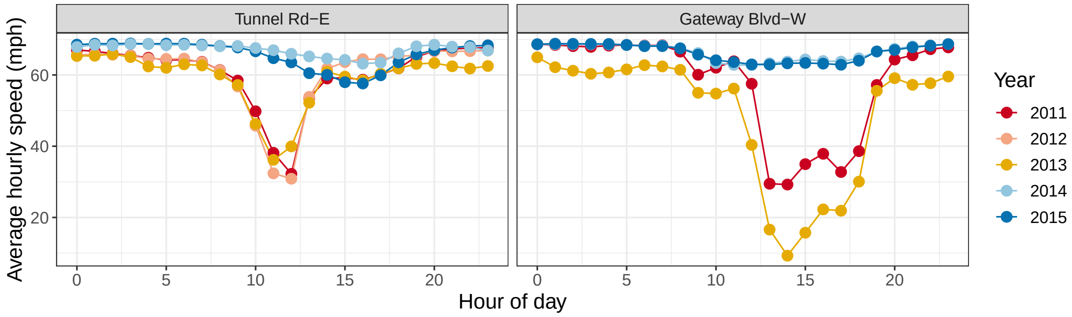
There are a number of urgent research questions in the induced travel literature, particularly regarding non-general purpose lanes. Future work on HOV and HOT lanes should follow the experimental bent of research on general purpose lanes to credibly estimate induced travel using data from real world road, bridge, and tunnel expansions. Moving beyond Hanna et al. (2017), research is needed on the role of non-general purpose lanes in different kinds of travel networks and on how drivers react to these lanes at the outset of their construction instead of their removal. Given the restrictions on the usage of HOV and HOT lanes, drivers who choose to make trips along these routes make calculated decisions about their willingness to carpool or pay tolls that drivers who use general lanes do not. These differences may complicate the dynamics of short- and long-run effects of capacity expansions discussed above and warrant further exploration.

Appendix B: Results for Weekends

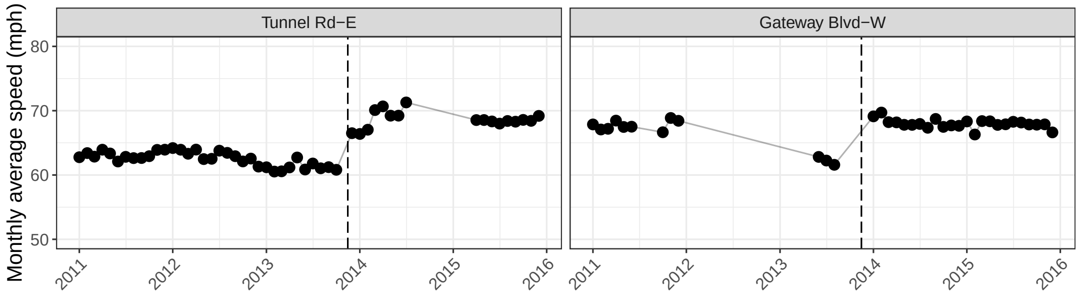
Evidence on Changes in Speeds After Lane Expansions

Figure 19: Weekend Speeds at SR-24 Caldecott Tunnel Fourth Bore

(a) All hours



(b) 6-8 AM



(c) 5-9 PM

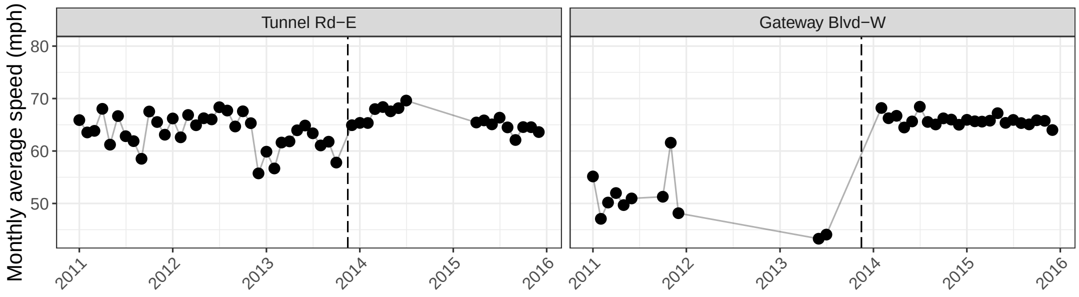
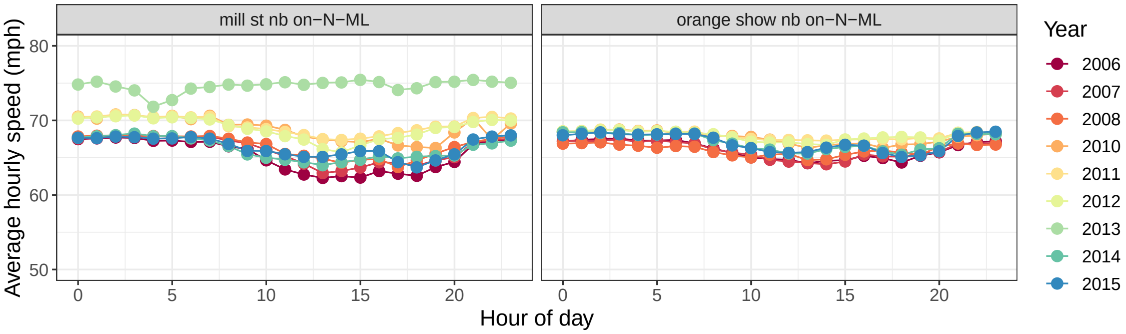


