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Publication Date

2026-06-25

Peer reviewed|Thesis/dissertation

Where Does the Traffic Go? Evaluation of Highway Infrastructure Projects in California

By

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Transportation Technology and Policy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2026

ABSTRACT

To understand the impacts and outcomes of transportation infrastructure projects, it is vital to evaluate projects and verify if they met their expectations. I-405 Sepulveda Pass and I-880 Cypress Freeway serve as examples of California's most traveled corridors in major metropolitan regions, and both roadways have experienced capacity-changing construction projects in their lifetimes. To evaluate the effect of changing infrastructure capacity on vehicle flow volumes and speed, I performed an interrupted time series with fixed effects regressions and graphical exploratory analyses. Additionally, I calculated volume and capacity ratios for insight into congestion and traffic distribution within the network. Both cases showed that the observed influences of capacity changes on travel patterns was inconsistent with the project documents. Currently, planning agencies have intentions to significantly transform these corridors; therefore, it is critical to make well-informed decisions for the future by reviewing the outcomes of major historical infrastructure projects.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the Transportation Technology and Policy graduate program for giving me the opportunity to explore my interests in transportation, my peers for providing a welcoming community to learn and grow with some fun along the way, and the faculty for guiding my understanding of the many nuances of transportation.

Within the faculty, I would like especially to thank my advisor, Dr. Handy, who entrusted me early on with a researcher role that ultimately shaped my focus for my thesis and for providing thoughtful feedback and discussion along the way. And to the rest of my committee, Dr. Barajas and Dr. Volker, thank you for your support and advice throughout my time as a VaLUE Lab member and in developing my thesis. I would also like to thank Dr. Amy Lee for your guidance and great discussion as I explored what questions I sought to answer with my thesis and grew as a researcher.

I would like to thank my family: my parents, my sister, and her puppy, Atlas, for providing encouragement and compassion all the way from the other coast. I am grateful I was able to share some of my experience and play tour guide of Davis and California for you all. I would also like to thank the rest of my East Coast community for checking in and always being there for a virtual chat. And especially to Sam, for your kindness and support as we both navigated graduate school from afar.

And a special shoutout to the UC Davis Triathlon Club, for being my family on the West Coast, my workout buddies, and for sharing the love for this sport. And to Lincoln Sabini, for reaffirming my life's purpose to build a transportation system safer for everyone, including cyclists. You will always be in our hearts. We miss you!

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INTRODUCTION

Much of the trajectory of the United States' built environment and, specifically the state of California's, was set in the mid-1900s and has shaped the connectivity and accessibility of communities today. Before sweeping changes in environmental law and regulation during the 1970s, planning and construction of infrastructure largely disregarded the negative impact on preexisting natural resources and society, degrading these resources and displacing communities. In response, anti-freeway movements, paired with environmental and civil rights movements, called for governmental action for protection and conservation. Following the federal enactment of the National Environmental Policy Act (NEPA), the state of California created its own environmental review process, the California Environmental Quality Act (CEQA).

Since the enactment of CEQA, the state of California has grappled with alleviating congestion in its sprawling metropolitan areas while protecting its vast and unique natural environment. Two highway projects in the Bay Area and the Los Angeles region highlight this difficulty in predicting a project's long-term travel and environmental impacts. The example projects - I-405 Sepulveda Pass Improvement Project, a highway expansion, and the Cypress Freeway Relocation Project in West Oakland (Bay Area), a freeway removal and replacement - followed CEQA when built, but long-term outcomes were misaligned with predictions. In case studies of these corridors, statistical analyses of vehicle flows and speed as well as operational insights from volume and capacity ratios emphasize this misalignment.

BACKGROUND

In the year 1970, increased awareness of human activities' impact on the environment, led by growing social movements, inspired President Richard Nixon to sign the National Environmental Policy Act (NEPA) into federal law. A few months later, California Governor Ronald Reagan followed suit, signing the California Environmental Quality Act (CEQA) into state law. While NEPA ensures federal agencies measure and disclose activities that impact the environment in a detailed statement (National Environmental Policy Act of 1969, 1970), CEQA requires all government agencies, from state to local in California, to publicly disclose environmental impacts due to human activities that require government approval (California Environmental Quality Act, 1970). Both laws apply to public-led transportation and land development projects, but CEQA takes the application a step further by also requiring private developers to follow the CEQA process when their project requires discretionary approval by a public agency (*Friends of Mammoth v. Board of Supervisors of Mono County*, 1972).

If environmental impacts from a project are found to be significant, an environmental impact report (EIR) must be prepared, following CEQA. The EIR consists of several resource chapters, including Transportation. Within the Transportation chapter, the lead agency must document the impact the proposed project will (or will not) have on the current transportation system. Prior to Senate Bill (SB) 743, enacted in 2013 and put into effect in 2020, transportation impacts from land development projects were measured in terms of vehicle delay using the metric Level of Service (LOS). With this metric, transportation projects that expanded capacity were predicted to improve a roadway's LOS and deemed to have little to no impact on transportation according to CEQA. The passing of SB 743 marked a shift in the measurement of impacts on the transportation system. Beginning in September of 2020, all impacts to the transportation system

from land development are measured in terms of vehicle-miles-traveled, or VMT (Steinberg, 2013). By measuring the total distance all vehicles travel through a corridor, VMT can be directly translated to air pollution, greenhouse gas emissions, noise, and energy usage generated from vehicular travel on the transportation system (Research, 2018). In contrast to the LOS metric, under the VMT metric, projects that expand a roadway's capacity for vehicular travel have a greater impact on the transportation system due to the projected increase in travel.

In contrast, projects that remove road capacity have the potential to reduce VMT and could positively impact the environment. Because these types of projects are rarer than capacity expansion projects, knowledge of their impact on the transportation system and the environment is limited. Since the removal of Harbor Drive in Portland in 1978, at least fifteen more freeways have been removed with many more in the planning phase. This prompts a need and growing opportunity for more recorded real-world observations of what happens to traffic when a freeway is removed and the possible benefits to the environment that comes with it.

Under the Biden administration, the Reconnecting Communities Pilot Program spurred the recent growth in freeway removal proposals. From 2023 to 2025, the program awarded over \$4 billion in grants to 257 projects aimed at community reconnection (Transportation, 2025). Only ten percent of the overall funding, about \$400 million, went toward true freeway removal projects, while over a billion dollars was granted to projects that maintained or expanded overall capacity by capping or building land bridges over divisive freeways (Harrington, 2025). Nevertheless, this program put more freeway removal proposals on the table and in the plans.

LITERATURE REVIEW

State of Forecasting Induced Travel

Metropolitan planning organizations (MPOs) developed travel demand models (TDMs) to forecast future changes in regional travel. TDMs employ socioeconomic and travel survey data as well as information on the region's transportation network as inputs. From there, the traditional versions of these models follow a four-step process with trip generation, trip distribution, mode choice, and network assignment. A review of the TDMs of California MPOs found the “[t]he induced travel effect receives limited attention in both plans and [travel demand] model documentation” (Handy et al., 2024). The current practice of travel demand modeling falls short of incorporating the effects of the short-lived reduction of travel costs from roadway expansion on dynamic travel behaviors

In the past decade, multiple studies have determined that inaccuracies in travel forecasts can lead to unintended outcomes. A recent study on traffic forecasting examined almost 1,300 transportation construction projects in the United States and, of the 22% that were capacity expansion projects, most observed traffic levels to exceed the projects' forecasts (Hoque, et al., 2022), meaning more travel occurred on the project corridors than was originally expected. This cascades into misalignment of expected benefits such as congestion reduction and time travel savings, as well as underestimated costs such as more air pollution and greenhouse gas emissions. For example, a case study on a road widening project in London found an overestimation of travel time savings resulting in the actual economic benefit of the project being much lower than expected (Metz, 2021). A possible explanation for these shortcomings in expectations compared to actual outcomes is the phenomenon of induced travel. Induced travel

occurs due to the initial lowering of costs to driving when a roadway is expanded, and, therefore, prompting more driving.

Measurement of Induced Travel

While overlooked in practice, empirical research and the laws of supply and demand have repeatedly provided evidence of induced travel in the transportation system. The concept of induced travel was explained by economist Anthony Downs in his paper, *The Law of Peak-Hour Expressway Congestion*. He described how commuters react to changes in travel time to achieve traffic equilibrium, and he explained these behaviors through his theory of triple convergence (Downs, 1962). Since his work, induced travel has been increasingly studied by researchers, usually measured by an elasticity: percent change in roadway capacity (lane-miles) compared to percent change in amount of vehicle travel (vehicle-miles-traveled). For example, researcher Robert Cervero compiled and compared studies measuring induced travel from the mid-1900's to early 2000's. In his review, he concluded that induced travel is a real occurrence and needs to be better integrated in the transportation planning process (Cervero, 2002). These same issues were echoed over a decade later by researchers Robert Noland and Christopher Hanson in their chapter, "How Does Induced Travel Affect Sustainable Transportation Policy?", where they review how methods to measure induced travel have evolved in the following decade (Noland & Hanson, 2013).

In empirical research, elasticities are used to quantify the percent change in travel volumes compared to the percent change in capacity. In this way, the growth in traffic volumes is normalized by the extent of the expansion, in terms of lane miles, and can be compared across facility-level to region-level studies. Anderson et al. (2021) focused on four California highway facilities that were widened and determined their respective elasticities, in terms of change in

short-term traffic flows and change in number of lanes. The statistical analysis resulted in elasticities ranging from 0.152 to 0.843 (Anderson et al., 2021). At a regional-level, Duranton and Turner (2011) aggregated highway widening projects within a metropolitan statistical area (MSA) by measuring the total lane-miles of the built environment compared to Average Annual Daily Travel (AADT). In their analysis, they determined elasticities for urban Interstate highways within an MSA to range from 0.86 to 1.03 (Duranton & Turner, 2011). Following these studies and others, researchers at UC Davis developed the California Induced Travel Calculator based on the conclusion that long term elasticities for Class 1 to 3 roadways range from 0.7 to 1 (Volker et al., 2020).

With a large body of induced travel measurements from empirical studies, the question is no longer about its existence but how its measurement can be incorporated into travel demand forecasting (Deakin, 2020). Areas of improvement include modeling feedback loops, integrating land use changes, and implementing robust travel evaluation metrics (beyond congestion and delay). This requires changes to guidelines on traffic impact analyses, some of which are already included in Caltrans' Traffic Analysis Framework (Caltrans, Transportation Analysis Framework Second Edition: Evaluating Transportation Impacts of State Highway System Projects, 2025), as well as innovations, such as the NCST Induced Travel Calculator (Volker et al., 2020), to provide a standardized methodology for practitioners to follow in measuring induced travel.

Evidence on Reduced Travel

As with the occurrence of induced travel, where adding road capacity materializes additional trips on the expanded road, its inverse, reduced travel, suggests removing capacity “will shift demand towards more environmentally friendly modes of travel like transit, walking, and biking” and reduce automobile trips (Mohl, 2011). There are fewer studies on reduced travel, compared

to induced travel, specifically on how to measure its occurrence and translate it into practice. The rarity of projects that can reduce travel, like freeway removals, results from multiple circumstances needing to converge simultaneously. These circumstances include deteriorating conditions (in terms of physical quality and safety), a window of opportunity to experiment (natural disaster closing a freeway), costs of rehabilitation are less than removal, and changing values (reconnection over mobility) for a policy entrepreneur or collective group to propose this type of project (Napolitan & Zegras, 2008). Despite this, some studies do provide evidence of the phenomenon of reduced travel and its outcomes.

One of the first studies on road capacity reduction effects on vehicle travel was completed by a London-based research team in 1998. This first-of-its-kind study aimed to understand the technical feasibility of capacity reducing projects and refuted the assumption that the capacity loss would cause traffic to redistribute to parallel routes and cause congestion. By examining almost 100 international case studies of capacity reduction scenarios, the research team determined that a small but significant percentage of traffic (on average, between 16-25%) had disappeared from the area following capacity loss (Cairns et al., 1998). In addition to less traffic on the roadways, other benefits from capacity reduction projects include neighborhood connectivity, improved air quality (Patterson & Harley, 2019; Pugh, 2024), safer active travel conditions (Seattle Urban Mobility Plan, 2008), freeing up land for economic development (Billings et al., 2013; Khalaj et al., 2020), and even reductions in crime rates (Seattle Urban Mobility Plan, 2008). Following the initial Cairns et al. study, researchers have evaluated road diets and freeway removals to better understand changes in travel patterns from these types of projects.