Figure 20: Weekend Speeds at I-215 San Bernardino Widening Project

(a) All hours



(b) 4-6 PM

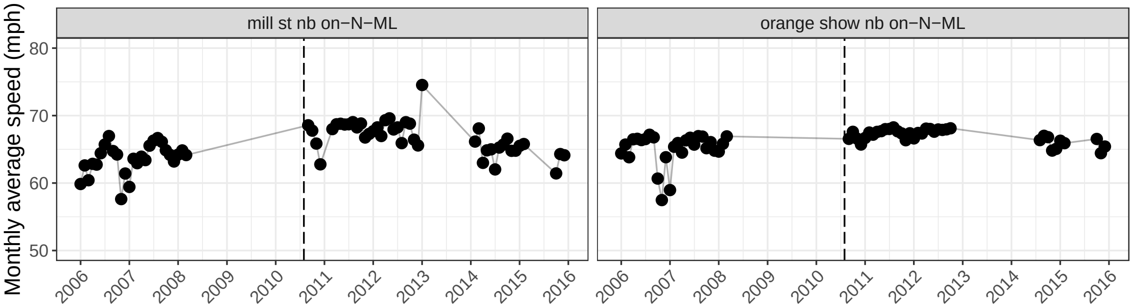
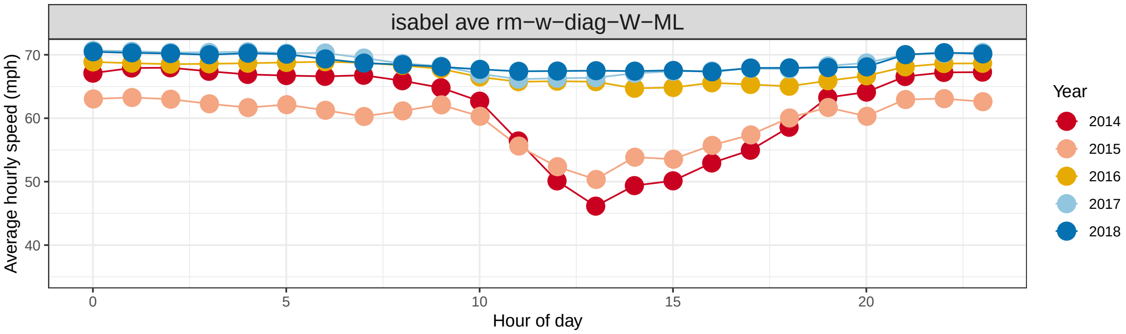


Figure 21: Weekend Speeds at I-580 Express Lanes Project

(a) All hours



(b) 6-8 AM

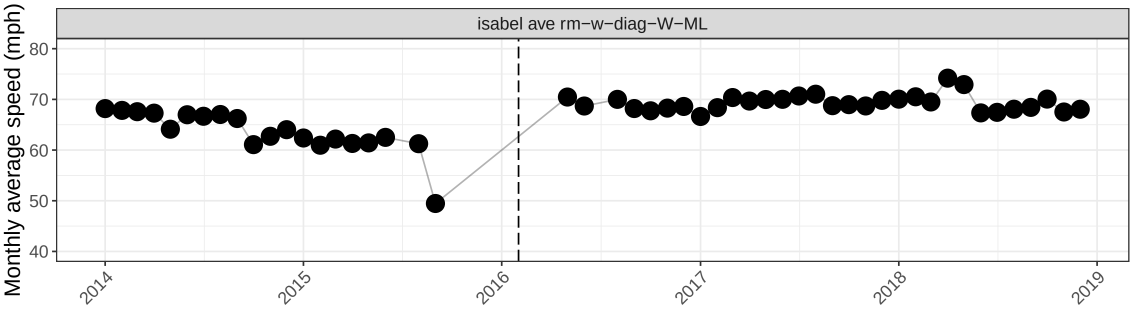
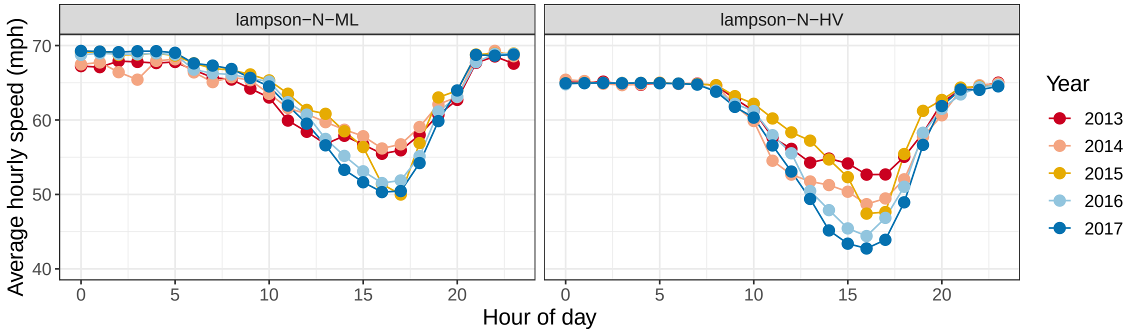
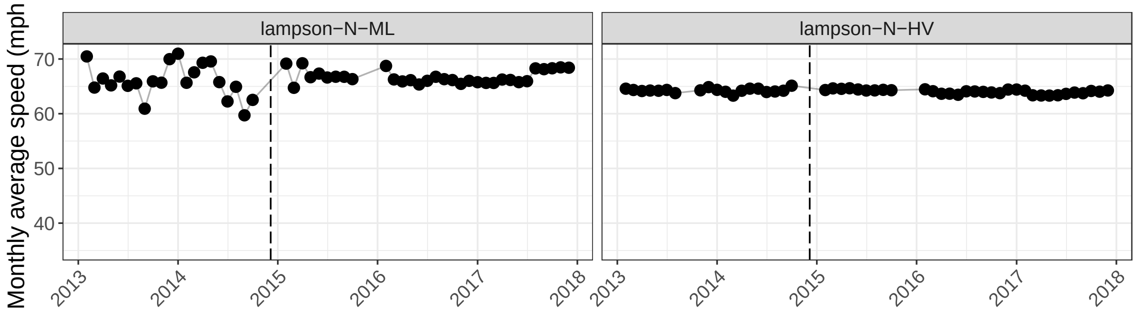