Reduced Travel from Road Diets

Road diets typically convert a four-lane road with two through lanes in either direction to three lanes: two through lanes and a two-way left turn lane (FHWA, 2022). Complete street design takes road diets a step further by reallocating road space to non-motorized modes, such as providing bike lanes and widening sidewalks. To determine the effects of road diets on personal vehicle travel and other modes, researchers have completed before-and-after traffic studies for these types of roadway projects. Studies on road diets and complete streets in the United States have found that traffic does not divert within the project area's network, and, in some cases, overall travel decreased (Schlossberg et al, 2013; Shu et al, 2014). Later studies improved the pre- and post-traffic study method for road diets by comparing the intervention street with a similar control street while accounting for changes in the surrounding street network (Nixon et al, 2017; Jouliot, 2018; Olhms et al, 2020). This mix of quantitative and qualitative analyses presents evidence of improved traffic conditions through redistribution to underutilized infrastructure and other modes when a car-serving lane is removed from a roadway. The findings of these studies are summarized in Table 1.

Table 1: Changes in road capacity (lane-miles) and transportation modes after a road diet.

Project Name	Years Measured	Change in Capacity	Change in Traffic Volumes	Source
Ocean Park Blvd, Santa Monica (lane diet)	2011-2013	+50% sidewalk space -40% roadway space	0% Vehicle traffic -26% Emission-weighted traffic volumes +37% Pedestrian traffic	Shu et al (2014)
Lincoln Ave, San Jose	2014-2016	-12.5% lane-miles	- 6% Treatment street -5% Neighborhood streets -2% N & S of road diet 0% Major street	Nixon et al (2017)
Road Diets in LA	2005-2009	-25% lane-miles for each project	+8% Treatment streets -0.6% Control streets	Jouliot et al (2018)
Road Diets in Virginia	2017-2019	-25% lane-miles for each project	- 3% Treatment street (weekdays)	Olhms et al (2020)

While these road diet studies show evidence of improved transportation systems, research shows corridor-specific modeling of these interventions doesn't always predict these effects due to the following limitations. Mayerthaler et al. suggests this could be an effect of models inaccurately reproducing human travel behavior (Mayerthaler et al., 2010). Other limitations in travel demand modeling for complete streets include insensitivity toward non-motorized trips, inadequate representation of shared micromobility uses, limited representation of level of service characteristics for non-motorized modes and transit users, and increased level of detail (Ali, et al., 2024). While these limitations are specific to travel demand models used for arterials and roadways, improvements made to these models can apply to regional modeling for larger projects such as freeway to boulevard conversions. With the greater availability of studies on road diets and complete streets projects, these studies can inform the outcomes transportation analysts should expect from a rarer form of greater capacity reduction: freeway removal.

Reduced Travel from Freeway Removals

A more costly and construction-intensive approach to improving conditions for modes of travel, other than driving, is freeway removal. The regional travel demand models for capacity reducing freeway removals “project increased congestion due to a freeway-to-boulevard conversion, so cities are pressured to re-route and maintain traffic flow rather than attempt to reduce vehicle miles traveled” (Stehlin, 2023). Empirically, a research team at the University of Connecticut calculated volume/capacity ratios before, during, and after removal of multiple freeways. The team determined that the loss of the freeway did not completely redistribute traffic volumes throughout the network, but that traffic volumes decreased post-removal (Billings et al., 2013). This misalignment of the actual outcomes from capacity-reducing projects can prevent these potentially beneficial projects from being planned, along with all the necessary conditions from the converging policy streams theory by Napolitan and Zegras.

Ultimately, more documentation of reduced travel or “traffic evaporation” and mode shift can better inform transportation officials on the environmental and mobility benefits of capacity reduction (Nello-Deakin, 2020). The Appendix “Freeway Removals in the United States” lists freeway removal projects in the US with their corresponding changes in travel patterns throughout the local network and other important characteristics. In almost all cases where traffic data was available, traffic volumes through the corridor decreased just after freeway removal. The most common reasons for removal included physical damage and urban/economic development. In terms of efficiency in traffic operations, low traffic volumes hinting at capacity underutilization and high traffic volumes suggesting congestion were both reasons supporting freeway removal.

Inconsistency between forecasts and actual travel outcomes can lead to overestimation of benefits and underestimation of costs for capacity expansion projects. This inconsistency may stem from the current modeling practices inability to capture induced travel. The effects of induced travel must be included in the planning process, especially in the measurement of environmental impacts. More research is needed to evaluate the actual outcomes of expansion projects and compare these outcomes to the initial project goals and anticipated environmental impacts.

Reduced travel must be acknowledged as a phenomenon in capacity removal of transportation infrastructure with its effects included in modeling and planning as well. To understand its effects to the same level as that of induced travel, more data collection and observation of outcomes from capacity removal projects, such as freeway removal, must occur and be studied.

Freeway building through urban areas has resulted in many negative externalities. Improved understanding of freeway removal's outcomes on traffic operations will reduce uncertainties in the planning process and traffic analysis, allowing these projects to reach their 'groundbreaking' ceremonies. This thesis evaluates a capacity expansion project's traffic outcomes and compares findings with the project's forecasts, expected impact, and expectations. Additionally, this thesis applies a novel method to evaluate travel patterns after a freeway removal and replacement project and provides insight into travel mode and route changes.

METHODS

To explore how actual outcomes differ from expected outcomes and the resulting impact on the environmental review and congestion analysis, I studied highway projects in California. The highway projects chosen meet the following criteria: 1) located in California's major metropolitans as evidence for induced travel and reduced travel is most prevalent in urban areas; 2) completed at least a decade ago to provide ample time for before/after evaluation; 3) continued investment in construction projects for the corridor of choice as this indicates transportation problems prevail; 4) availability of data and documentation for thoroughness. While these were not the only projects available, the richness of data and nuances of these projects made them stand out. Highway expansions with HOV lanes and freeway removals that result in replacement are rarer and under studied. The case study highway projects chosen are listed in the table below:

Table 2: Case studies chosen to answer research questions.

Project Name	Highway	County	Construction (Years)	Change In Total Lanes (%)	Project Cost (Billions)
Sepulveda Pass Improvements (Widening) Project	I-405	Los Angeles	2009-2014	5 to 6 (+20%)	\$1.2*
Cypress Freeway Replacement Project	I-880	Alameda	1989-2001	8 to 6 (-25%)	\$1.0**
*2015 dollars; **1998 dollars					

For these case studies, I sought to answer the following questions:

1. How do project forecasts, expectations, and/or goals compare to observed travel outcomes for completed highway construction projects in California's major metropolitan areas?
2. What can be learned from project evaluation and applied to future planning of these corridors?

I hypothesize that, in the case of I-405 Sepulveda Pass, the analysts overestimated the congestion savings from adding a lane due to increased travel from expanded capacity. On the other hand, the temporary removal and eventual replacement of I-880 Cypress Freeway would cause reduction in vehicle travel and modal shift in the wake of less roadway capacity. By evaluating these completed projects, one can compare the project goals with actual outcomes and gain a deeper understanding of how these transportation construction projects affected travel in urbanized areas within California.

Data

To understand the traffic forecasts, expectations, and goals of the projects, I collected and reviewed project reports, CEQA documents, and supplemental studies such as Traffic Operations Analysis Reports (TOAR), as well as qualitative sources such as news articles. Project reports included studies completed by the lead agency, LA Metro, for I-405 and, in the case of I-880, federal agency audit documents as federal emergency relief dollars funded this project as the CEQA documents prepared by Caltrans were not readily available.

Observed traffic data, both vehicle flows and speeds, were sourced from Caltrans's Performance Measurement System (PeMS) database via vehicle detector stations. Vehicle detection stations, usually in the form of loop detectors that sense vehicles as they pass over the device, collect raw flow and speed data every five minutes. PeMS offers a change log for each vehicle detector in their database that records when the detectors were established, activated, disabled, and other important characteristics. Additionally, PeMS records observations as a percentage, for the time-based aggregation of flow, occupancy, and speed data points. In instances where an aggregation is not informed by 100% observed loop detection data, Caltrans follows an imputation procedure which is outlined in the "Help" tab of PeMS database. Caltrans' imputation procedure is as follows (Caltrans, 2007):

1. Referencing a paper by researchers from Berkeley (Chen et al., 2003), PeMS follows a linear regression approach to fill in missing values using spatially-near "good" loops and local coefficients
2. If neighboring good loops are not available or reliable, then Caltrans develops a linear regression based on global, instead of local, coefficients, confined to the district.

3. If adjacent loop data is inadequate to perform a linear regression, Caltrans will then use temporal medians. The temporal median is determined from loop data at the location of interest over the specific day of week and time of day that is missing over several weeks.
4. The last resort imputation method involves cluster medians. Clusters are formed within each district of detectors that share similarities in the context of their location. Caltrans gives the example of “a freeway headed into the downtown area of a city” which “would all have similar macroscopic patterns in that the AM and PM peak directions would be similar from commuting traffic” (Caltrans, 2007).

If no loop detector data was available, as was the case for I-880, annual flow data was collected from Caltrans’s Traffic Volumes Archives and Traffic Census Program. Ridership data from non-automobile modes, such as transit, was sourced from the transit agencies’ website to gain insight on modal shift for I-880 (i.e. Bay Area Rapid Transit (BART) and San Francisco Bay Ferry Service).

Analysis

To determine changes in travel trends, before and after construction of I-405, Anderson et al.’s (2021) interrupted time series analysis for highway expansion projects was replicated. First, an exploratory analysis of temporal traffic flow changes for a single vehicle detection station over daily and annual timeframes was conducted for visual changes. The statistical significance of the visual changes was determined with a fixed effects regression for the interrupted time series. The fixed effects regression was structured as follows:

$$Y_t = \beta_0 + \beta_1 \cdot [Post\ Expansion]_t + \theta_m + \alpha_d + \delta_h + \varepsilon_t$$

Equation 1: Fixed effects regression for an interrupted time series for vehicle flow and speed.

The dependent variable, Y_t , represented the natural log of total vehicle flows in all lanes with t indicating the timestamp for each data point. Subsets of time data included weekday versus weekend, and, more granularly, peak period versus off peak. The natural log transformation allowed for direct comparison of the coefficients of the variables as approximately a percent change. The variable of interest, $[Post\ Expansion]$, served as a dummy variable where it was equivalent to one if t was a timestamp after the expansion (falls after the completion date of May 23rd, 2014), otherwise it was equivalent to zero. Additionally, β_1 represented the coefficient of the lane expansion on the dependent variable. The control variables were fixed to account for variance due to changes from time. These included θ_m , month of the year; α_d , day of the week; and δ_h , hour of the day. Lastly, ε_t represented the error term, capturing effects unexplained by time variance or the explanatory variable. It was assumed to be uncorrelated with the explanatory variable.

To control effects related to the passage of time, such as population and employment trends, another regression model was developed with continuous time variables. The equation was structured as follows:

$$Y_t = \beta_0 + \beta_1 \cdot [Post\ Expansion]_t + Time + Post\ Expansion\ Time + \theta_m + \alpha_d + \delta_h + \varepsilon_t$$

Equation 2: Fixed effects regression for an interrupted time series for vehicle flow and speed, controlling for continuous time effects.

The “Time” variable controlled for continuous temporal effects across the entire project study period, from 2004 to 2019, by counting in increments of one for each month that passed. Similarly, the “Post Expansion Time” variable began counting in increments of one for each month that passed since the opening date of the project, with the first month as June 2014.

The final step included a control test, with a comparable facility, that did not undergo any transportation construction projects within the time of interest. The comparison site chosen for the I-405 case study was US Highway 101 through Cahuenga Pass. US 101 did not experience any construction projects in and near the segment of interest (Cahuenga Pass) during the years studied (2004-2019), parallels I-405 as another limited access route that bypasses Downtown LA, and is also geographically constrained by the Santa Monica Mountains. For these reasons, it can be hypothesized that US 101 should not show as great of magnitude in change in vehicle volumes and speeds as I-405. Additionally, US 101 is likely not an alternate route for I-405 as it does not serve as a direct connection to the LA airport (LAX), a major origin/destination of I-405, and it merges with I-5 before I-5 connects to I-405 at its northern and southern terminus. Therefore, I-5 would be a more suitable alternate route. The regression and exploratory analysis steps were repeated for the comparison site. The regression and statistical analyses were also repeated using the hourly speeds for both freeways as the dependent variable.

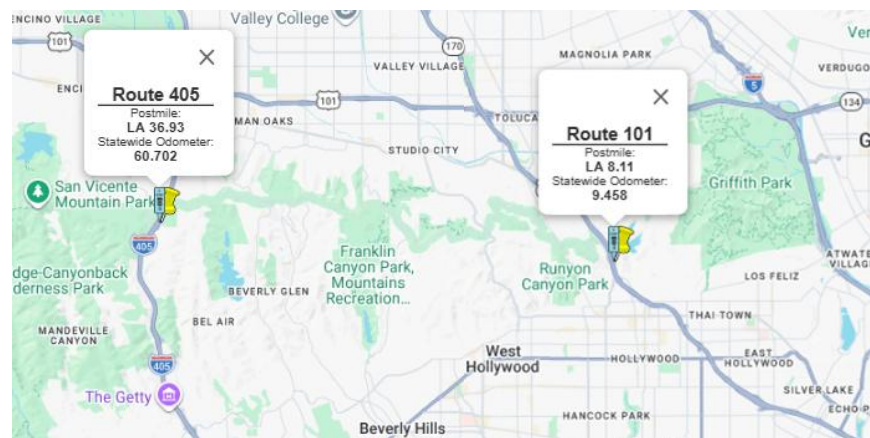


Figure 1: Geographic location of the vehicle detection stations from PeMS for I-405 and its comparison facility, US 101 (Source: [Postmile Query Tool](#)).