Figure 22: Weekend Speeds at I-405 West County Connectors Project

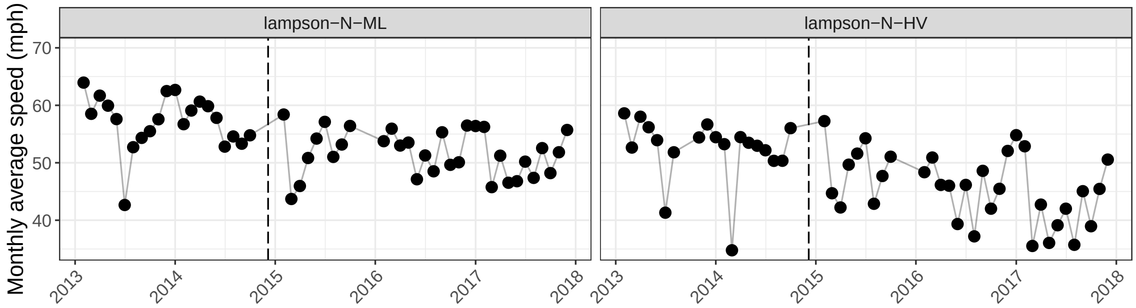
(a) All hours



(b) 6-8 AM



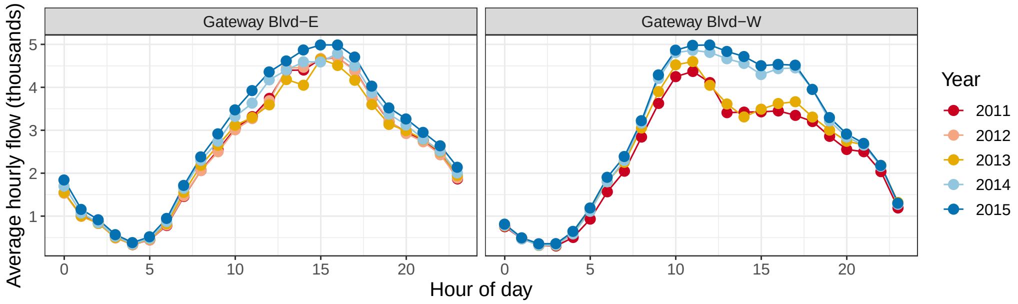
(c) 3-5 PM



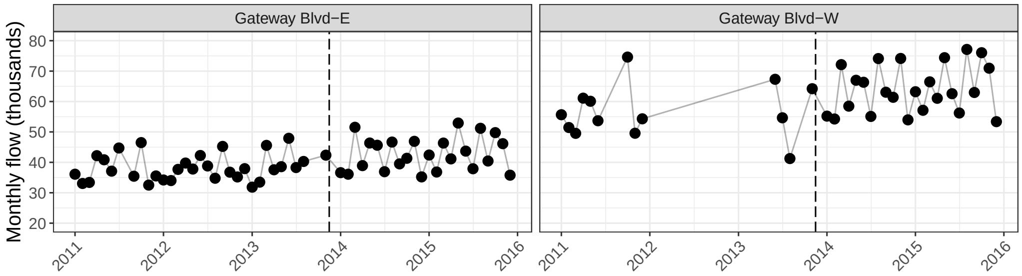
Evidence on Changes in Traffic Flows After Lane Expansions

Figure 23: Weekend Traffic Flows at the SR-24 Caldecott Tunnel Fourth Bore Project

(a) All hours



(b) 6-8 AM



(c) 5-9 PM

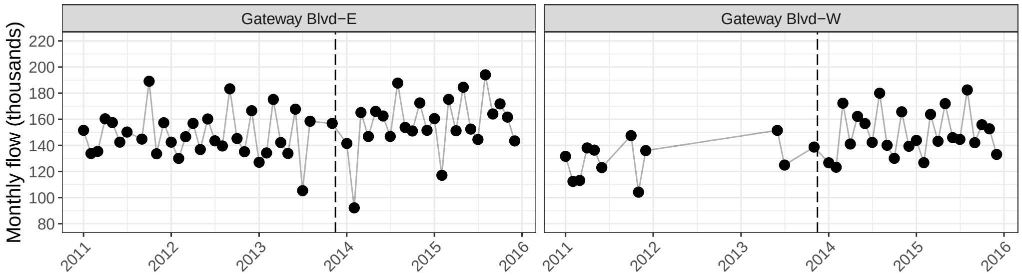
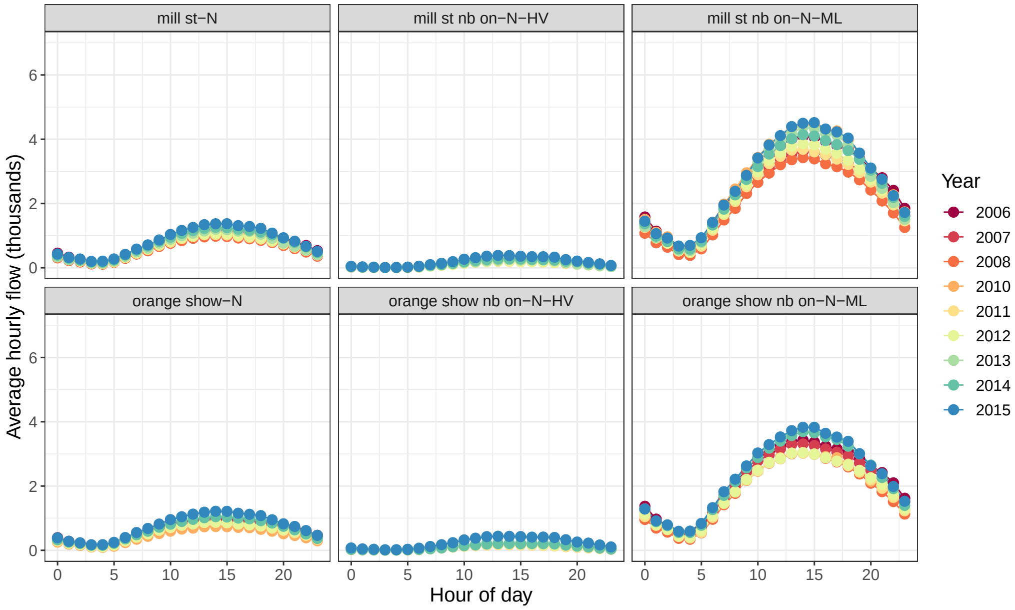