Data to determine FFS and truck proportions was available to calculate the capacity of I-405 Sepulveda Pass prompting usage of the Highway Economic Requirements System (HERS) Simplified Highway Capacity Calculation Method. This method did not assume free flow speed and truck proportion of total flow, but rather integrated these context-specific details into the capacity equation below:

$$Capacity = \frac{(2,200 + 10 \times (\min(70, FFS) - 50))}{1 + \%HV/100} \times Lanes$$

Equation 3: HERS method for calculating freeway capacity based on free flow speed, truck proportion, and number of lanes.

To determine free flow speed, hourly lane-specific speed data, during the off-peak hours only, was averaged across lanes over a three-month period. Similarly, the truck proportion was averaged over a quarter of a year across all lanes over all hours. Peak period speed was determined from hourly speeds averaged over the afternoon/evening peak period. Hourly speeds and truck proportions used in the calculation were measured at the Skirball/Mulholland mainline and Mulholland HOV vehicle detector stations. These calculations served as metrics, supported by the regression analysis, that provided insight into the congestion and efficiency of I-405 before and after expansion.

To determine congestion impacts for the I-880 case study, I replicated Billings et al.'s (2013) methodology of calculating volume/capacity ratios. As was the case for the Embarcadero and Central Freeways studied by Billings et al., the data and project documents available for the Cypress Freeway lacked similar detail in important capacity adjustment factors and are all located in the San Francisco metropolitan region. Therefore, the replication of the research

team's method and assumptions seemed appropriate. The first step was to calculate the base capacity of the road, which is the capacity it was designed to carry based on its free flow speed and number of lanes. Following the Highway Capacity Model (HCM) Exhibit 21-23, the equation for base capacity was:

$$\text{Base Capacity} = 1000 + 20 * \text{FFS}, \quad \text{FFS} \leq 60 \text{ mph}$$

Equation 4: Calculation of base capacity for a freeway.

For urban area freeways, free flow speed (FFS) was estimated to be 50 mph. As Oakland is an urbanized area, I followed this assumption. The base capacity was multiplied by the number of lanes (N) within the segment of choice as follows:

$$\text{Freeway Segment Capacity} = \text{Base Capacity} * \text{Lanes}$$

Equation 5: Calculation of freeway segment capacity.

Since the Cypress Freeway ultimately served as a connection between the Bay Bridge and downtown Oakland, I compared traffic volumes on I-580 and I-980, measured at the I-80/Bay Bridge connection and the Market Street connection, respectively.

To calculate the numerator for the volume/capacity ratio, peak hour flow volumes were collected from Caltrans Traffic Census Program reports for each freeway in the Oakland network. For I-405, more granular data was available from a PeMS vehicle detection station. The maximum peak hour was extracted from aggregating five-minute flow data over a week period in September to determine the maximum peak hour volume flow for the freeway segment of interest. The maximum peak hour volume represents the greatest amount of vehicle volumes that move through the segment of interest at a given time, which would indicate the most congested period.

FINDINGS FOR I-405

Interstate 405 is a freeway in Los Angeles County that crosses the San Fernando Valley and runs parallel to I-5, with connections to the Los Angeles International Airport. The I-405 Sepulveda Pass highway expansion project was proposed by LA Metro in the early 2000s to widen I-405 in the northbound direction from 5 to 6 lanes to accommodate an HOV lane. The widened freeway segment spans between I-10 and US 101 and is geographically constrained by the Santa Monica Mountains. According to the project's Final Environmental Impact Report (FEIR), the purpose for the I-405 Sepulveda Pass Highway Improvement Project was to "reduce the existing and forecasted traffic congestion" and "improve mobility" while also "minimizing potential environmental and economic impacts" (Caltrans, 2008). Along similar lines, the need for the project was to "fill in a gap in the overall HOV network, improve the current deficient Level of Service metrics, and reduce the high percentage of rear-end collisions" (Caltrans, 2008). The purpose and need for the project represent the goals and intended outcomes of the alternative chosen.

Figure 1.1-1: Project Location Map



Figure 2: Extent of the I-405 Sepulveda Pass Highway Improvements Project (Source: Caltrans (2008)).

This highway was initially built in the late 1950's as an eight-lane highway. In 1985, I-405 was restriped, which narrowed the lane widths and allowed for the facility to expand to ten lanes. In 2002, I-405 was converted or expanded, in some segments, to a 10 to 11-lane highway to accommodate the addition of an HOV lane for southbound travelers between Waterford St to North of Burbank Boulevard (Caltrans, 2008). The most recent, large-scale construction project on I-405 in the Sepulveda Pass segment was the addition of an HOV lane for northbound travelers, completed in 2014. This most recent expansion is the focus for graphical and statistical analyses.

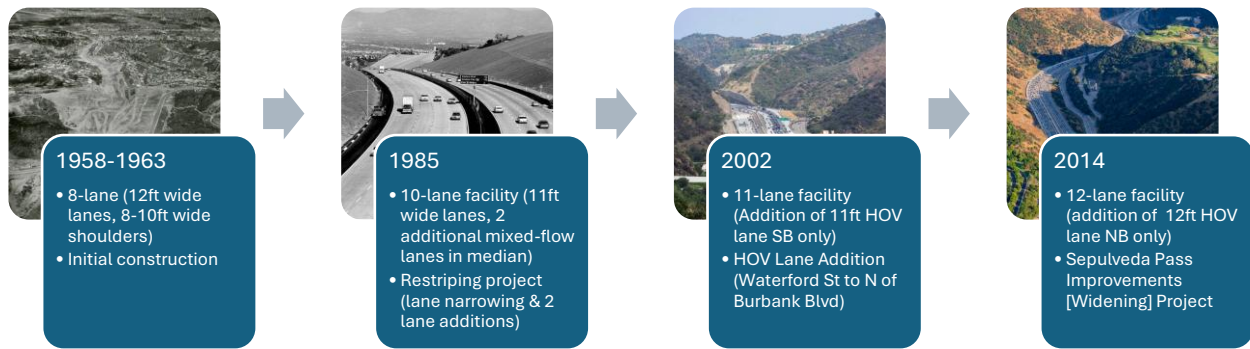


Figure 3: Timeline of major historical transportation construction projects on I-405 within its Sepulveda Pass segment (Sources: [LA Metro The Source Archives](#); [Metro Transportation Research Library and Archives](#); [HNTB](#)).

Currently, the local agency is studying plans for either converting the HOV lanes to HOT or express lanes as well as the potential expansion of the highway to accommodate another HOT or express lane in both directions (LSA, 2022). Plans are also on the table for an underground rail service, parallel to I-405, to establish a multimodal corridor through Sepulveda Pass (HTA Partners, 2026).

The exploratory analysis focuses on the impact of the most recent expansion of HOV lanes for northbound travel on I-405 through Sepulveda Pass. According to the project's technical studies, traffic data from 2003 was increased by 3% to estimate 2005 volumes, the baseline year (IBI Group, 2006). These 2005 traffic volumes were extrapolated to predict 2015 (opening year) and 2031 (design year) traffic volumes using an annual growth rate of 1.47% (Caltrans, 2008). The growth rates used in the forecasting process reflect Southern California Association of Governments' (SCAG) regional growth rates for the project area (IBI Group, 2006). The projected volumes reported in the EIR are the same whether the project is built following the

consultant's assumption that the capacity increasing addition of HOV lanes will not affect travel trends (IBI Group, 2006).

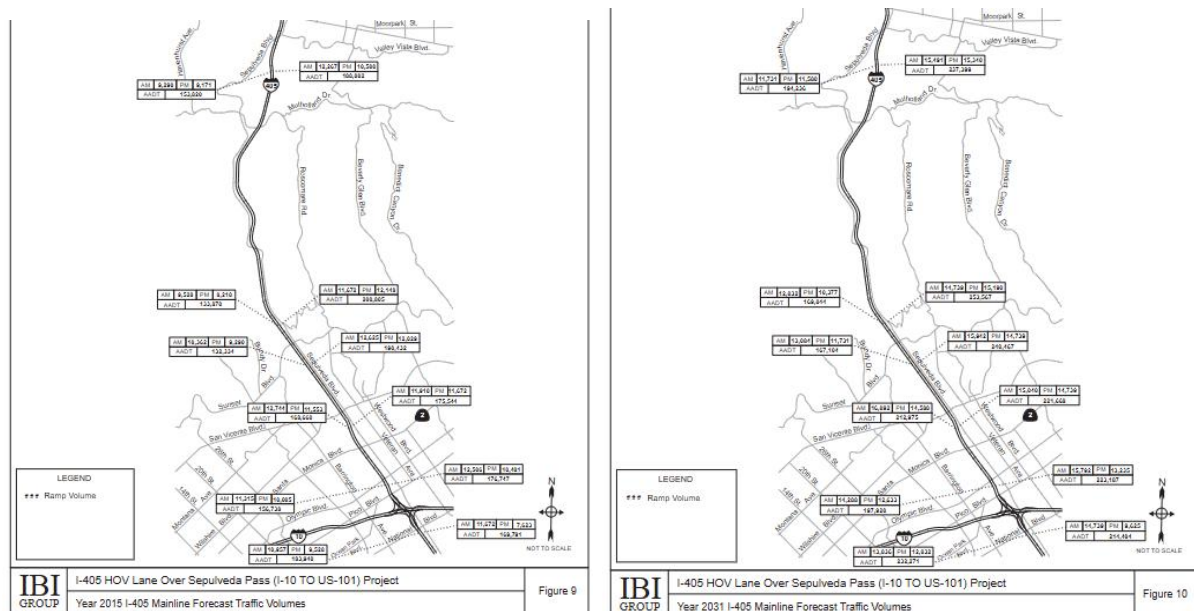


Figure 4: AADT and Morning/Afternoon Peak Hour forecasts for 2015 and 2031 (Source: IBI Group, 2006).

To compare the projected growth on the corridor with the actual growth, Average Annual Daily Travel (AADT) data was accessed from two vehicle detection stations in PeMS within the project limits that were nearest to the locations highlighted in Figure 4 above. Additionally, the vehicle detection station chosen, Santa Monica and Skirball/Mulholland, are near major exits on I-405 and contain the highest percentages of observed data (Skirball/Mulholland performed the best). Figure 5 compares the observed AADT growth for 2015, 2019, and 2022 to the projected growth rate for each of these years with the baseline year as 2005.

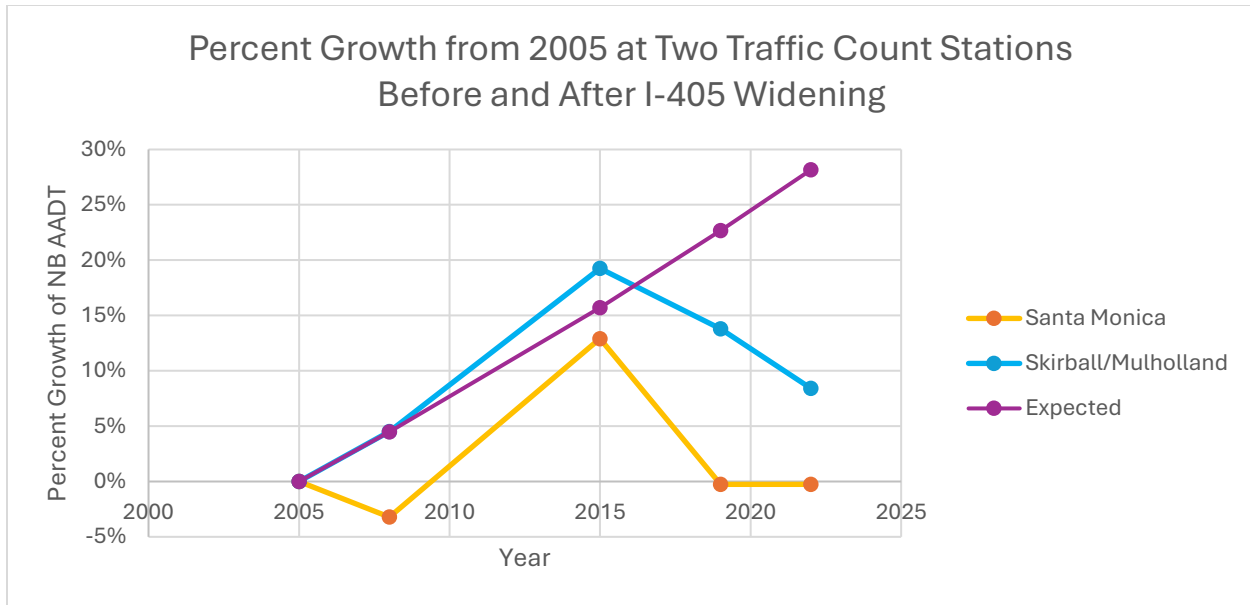


Figure 5: Comparison of the expected percent growth of traffic volumes (based on an annual growth rate of 1.47% from TAR) to actual percent growth of traffic volumes at two traffic count stations (located near Santa Monica and Skirball/Mulholland exits) starting at baseline year 2005.