Figure 24: Weekend Traffic Flows at the I-215 San Bernardino Widening Project

(a) All hours



(b) 6-8 AM

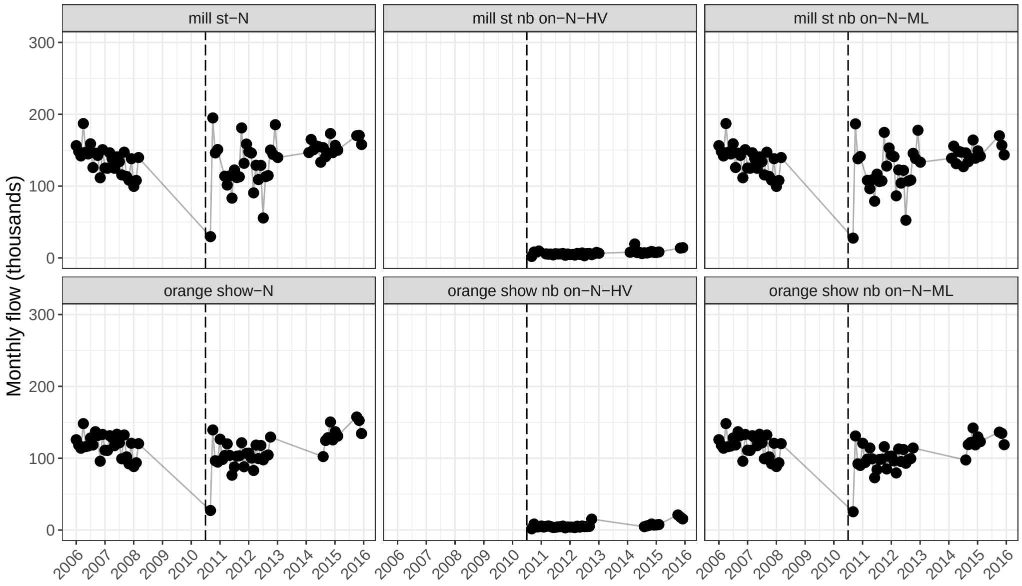
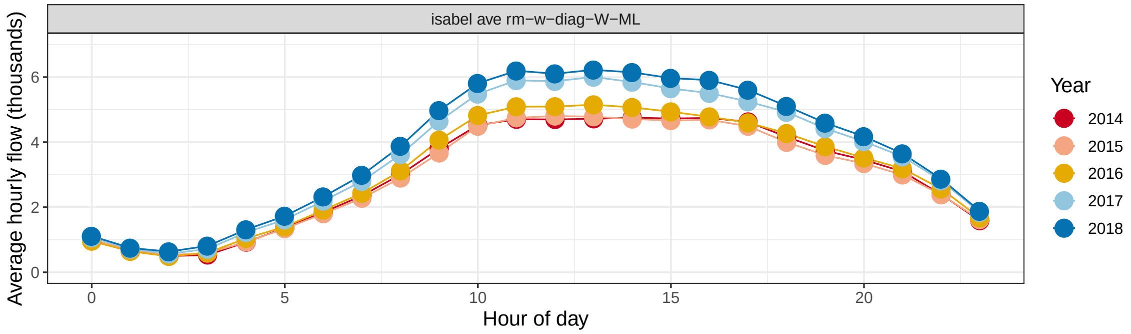