Figure 5 shows that the opening year of 2015 was on track to follow the predicted growth from 2005. While travel in the NB lanes still grew following 2015, the rate was not constant, as predicted, and lessened in the years following the project's completion. This lessening of growth, especially in the case of the Santa Monica vehicle detection station where travel was decreasing after 2019, could be attributed to the lockdown conditions following the COVID-19 pandemic in the beginning of 2020. Figure 6 gives a sense of regional changes in travel, measured as vehicle-miles-traveled, in response to quarantine during the pandemic.

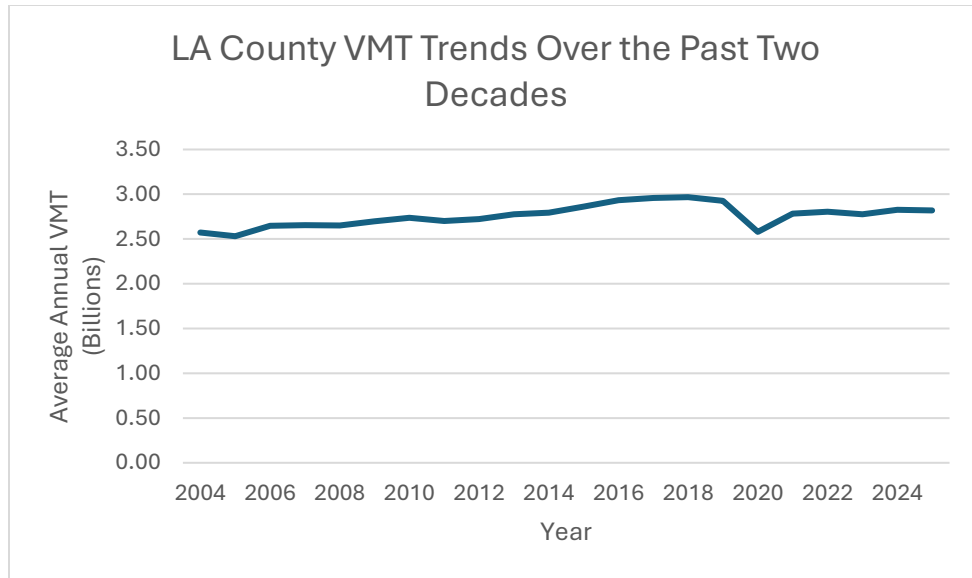


Figure 6: Vehicle-miles-traveled annual averages for LA County before, during, and after I-405 Sepulveda Pass Widening and the COVID-19 Pandemic.

To understand the short-term increase in traffic post-expansion (2015-2019) and as preparation for the interrupted time series analysis, Figure 7 through Figure 14 compare vehicle volume trends, in terms of hourly flows, on I-405 Sepulveda Pass and US 101. These hourly volumes are aggregated vehicle detection data that a PeMS user can directly download from the station time series data portal. The data is aggregated from imputed and observed traffic counts.

For I-405, there were 15,770 hourly flows that contained imputed data (less than 100% observed), which made up about 20% of the hourly flows available from PeMS for the Skirball/Mulholland vehicle loop detectors. For US 101, there were 42,976 hourly flows that contained imputed data, which amounted to about 54% of the hourly flows available from PeMS for the Cahuenga vehicle loop detector included.

Results

Figure 7 through Figure 14 and Table 3 compare the full dataset with the 100% observed data subset for the Skirball/Mulholland mainline loop detector for I-405, the Mulholland HOV loop detector for I-405, and the Cahuenga mainline loop detector for US 101.

The differences between Figure 7, all the data, and Figure 8, just the observed data, are minimal. Both figures show greater hourly averages for the peak period flows post-expansion, around 9,000 veh/hour at 7pm compared to around 8,000 veh/hour before the project. Additionally, off-peak hourly volumes are slightly greater in the post-expansion years than pre-expansion.

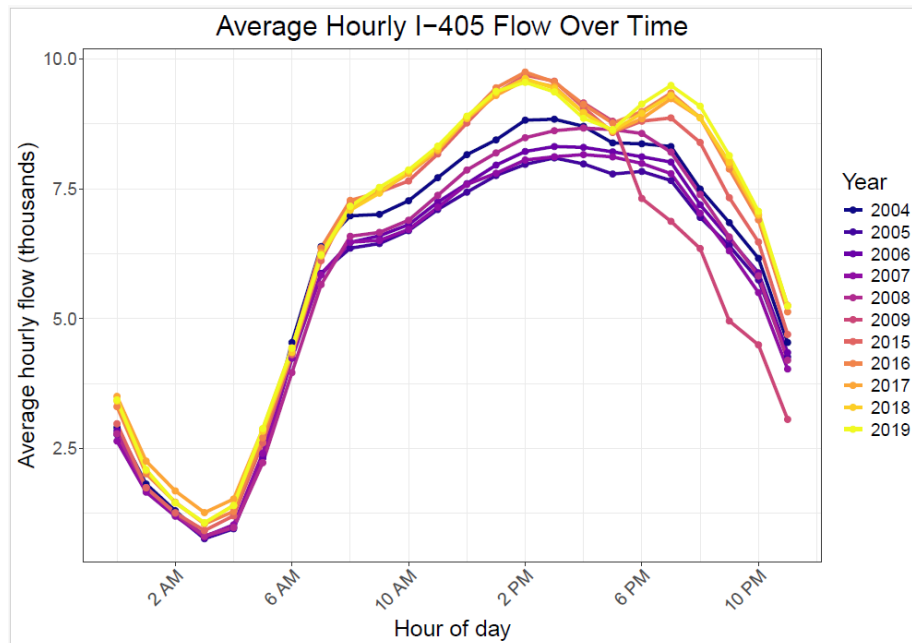


Figure 7: Average hourly flow (veh/hour) for five years before and five years after construction period (2009-2014) on I-405 (including HOV lane addition) using imputed and observed hourly flow data from PeMS' Skirball/Mulholland mainline and HOV lanes loop detectors.

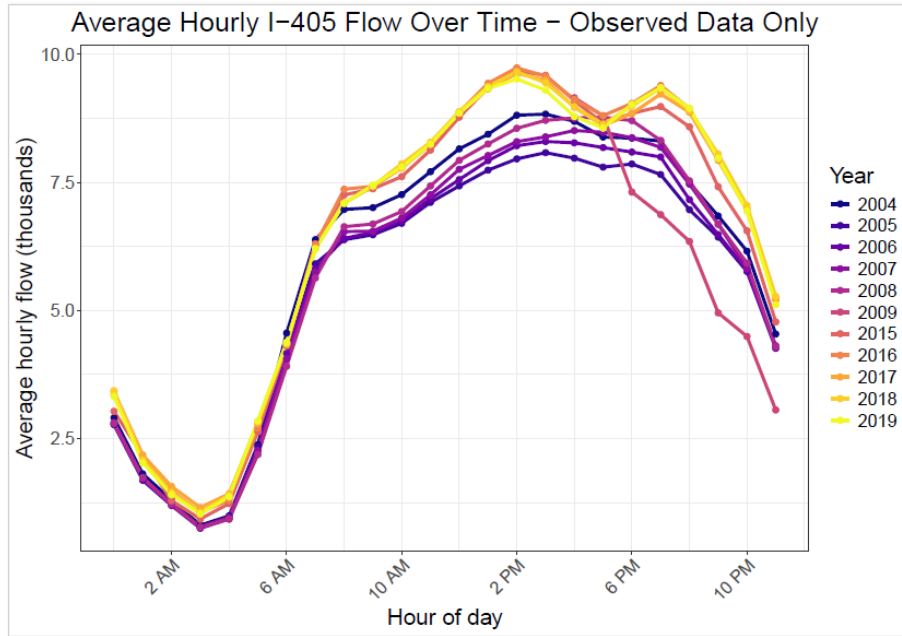


Figure 8: Average hourly flow (veh/hour) for five years before and five years after construction period (2009-2014) on I-405 (including HOV lane addition) using observed (excludes imputed) hourly flow data from PeMS' Skirball/Mulholland mainline and HOV lanes loop detectors.

Figure 9 and Figure 10 aggregate the hourly flows into annual averages and focus on the afternoon/evening peak period for I-405. Both sets of data (all and observed only) show higher hourly flows post-expansion than prior to the project, an increase of about 600 to 1,000 veh/hour. The vertical dotted line marks the construction completion date of the capacity expansion project.

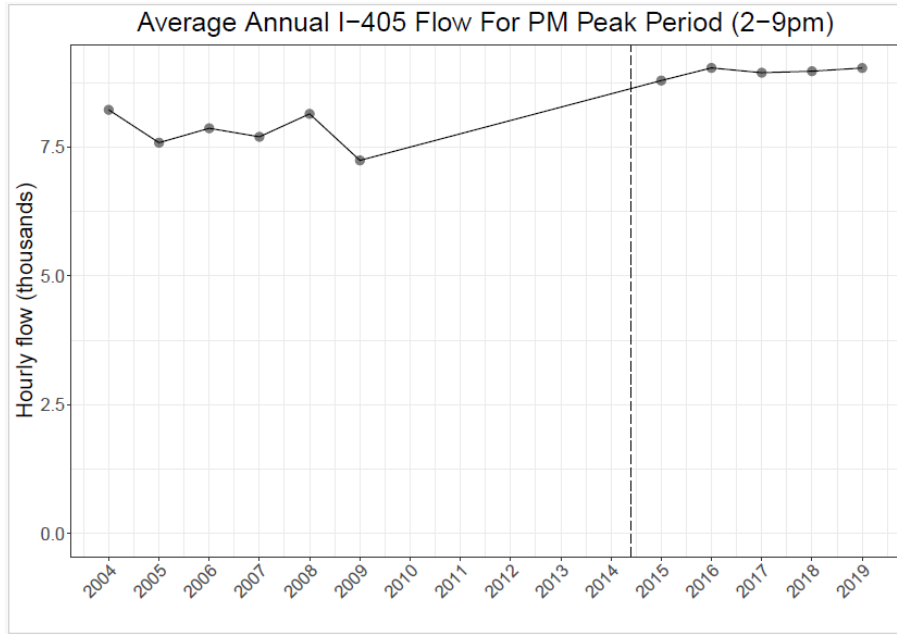


Figure 9: Average annual hourly flow for the PM peak period (2-9pm) on for five years before and five years after construction period (2009-2014) using imputed and observed hourly flow data from PeMS' Skirball/Mulholland mainline and HOV lanes loop detectors.

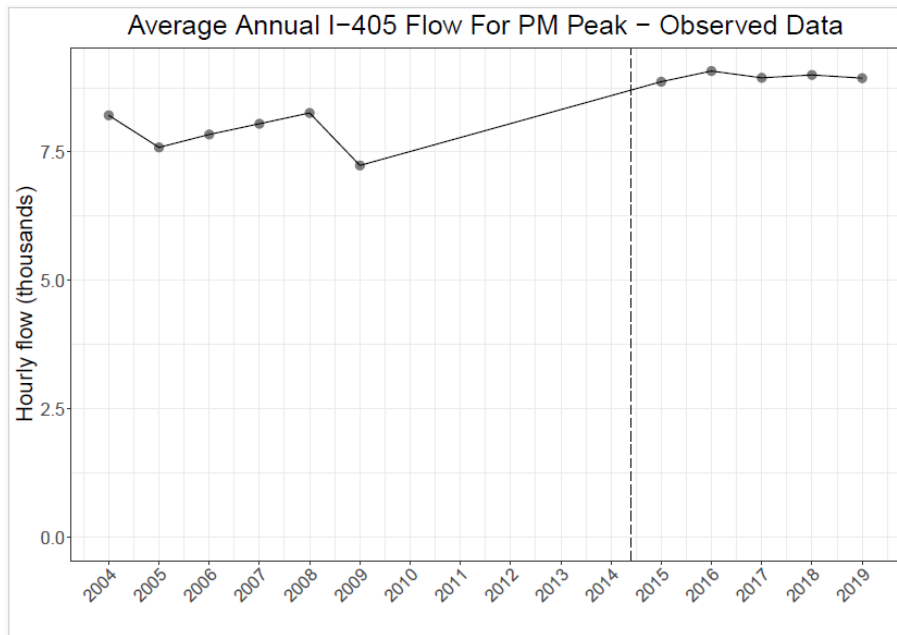


Figure 10: Average annual hourly flow for the PM peak period (2-9pm) on for five years before and five years after construction period (2009-2014) using observed (excludes imputed) hourly flow data from PeMS' Skirball/Mulholland mainline and HOV lanes loop detectors

The following series of figures illustrates the hourly flow trends of the comparison site, US 101, with all the data and just the 100% observed data for I-405's afternoon peak period from 2pm to 9pm. The most noticeable difference between Figure 11 and Figure 12 is that the years 2005, 2006, and 2009 are not represented in Figure 12. Additionally, 2004 reached greater hourly flow maximums in the observed data that were dampened by the imputed data. In Figure 11, the imputed data shows an increase between 1,500 to 2,000 more vehicles per hour on average for the morning peak period during the post-expansion years while Figure 12, just the observed data, shows up to 1,250 more vehicles/hour post-expansion, ignoring trends from 2004.

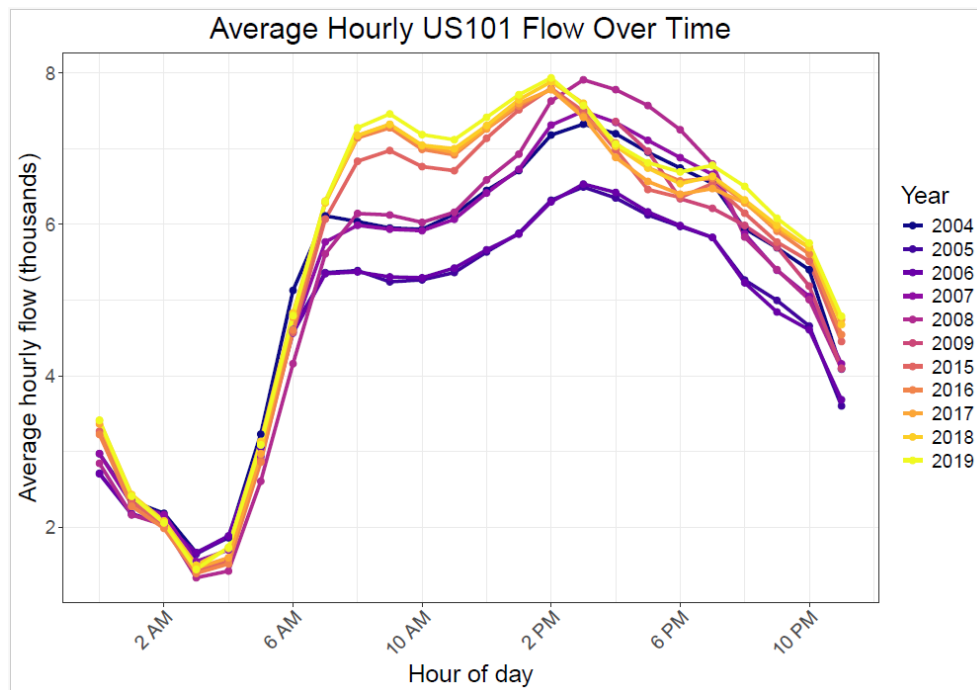


Figure 11: Average hourly flow (veh/hour) for comparison facility, US 101 Cahuenga Pass, over the same period using imputed and observed hourly flow data from PeMS' Cahuenga mainline loop detector.

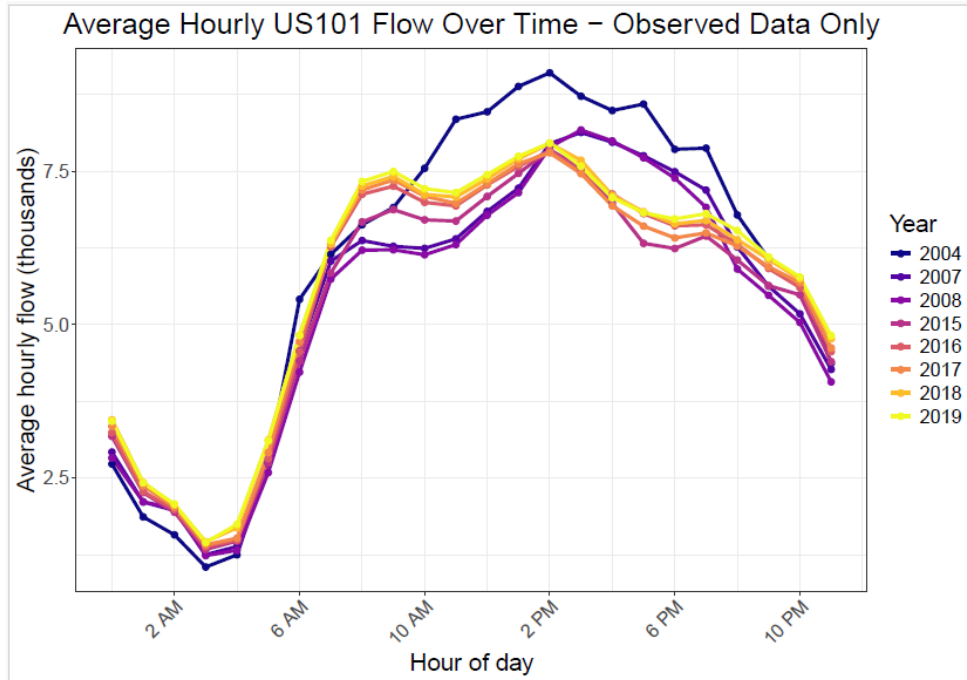


Figure 12: Average hourly flow (veh/hour) for comparison facility, US 101 Cahuenga Pass, over the same period using observed (excludes imputed) hourly flow data from PeMS' Cahuenga mainline loop detector.

In terms of the afternoon/evening peak period, the inclusion of all the data, in Figure 13, suggests a slight increase in hourly flows annually post-expansion whereas the observed data, Figure 14, shows a decline. This could be an effect of the temporal median imputation method that Caltrans uses to fill in missing data points. The influence data from past time periods can dampen the actual time effects observed in an interrupted time series approach to analysis.

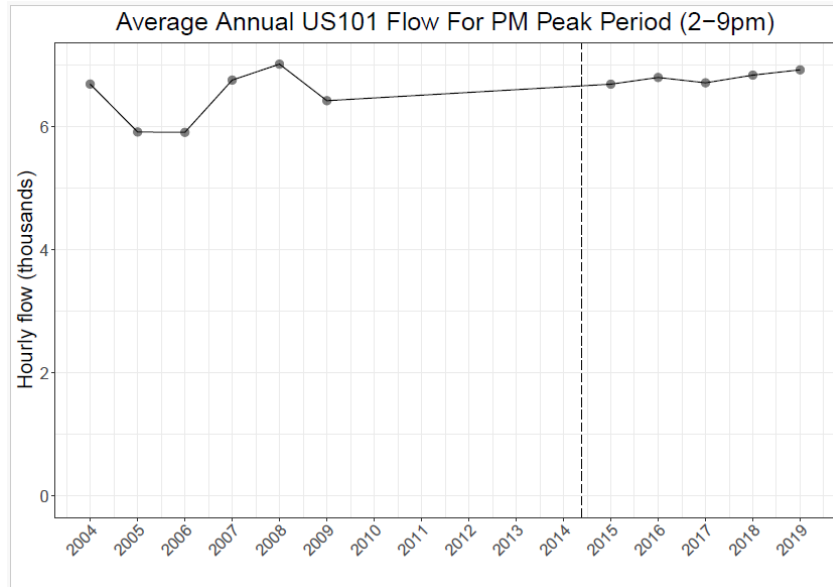


Figure 13: Average annual hourly flow for the same PM peak period (2-9pm) on the comparison facility, US 101 Cahuenga Pass, using imputed and observed hourly flow data from PeMS' Cahuenga mainline loop detector.

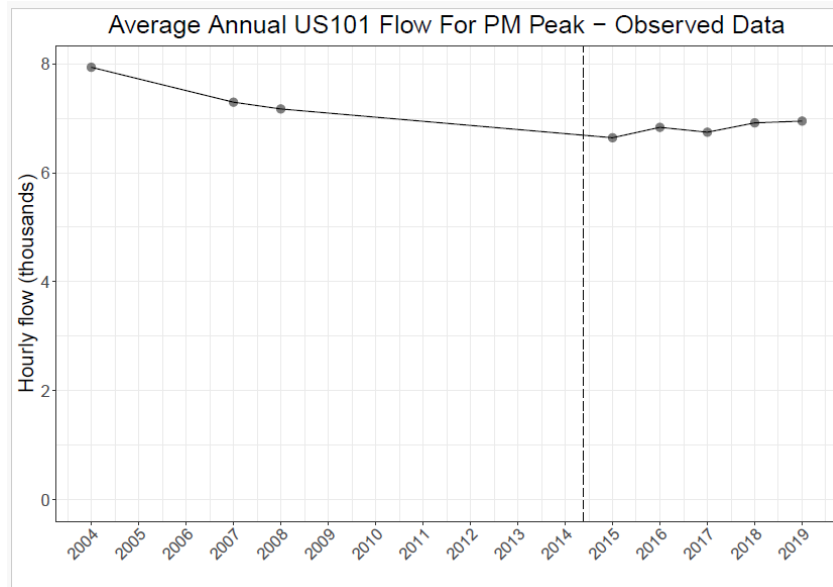


Figure 14: Average annual hourly flow for the same PM peak period (2-9pm) on the comparison facility, US 101 Cahuenga Pass, using observed (excludes imputed) hourly flow data from PeMS' Cahuenga mainline loop detector.

The graphical analysis indicates that I-405 experienced traffic growth post-expansion whereas US 101, which was not expanded, did not experience the same growth. Statistical analysis with the fixed effects regression points to whether the post-expansion is a significant indicator for this

growth, controlling for other factors. The results are listed in the Appendix “Summary Statistics from Fixed-Effects Regression”. Models following the same regression equation were developed using the dataset with imputed values and the dataset with just observed values.

For the regression statistical analysis, the coefficient of the explanatory variable, “post construction”, remains statistically significant for all subsets of I-405 and US 101 hourly flows. The coefficient of this variable approximates the percent change in hourly vehicle flows by taking the natural log of these flows, before and after the HOV lane addition was completed. The indicator, “post-expansion” functions as a dummy variable where timestamps before the completion date of May 23rd, 2014 are valued at zero, and timestamps after the completion date are valued at one. Table 3 below lists the coefficient of the post-expansion explanatory variable as a percent change for results from Equation 1:

Table 3: Coefficient of the explanatory variable as an approximate percent change for hourly flows before and after I-405 HOV lane expansion for I-405 and the counterfactual, US 101.

Freeway	I-405		US 101	
	With Imputed	Observed Only	With Imputed	Observed Only
<i>Data Subset</i>				
<i>Evening Peak</i>	12.2%	10.9%	5.5%	-4.7%
<i>Off Peak</i>	16.6%	16.3%	9.7%	9.1%
<i>Weekday</i>	15.1%	14.6%	8.6%	5.5%
<i>Weekend</i>	16.6%	16.1%	8.9%	6.4%

Overall, the imputed data indicates a greater percent change compared to the 100% observed data for both freeway segments. Both I-405 and US 101 show greater percent changes for the off-peak and weekend subsets compared to the weekday and peak periods. The I-405 imputed and observed results tend to be more similar compared to that of US 101. For example, the most striking difference for US 101 is in the evening peak period where the percent change differs in

direction, with observed data showing a decrease and imputed data showing an increase. In terms of number of observations, 100% observations for US 101 are half of the total observations (including imputations) for each subset. I-405's observations for each subset and data type are much closer in value. Most are of the same magnitude, with the exception being the evening peak for US 101. This is also the data subset with the lowest number of observations. In all the close similarity in the results of the subsets and the high number of observations of fully observed data points, indicates that both can be believed, but results from the dataset with only observations should be relied on as its more grounded in reality.

The modeling results suggest that the HOV lane addition contributed to some of the increased travel I-405 experienced in the years following the highway expansion project. Travel on I-405 increased to a greater extent than travel on US 101, and this increase was determined to be statistically significant in terms of the post-expansion explanatory variable. In terms of measurement of induced travel, the 20% in lane-miles of capacity, and the 16.3% increase in observed hourly flows during the peak period indicate an elasticity of about 0.8. This follows the literature's suggestion of an elasticity between 0.7 to 1.0 to be measured for three to ten years after capacity expansion on major roadways with Class 1 roadways (such as I-405) at the higher end and Class 2 and 3 at the lower end (Volker et al., 2020). Returning to Figure 5, project forecasts, represented by percent change in growth from 2005, were based on regional growth rates from SCAG which are usually derived from expected population and employment growth rates. Missing from the forecasting analysis was that capacity growth can induce more travel. If the original forecasts accounted for capacity expansion's effect on travel patterns, the predictions may have been closer in accuracy without overreliance on estimating regional growth from population and employment.