Figure 25: Weekend Traffic Flows at the I-580 Express Lanes Project

(a) All hours



(b) 6-8 AM

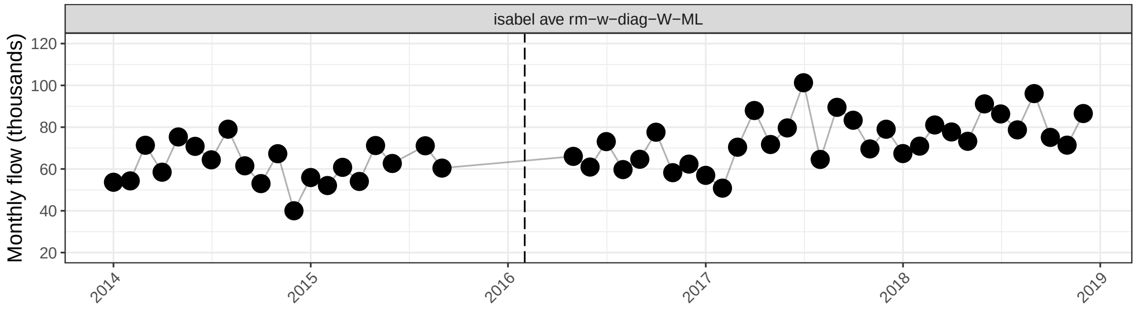
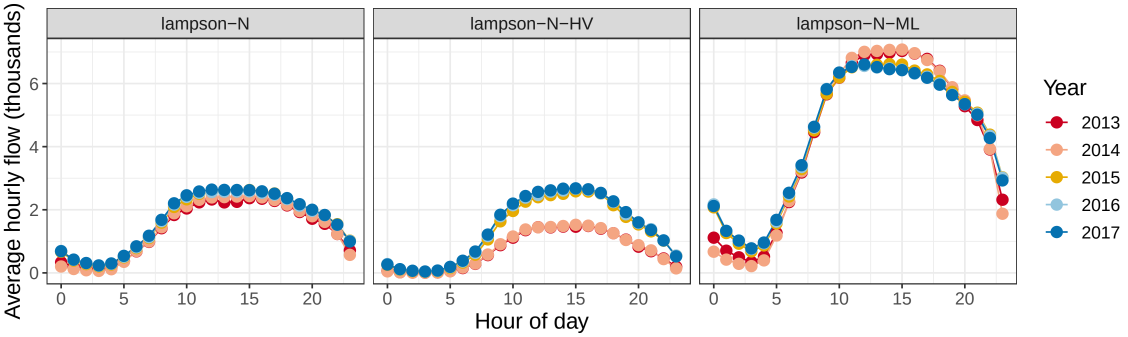
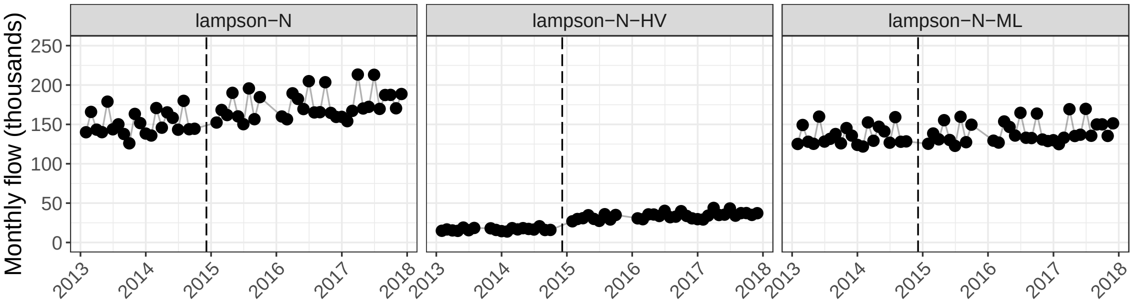


Figure 26: Weekend Traffic Flows at the I-405 West County Connectors Project

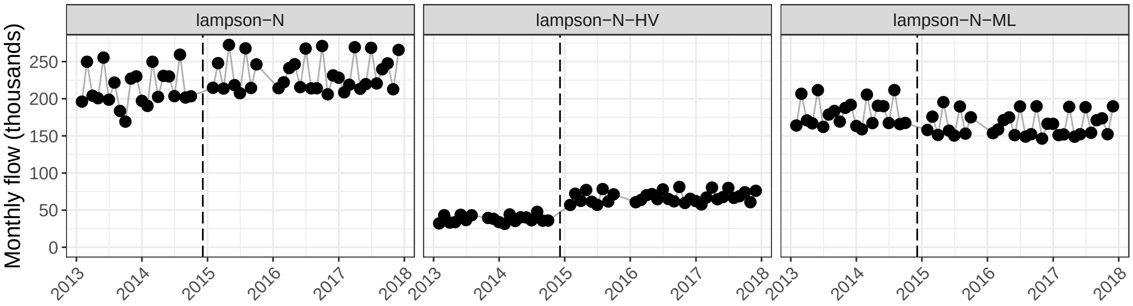
(a) All hours



(b) 6-9 AM



(c) 3-5 PM



Appendix C: Missing Observations in PeMS Data

We use PeMS data on 5-min vehicle flows as the outcome of interest in our regression and graphical analysis. As noted in our Materials and Methods section, PeMS data does not always cover every 5-min interval during the study period, and as a result we have missing data.