The coefficient of the post-expansion explanatory indicates an overall decrease in vehicle speeds once the HOV addition was completed on I-405 as shown in Table 4 using results from Equation 1. The indicator variable was found to be statistically significant, and the results are listed in the Appendix “Summary Statistics from Fixed-Effects Regression”.

Table 4: Coefficient of the explanatory variable as an approximate percent change for hourly speeds before and after I-405 HOV lane expansion for I-405 and the counterfactual, US 101.

Freeway	I-405		US 101	
	With Imputed	Observed Only	With Imputed	Observed Only
<i>Data Subset</i>				
<i>Evening Peak</i>	-17.6%	-18.0%	-28.0%	-24.8%
<i>Off Peak</i>	-1.7%	-1.9%	1.0%	-4.7%
<i>Weekday</i>	-6.5%	-6.8%	-8.0%	-11.2%
<i>Weekend</i>	-2.8%	-3.2%	-0.6%	-5.2%

For the observed data, both I-405 and US 101 experienced slower speeds after the construction project’s completion date compared to before, with the counterfactual experiencing the greatest change in speed for most cases. A striking difference in the observed and imputation-inclusive data is an increase in speeds for US 101 in the off-peak hours. While the post-expansion indicator is statistically significant, I-405 and the counterfactual experienced similar trends so it is inconclusive whether the expansion led to the observed deterioration of traffic operations. However, the overall decreasing speed changes suggest that the expansion did not result in improvement in traffic operations; therefore, most likely did not allow for the expected reductions in travel times.

The statistical results from Equation 2 are also listed in the Appendix “Summary Statistics from Fixed-Effects Regression”. In all models, the continuous time variables were generally found to be statistically significant with little effect, less than +/- 1% and, in some cases, zero in terms of

coefficient size, on the change in hourly flows and speeds for both I-405 and US 101 over all data subsets. Table 5 summarizes the findings of the post-expansion indicator variable coefficients with this regression model:

Table 5: Coefficient of the explanatory variable as an approximate percent change for hourly flows and speeds before and after I-405 HOV lane expansion for I-405 and the counterfactual, US 101, specifically controlling for continuous time effects.

Freeway		I-405		US 101	
Data Subset		With Imputed	Observed Only	With Imputed	Observed Only
Evening	Flows	12.5%	6.9%	-10.5%	63%
	Speed	-41.6%	-46.7%	-28.4%	-33.5%
Off Peak	Flows	22.4%	23.6%	14.7%	39.1%
	Speed	-0.4%	-2.1%	-10.4%	-10.1%

In some cases, the coefficients representing the percent change for hourly flows and speeds for I-405 and US 101 varied in comparison to the results from Equation 1 regression. Some major differences include the percent change in speeds for I-405 in all cases more than doubling in indicator coefficient size when controlling continuous temporal effects. Even though the magnitude changed, the trends are similar for models from both equations so similar conclusions can be drawn from both models.

Another major difference is the magnitude and direction of the percent change, indicated by the coefficient of the explanatory variable for flows on US 101 from observed only data, varied greatly compared to the results from Equation 1. For the observed only evening peak flows, Equation 2 garnered a percent change of 63%, while Equation 1 produced -4.7% for the same scenario. It is important to note that the explanatory variable was found to be less significant for Equation 2 in this case. A similar story but to a lesser extent, occurred in the off peak for US 101

where Equation 2 produced a percent change of 39.1% for the indicator variable coefficient, while Equation 1 determined the off-peak change in hourly flows to be 9.1%. While the lesser significance of the coefficient in the peak period case, as well as the lower number of observations for US 101 when removing imputed data dampens the strength of these differences, it is still important to note. In all, the main takeaway is that the post-expansion binary variable had a greater effect on the changes in flows and speeds than the continuous time variables for I-405 and is also reflected in the US 101 counterfactual. This indicates that the addition of the HOV lane was a significant cause of the growth in hourly flows and reduction of speeds on I-405 and was most likely not cause of other factors that tend to grow over time, such as population growth.

The congestion analysis indicates some uncertainty in traffic operations improvement for I-405 following the expansion with decreasing volume and capacity ratios and worsening peak period speeds in

Table 6 below:

Table 6: Changes in peak volume and maximum capacity for I-405 before and after expansion.

Year	2004*	2018*	2025**
Average FFS (mph)	69.9	68.7	65.3
Lane-miles	50	60	60
Truck Proportion (%)	7.1	6.0	4.2
Capacity (veh/hour, C)	11,200	13,500	13,550
Volume (veh/hour, V)	9,491	10,274	9,236
V/C Ratio	0.85	0.76	0.68

Avg. Peak Speed (mph)	49.0	43.2	49.6
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*100% Observed

**All Imputed

Discussion

These results imply that the freeway experienced more throughput-capacity from the lane addition and an increase in travel volumes (in the short term). Maximum capacity grew by 20.5% despite slower free flow speeds from 2004 to 2018. In that same time, peak hour volumes grew by 8%, leading to a decrease in V/C ratios after expansion. While the decrease suggests lessening congestion, travel speed during the peak hour did not improve. A reduction in speeds hints at gains in travel time and delay. The increased complexity of the infrastructure from the lane addition may have diminished expected gains in traffic operations, resulting in less efficient utilization of this freeway segment. This evaluation of the project demonstrates that capacity expansion did not fulfil its expectations to “reduce the existing and forecasted traffic congestion” and “improve mobility” (Caltrans, 2008) and can worsen these operations by inducing more traffic.

The lead agency, LA Metro, is currently studying the conversion and/or addition of Express Lanes, which would add a tolling element to the HOV network. The history of expansions in this corridor, as well as this evaluation, suggest that adding another lane will not improve travel conditions. Additionally, the Sepulveda Pass segment of I-405 is geographically constrained by mountains, which further restricts how many more lanes can be squeezed into this corridor. This evaluation suggests the focus to be on improving the efficiency of the corridor. Adding a transit service, such as an underground rail lane, would increase the person-throughput along the corridor and establish a stable travel time that improves with technological advancement.

Before the freeway era, rail service was the main mode of transportation between San Fernando Valley and the city of LA. With the building of the interstate system and introduction of buses, rail services, such as the Pacific Electric Railway's "Red Cars" of Cahuenga Pass, was terminated in 1952. Freeways became the only connection from the valley to the city (Early Views of the San Fernando Valley, n.d.). Almost 75 years later, rail service might be reintroduced to this corridor through the Sepulveda Transit Corridor Project, currently in the planning phase. The project aims to solve the continuing issue of "congestion on Interstate 405" which, according to planners, is "likely to worsen and spread over longer periods of the day unless substantial new system capacity is added" (HTA Partners, 2026). While this poses a solution that does not directly invest in car-oriented infrastructure, it still represents an increase in capacity in a corridor. The potential to construct a multimodal corridor offers an opportunity to experiment in increasing costs to travel by personal vehicle with dynamic tolling while lowering cost of transit by offering quality service to the existing transit network of downtown LA. Pricing strategies such as these could offer controls on travel growth, preventing potential rebounds in traffic growth due to more capacity.

FINDINGS FOR I-880

The construction of the Cypress Freeway, a double-decked viaduct through West Oakland, was completed in 1958. Its construction physically segregated the West Oakland neighborhood and demolished properties in its path, displacing around 600 families (Patterson & Harley, 2019).

The freeway was originally an extension of the Nimitz Freeway (SR 17) and later became classified as an interstate (I-880). A few decades later, the Loma Prieta Earthquake of 1989 damaged parts of the elevated Cypress Freeway, leading to its removal and eventual reconstruction on a new right-of-way. Caltrans quickly gathered emergency relief funds from the federal government to rebuild the destroyed facility to “alleviate severe congestion, mobility problems, and financial losses” (Anderson, 1996). The initial proposal for the removed viaduct was reconstruction. However, community coalitions in West Oakland, including Citizens Emergency Relief Team (CERT), rallied federal and local support around a new alternative: relocation (Burt, 2009).

After another round of environmental review, Caltrans adopted this new alternative which relocated this segment of I-880 to bypass West Oakland and, instead, border the Port of Oakland outside of the existing community (Anderson, 1996). The relocated freeway was mostly open to the public by 2001, aside from its northbound Bay Bridge connection, which was completed in the mid-2000’s. In Figure 15, the original freeway site is marked by the blue/gray dashed line, now the Mandela Parkway. The replacement is represented by the solid dark-blue line, with the final phase of construction represented by the solid red line (Bay Bridge and I-80 northbound connections). The above ground BART line is indicated by the light-blue dashed line. This line transitions to underground as it approaches downtown Oakland.

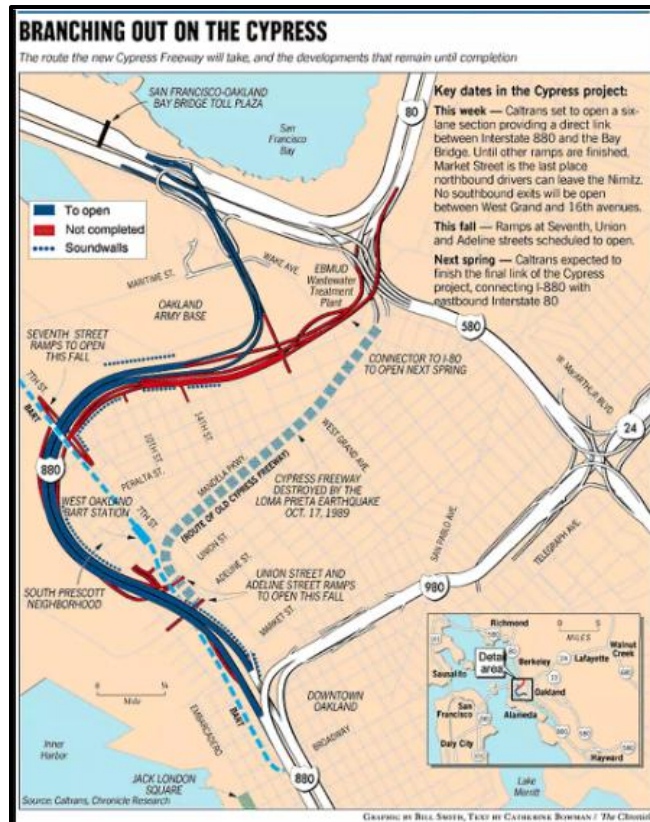


Figure 15: Map of I-880's replacement around West Oakland along with the city grid and other freeways and transit lines in the network (Source: Caltrans, published in [The East Bay Times](#)).

The sudden collapse and closure of the Cypress Freeway in 1989 reduced the region's roadway capacity and disrupted travel routines in the following decade. News articles document traffic congestion but also increases in public transit ridership. An article from SFGate recorded an increase in BART ridership to 360,000 users per day immediately after the earthquake and a sustained increase of 15-20% in the years after (Bowman, 1997). Additionally, capacity losses in the road network revived the Oakland-Alameda ferry service. Ridership increased to 435,000 passengers between 1996-1997, almost ten years after the earthquake hit (Bowman, 1997). The temporary closure of the Bay Bridge, due to its collapse from the earthquake, could also be a cause of this increase. Figure 16 shows regional ridership trends annually for these transit

services before and after the earthquake hit in 1989. As the earthquake damaged many freeways and bridges in the Bay Area network; including the Cypress, Embarcadero, and Central Freeways along with the Bay Bridge, the sustained increase hints at the ability of a significant event, like an earthquake, to trigger long-term shifts in travel modes due to substantial changes in the available network.

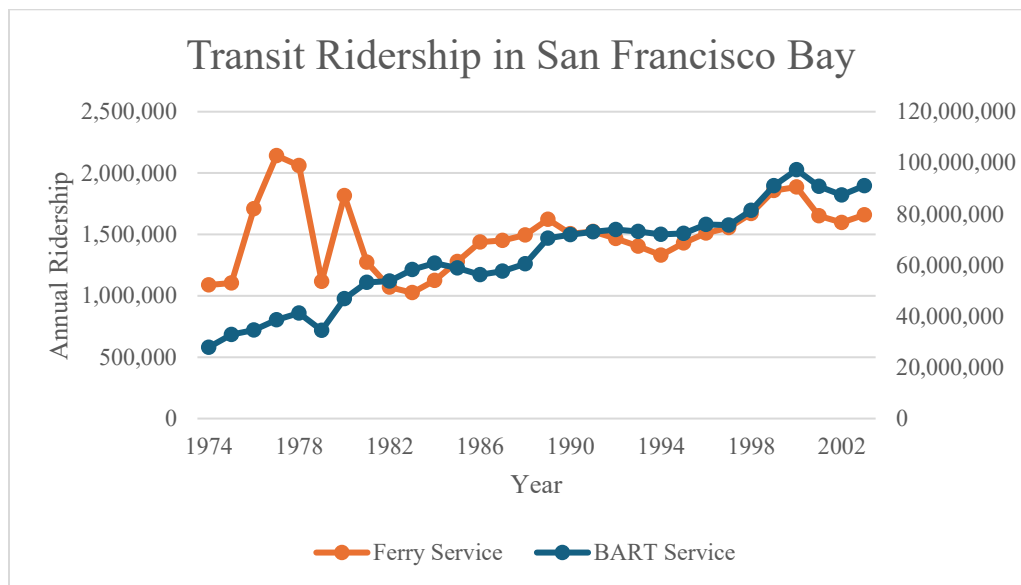


Figure 16: Regional transit ridership prior to and after the earthquake hit (dotted black line). (Data Sources: Ferry ridership from Golden Gate Bridge Highway and Transportation District & BART ridership from BART Ridership Reports.)

In addition to regional modal shift, the following volume/capacity analysis hints at the displaced I-880 traffic filling the available roadway capacity on freeways adjacent to the Cypress Freeway, particularly I-980 and I-580. Since the Cypress Freeway served as a connection between the Bay Bridge and downtown Oakland, I compared traffic volumes on I-580 and I-980, measured at the I-80/Bay Bridge connection and the Market Street connection, respectively. These connections are circled in Figure 17 below.

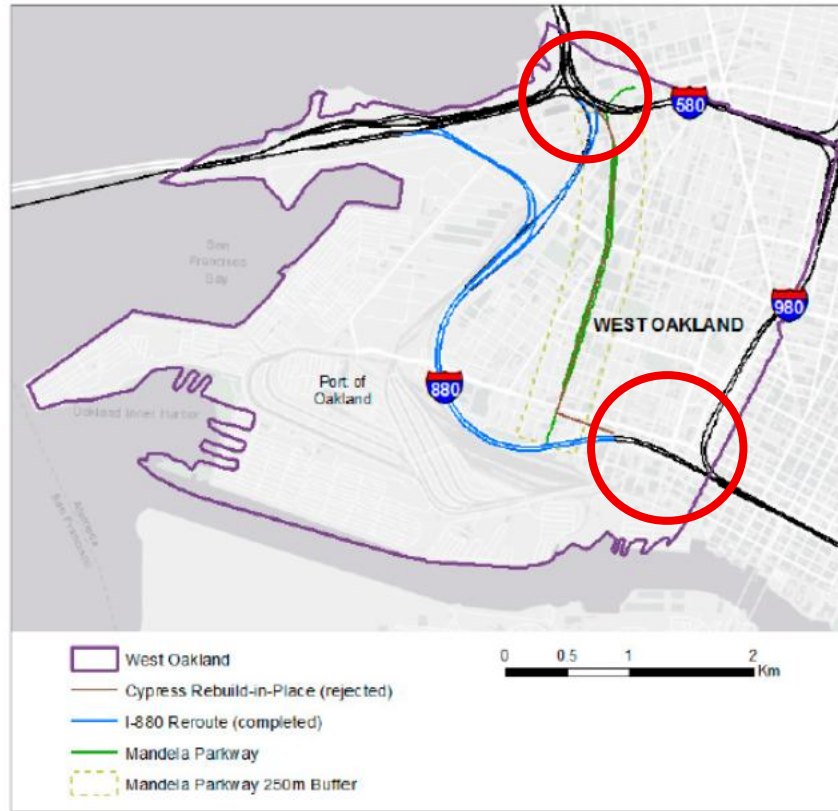


Figure 1. Map of West Oakland study area.

Figure 17: Locations of interest for Volume/Capacity ratio analysis. Base map sourced from Patterson and Harley (2019).

Results

Figure 18 and Figure 19 illustrate annual traffic volume trends at the locations circled in Figure 17 using AADT volumes recorded by Caltrans Traffic Census Program Archives. Figure 18 focuses on the connection to the Bay Bridge from Oakland via I-880 or I-580.

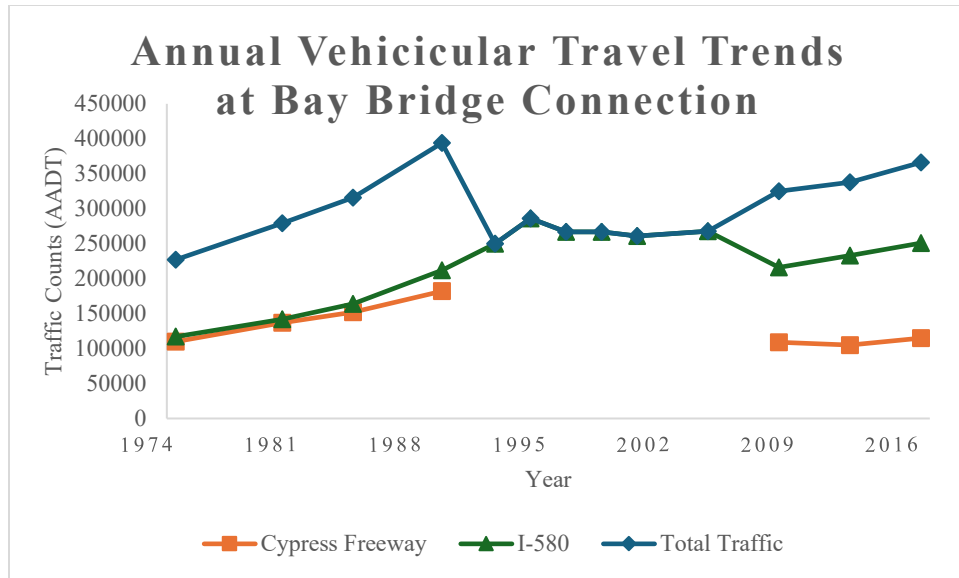


Figure 18: Comparison of AADT on the Cypress Freeway and I-580 prior to the earthquake and after the Bay Bridge Connection construction was fully completed. AADT counts measured at the Bay Bridge connection for each freeway.

An overall trend evident in Figure 18 is a 17.5% decrease in AADT in the I-580/I-880 network from 1989 to 2008. This trend may reflect a dispersion of shorter trips within the project area to the urban street network and shift to transit ridership. The decrease in total travel on this dual freeway network was spurred by the closure of I-880 where a sizable portion of travel volumes that once used the freeway to access the Bay Bridge diverted to I-580. With a loss of the I-880 connection, there was an 18% growth in travel from I-580 to the Bay Bridge from 1989 to 1992, which, assuming the entirety of the growth was from I-880, is only about 21% of the total traffic that utilized I-880's Bay Bridge connection prior to the earthquake. Jumping ahead about 20 years, when the I-880 replacement Bay Bridge connection was finished, only about 60% of the volumes measured in 1989 using this connection on I-880 returned in the years following the project's completion. This loss in vehicle volumes could be attributed to the increase in transit ridership as well as personal changes in housing and/or employment location at the regional

level. Figure 19 illustrates changes in vehicle volumes accessing downtown West Oakland via the freeway network.

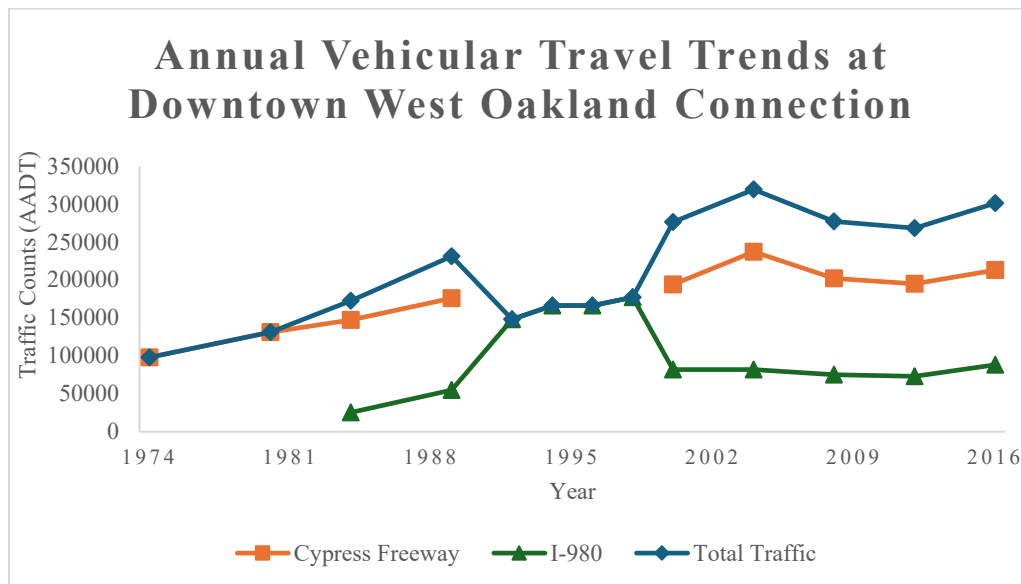


Figure 19: Comparison of AADT on the Cypress Freeway and I-980 prior to the earthquake and after the construction of the connection to downtown West Oakland was completed. AADT counts were measured at each freeway's Market Street traffic count station.

By the year 2000, total AADT (indicated by the dark blue trend) in the downtown network increased by about 20% compared to travel conditions right before the earthquake. During the years that I-880's connection to downtown West Oakland was under construction, the total traffic in this dual freeway network initially decreased by about 36% and held steady until the freeway relocation was opened. It is possible that some shorter trips were absorbed by West Oakland's urban street network and longer distance trips cascaded to other regional connecting freeways, such as I-680. However, the initial increase in AADT on I-980 suggests most travelers on I-880 took advantage of the available capacity and nearness of I-980 as an alternate route. I-980 was opened to the public just five years prior to the Loma Prieta earthquake and was underutilized as of then. With this availability, I-980 absorbed about 53% of the traffic volumes that traveled on I-880 just before the earthquake hit. A decade later, the connection to downtown West Oakland on

I-880 was complete. Traffic volumes on I-980 and I-880 bounced back and surpassed where they had been in 1989, increasing by 50% and 10%, respectively . However, I-980 became underutilized again as peak hour travel met almost half of its available maximum capacity in 2008.

Following the Billings et al. (2013) methodology of calculating volume/capacity ratios, I determined the changes in annual traffic volumes in relation to the vehicular capacity of the freeways before, during, and after the Cypress Freeway's closure and replacement. Table 7 and Table 8 show changes in these ratios on the freeway networks as I-880 was rebuilt. The calculations are explained in Appendix "Volume/Capacity Calculations – I-880".

Table 7: Changes in volume/capacity ratios before and after the closure and rebuilding of I-880 in Oakland for the Bay Bridge connection.

Analysis of traffic evaporation (I-580 Junction)

<i>Highway</i>	<i>AADT</i>	<i>Peak Hour Flow (Volume)</i>	<i>Capacity</i>	<i>Volume/Capacity</i>
1989: Loma-Prieta Earthquake				
Cypress Freeway	182,000	16,300	16,000	1.02
I-580	212,000	20,100	20,000	1.01
Total AADT	394,000			
1994: Five Years Post-Earthquake				
Cypress Freeway	-	-	-	-
I-580	276,000	27,000	20,000	1.35
Total AADT	276,000			
2000: Ten Years Post-Earthquake				
I-880	-	-	-	-
I-580	261,000	20,300	20,000	1.01
Total AADT	261,000			
2008: I-880 Bridge Connection Complete				
I-880	109,000	7,200	12,000	0.60
I-580	216,000	18,000	20,000	0.90
Total AADT	325,000			
Data Source: Caltrans Traffic Census Program; Calculations in Appendix				

Table 8: Changes in volume/capacity ratios before and after the closure and rebuilding of I-880 in Oakland for the downtown Oakland connection.

Analysis of traffic evaporation (I-880 Market Street Connection)				
Highway	AADT	Peak Hour Flow (Volume)	Capacity	Volume/Capacity
1989: Loma-Prieta Earthquake				
Cypress Freeway	176,000	15,800	16,000	0.99
I-980	55,000	3,500	12,000	0.29
Total AADT	231,000			
1994: Five Years Post-Earthquake				
Cypress Freeway	-	-	-	-
I-980	166,000	16,500	12,000	1.38
Total AADT	166,000			
2000: I-880 Downtown Connection Complete				
I-880	194,000	13,900	12,000	1.16
I-980	82,000	5,900	12,000	0.49
Total AADT	276,000			
2008: I-880 Replacement Complete				
I-880	202,000	13,300	12,000	1.11
I-980	75,000	5,400	12,000	0.45
Total AADT	277,000			
Data Source: Caltrans Traffic Census Program; Calculations in Appendix				

As indicated by the ratios in the last columns of Table 7 and Table 8, both I-580 and I-980 experienced volume to capacity relationships greater than one during the I-880 construction years, which would point to congestion experienced during peak hour travel. The opening of I-880's replacement redistributed traffic throughout the freeway network and led to a reduction in ratio values, suggesting a lessening of congestion. Once travel patterns settled in 2008, the freeways I-980, I-580, and I-880's bridge connection have available capacity during the peak

hour travel time (ratio less than one), indicating planners overbuilt Cypress Freeway's replacement.