While we take multiple steps to address the issue of missing data in our empirical strategy, it is useful to understand at what times data is missing in our sample. In Figures 27 through 30, we plot the percentage of non-missing 5-min observations in our data for each month of the sample period for all of our study sites. These figures capture the total available data for any given month.

It is important to note that this measure is not simply the converse of the percent missing variable we define for our regression analyses. The percent missing variable in our regression analysis is the percentage of 5-min observations that are not captured in the *hour* that the observation occurs, and hours with no observed data are dropped from the analysis entirely. Figures 27 through 30, meanwhile, capture the percentage of 5-min intervals observed across an entire *month*.

Consider an example in which the PeMS monitors do not record data for 10 days out of 30 days in a month, but the 20 days for which data are recorded are completely observed. In this example, the percent missing variable in the regression will be zero, because we observed every 5-min flow in any given hour for which we have some data. However, a figure in Appendix C will show that we only observe 67% of 5-min observations because we are missing one third of the total number of observations possible that month. The percentage of total monthly 5-min flow observed in Figures 27 through 30 is designed to show the extent to which we have missing observations in our data. It is not designed to reflect the quality of the data we are able to use in our analysis, as time periods with no data at all are not included in our regression analyses.

Figure 27: Percentage Observed, SR-24 Caldecott Tunnel

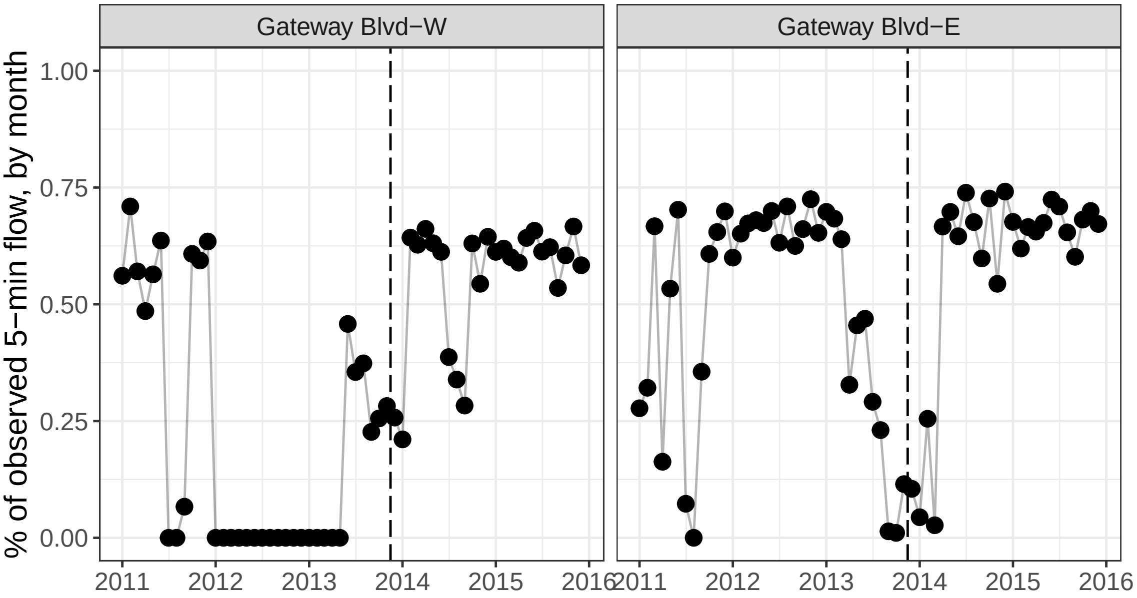


Figure 28: Percentage Observed, I-215 San Bernardino Widening Project

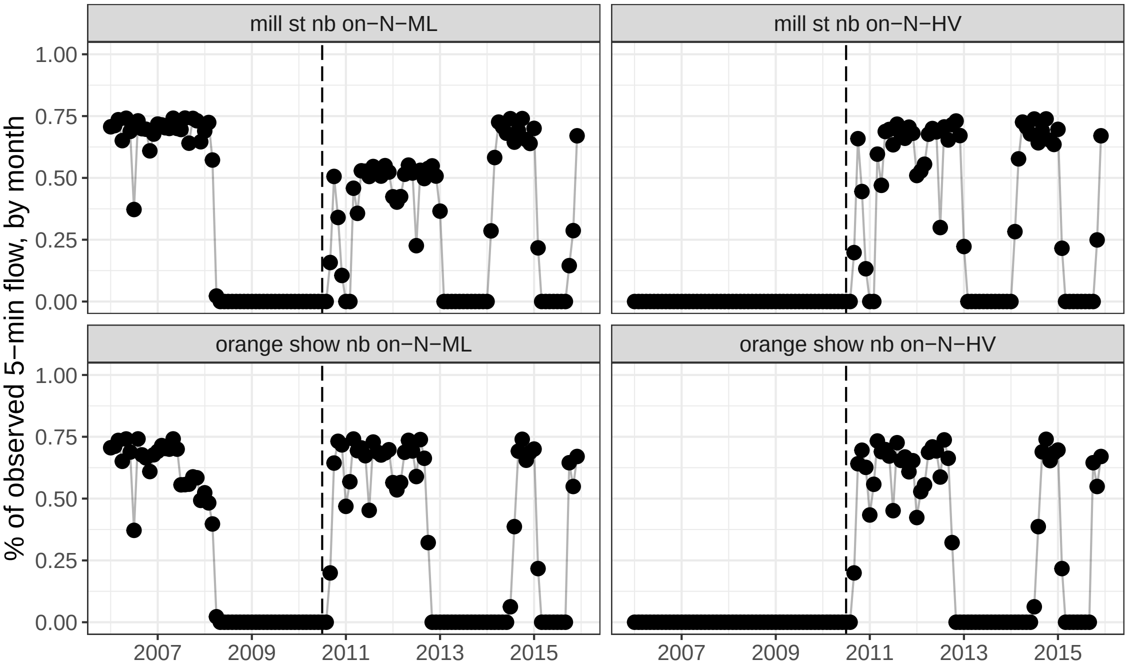


Figure 29: Percentage Observed, I-580 Express Lanes Project

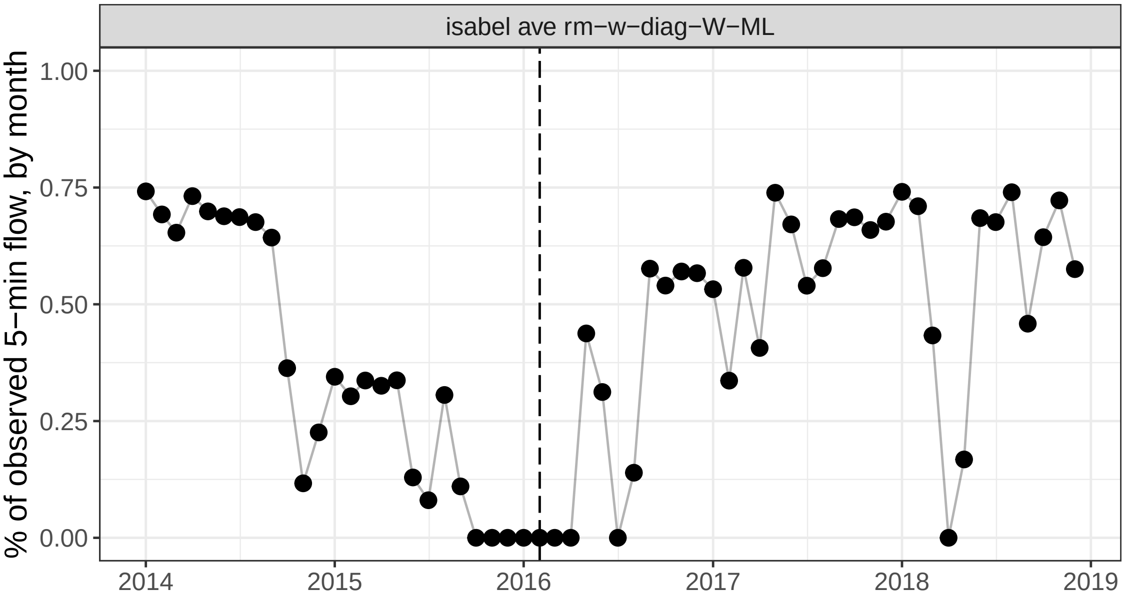


Figure 30: Percentage Observed, I-405 West County Connectors Project