Discussion

The area experienced a reduction in capacity, in terms of number of lanes, as the newly constructed I-880 segment had one less lane in each direction (a reduction from 8 to 6 lanes) compared to its predecessor, the Cypress Freeway. However, capacity measurement in terms of lane-miles argues that the Cypress Freeway Replacement Project was a capacity expansion. The relocated I-880 freeway segment was more than double in length compared to its predecessor. This classification questions how expanding capacity is understood as more lane miles provide more space for more vehicles, however, the lengthier segment requires more driving, more vehicle-miles-traveled, to reach one's destination compared to its predecessor. Additionally, subsequent transportation projects converted the Cypress Freeway's footprint to a surface boulevard in 2005. Named the Mandela Parkway, this boulevard has two lanes in each direction, replacing more of the lost capacity (although designed for slower travel).

Similar freeway removal to replacement projects include Boston's Central Artery, also known as the "Big Dig," and the Alaskan Way Viaduct in Seattle (more details in the Appendix "Freeway Removals in the United States"). These projects added capacity to their respective corridors by tunneling underneath the freeway's original footprint, and, in the case of the Central Artery, increasing the new freeway's number of lanes compared to its predecessor and allowing for an additional 60,000 vehicles to travel through the center of Boston (Billings & Garrick, 2013). On the surface, these projects serve as examples of what open public spaces could provide for urban communities, however, hidden underground but central to the projects, these cities remain car oriented. This underscores how infrastructure is built with many goals, sometimes contradictory

in mind, and yet continue to follow the status quo with glimpses of how communities can be better designed and built.

In the case of I-880, the immediate loss of freeway capacity post-earthquake did lead to congested freeways. However, these “deteriorating” travel conditions did not deter most travel. Instead, travelers uncovered redundant infrastructure within the system and revitalized dwindling transit services. The decade-long construction of the relocated freeway may have given travelers enough time to change their travel habits, home and employment locations, etc. As a result, the restoration of capacity did not see a dramatic increase in personal vehicle travel. Instead, the network saw traffic levels below or close to its maximum capacity. The City of Oakland and Caltrans are now studying reconnection strategies, including freeway removal, to reconnect communities long divided along the I-980 corridor (Caltrans, 2025). Understanding how capacity reduction has impacted the community in the past will better inform engineers and planners of how to guarantee that future travel needs are met while also taking advantage of other investments in infrastructure, such as transit or other underutilized roadways in the network, that may fill in the gaps. Additionally, this would better inform future grant programs, similar to Reconnecting Communities under Biden, to ensure the transportation infrastructure projects receiving funds are fostering community reconnection.

Further volume and capacity analysis, including traffic trends for Mandela Parkway and the surrounding urban street network, would provide a deeper understanding of total network changes, and the city grid’s ability to absorb “displaced” travel.

CONCLUSION

While the conclusions from just two case studies are not generalizable, prior studies of similar projects are consistent with the findings of these case studies, which contribute to deeper understanding of highway expansions and freeway removals in California and beyond.

I-405

I-405, a freeway notoriously nicknamed “Car-mageddon” (Tumposky & Dorning, 2011) or “Jamzilla” (Brovermen, 2014) by news sources, has experienced infamous congestion through the Sepulveda Pass corridor before, during, and after the highway widening project. This anecdotal data is backed by evidence of increased travel along with a reduction in travel speeds and increased congestion ratios with the completion of the HOV lane addition. Since its initial construction in the 1960’s, where it replaced passenger rail lines, this highway has been unable to accommodate the sprawl and growth of the LA region that it helped to support. And this most recent expansion has led to more growth in travel. The total VMT at peak hour amounted to 95,000 VMT, and, in a few years after construction, VMT increased to 103,000 at peak hour at speeds 6 mph slower than before construction.

The increase in travel and reduction in speeds hints at worsened air quality that doesn’t align with the Final Environmental Impact Report’s conclusion that “[t]he project alternatives would improve movement, increase capacity, and improve overall traffic operation in the general vicinity, thereby lowering the concentration of pollutants emitted by the motor vehicles” (Caltrans, 2008). Instead, the project did not improve movement and overall operations, which could increase air pollutant concentrations. As the South Coast Air Basin, where the project is located, does not meet attainment for several federal and state criteria pollutant levels, exceedance of baseline levels would worsen an already harmful air quality situation for areas

near the project. In terms of energy, the expected “energy savings associated with reduced congestion as result of improvements to the I-405 freeway” would counter the increase associated with more travel and construction for the project (Caltrans, 2008). In analyzing the actual outcomes, the reduced speeds during the afternoon’s most congested hours points to an increase in energy expenditures, which leads to more greenhouse gas emissions. At the time of the environmental review for I-405 widening project, Caltrans stated that “modeling and gauging the impacts associated with an increase in GHG emissions levels, including carbon dioxide, at the project level is not currently possible” (Caltrans, 2008). Therefore, the final environmental impact report does not provide a baseline to compare expected with actual outcomes in terms of emissions.

I-880

The removal of the eight lane Cypress Freeway in 1989, its relocation as a new six lane freeway around the Port of Oakland, and the redevelopment of its original footprint as a four-lane boulevard carries a similar story to that of other freeway removal and replacement projects.

While other freeways in the Bay Area such as the Embarcadero and Central Freeways saw the end of their lifetime in the wake of the Loma Prieta Earthquake, the Cypress Freeway was reborn into a lengthier freeway segment, just outside of the West Oakland community. The loss of freeways on the other side of the Bay Bridge, as well as transit revival, helped sustain the decline in vehicle travel following I-880’s removal. But measurement of travel, in terms of VMT, before the earthquake and after the freeway’s reopening, suggest a constant amount of travel at around 273,000 VMT. The 40% loss of average annual daily travel (AADT) at I-880’s Bay Bridge connection is fully negated by the 115% increase in lane-miles of the freeway segment. Instead

of using the changing network to entice less driving, the longer freeway ended up maintaining the overall vehicle-miles-traveled to San Francisco.

The 115% increase in capacity is even more pronounced in I-880's downtown connection's travel where AADT increased by 14.7% from before the earthquake to after the opening of the relocated freeway. This equates to a 48% increase in VMT. Freeway removals must be planned carefully, with changes in the whole network following the same vision, whether to make travel by vehicle easier, or to entice other, more environmentally friendly modes of travel.

The I-405 and I-880 infrastructure projects follow the “predict and provide” mindset where we must build more transportation infrastructure through expansion “to meet inferred latent demand” (Goulden et al., 2014). In this approach, models forecast how much travel (mostly by car) is likely in the future. The forecasts then justify where and how much additional roadway capacity is needed. This becomes a self-fulfilling prophecy by lowering the costs of driving today will entice even more driving tomorrow. Instead, transportation planners could shift to a mindset of “decide and provide”. Researchers from the UK describe this paradigm shift from mobility focused to access (Paddeu et al., 2024). In this shift, transportation planners can escape the feedback loop of expanding roads and, instead, take advantage of people's changing travel habits to design better solutions for travel not just by personal vehicle.

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APPENDIX

I-405 Skirball/Mulholland Vehicle Detection Station Data Compared to Forecasts

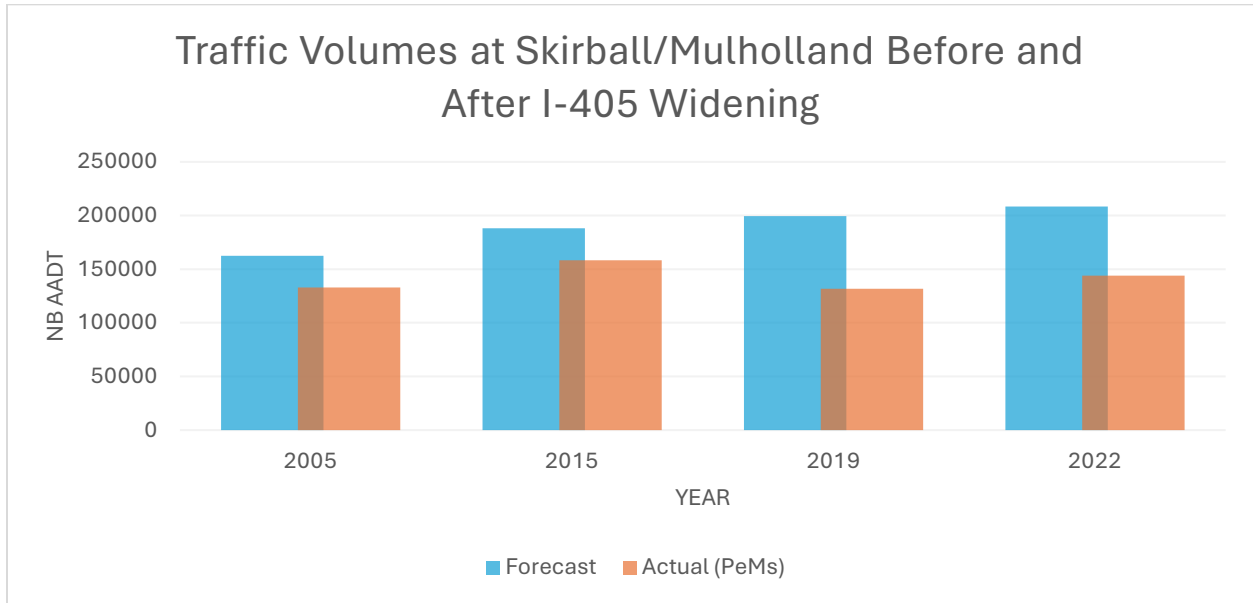


Figure A - 1: Comparison of AADT for Northbound only at Skirball/Mulholland vehicle detection station between forecasted volume and observed volume before and after the construction period of 2009-2014.

Summary Statistics from Fixed-Effects Regression

Table A - 1: Statistical analysis of all the data (left) and observed data (right) regressed over the evening peak period (2pm-9pm, weekdays) and off peak period hours (all other times) for I-405 hourly flows.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	0.122*** (0.002)	0.166*** (0.002)	Post Construction	0.109*** (0.002)	0.163*** (0.002)
R2	0.378	0.895	R2	0.365	0.897
Num.Obs.	18781	60094	Num.Obs.	15070	48035
Baseline Hourly Flow	7955	4978	Baseline Hourly Flow	8046	5013
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 2: Statistical analysis of all the data (left) and just the observed data (right) regressed over the weekdays and weekend for I-405 hourly flows.

	Weekday	Weekend		Weekday	Weekend
Post Construction	0.151*** (0.001)	0.166*** (0.002)	Post Construction	0.146*** (0.002)	0.161*** (0.003)
R2	0.956	0.944	R2	0.958	0.943
Num.Obs.	56336	22539	Num.Obs.	45054	18051
Baseline Hourly Flow	5764	5497	Baseline Hourly Flow	5815	5545
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 3: Statistical analysis of all the data (left) and observed data (right) regressed over the evening peak period (2pm-9pm, weekdays) and off peak period hours (all other times) for US 101 hourly flows.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	0.055***	0.097***	Post Construction	-0.047***	0.091***
	(0.003)	(0.003)		(0.010)	(0.006)
R2	0.173	0.657	R2	0.121	0.597
Num.Obs.	18775	60076	Num.Obs.	8482	27417
Baseline Hourly Flow	6517	4521	Baseline Hourly Flow	7327	4728
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 4: Statistical analysis of all the data (left) and just the observed data (right) regressed over the weekdays and weekend for US 101 hourly flows.

	Weekday	Weekend		Weekday	Weekend
Post Construction	0.086***	0.089***	Post Construction	0.055***	0.064***
	(0.002)	(0.006)		(0.005)	(0.012)
R2	0.817	0.553	R2	0.791	0.448
Num.Obs.	56328	22523	Num.Obs.	25482	10417
Baseline Hourly Flow	5058	4844	Baseline Hourly Flow	5434	5106
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 5: Comparison of Average Hourly Speed before and after HOV lane addition at Skirball/Mulholland vehicle detector on I-405 over observed and imputed data.

	Evening Peak	Off Peak		Weekday	Weekend
Post Construction	-0.176*** (0.004)	-0.017*** (0.001)	Post Construction	-0.065*** (0.001)	-0.028*** (0.002)
R2	0.489	0.424	R2	0.620	0.420
Num.Obs.	18781	60094	Num.Obs.	56336	22539
Baseline Hourly Speed	52	66	Baseline Hourly Speed	62	64
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 6: Comparison of Average Hourly Speed before and after HOV lane addition on I-405 at Cahuenga vehicle detector on US 101 over observed and imputed data.

	Evening Peak	Off Peak		Weekday	Weekend
Post Construction	-0.280*** (0.004)	0.010*** (0.001)	Post Construction	-0.080*** (0.002)	-0.006*** (0.002)
R2	0.592	0.391	R2	0.626	0.422
Num.Obs.	18781	60094	Num.Obs.	56336	22539
Baseline Hourly Speed	50	62	Baseline Hourly Speed	59	61
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 7: Comparison of Average Hourly Speed before and after HOV lane addition at Skirball/Mulholland vehicle detector on I-405 over only observed data.

	Evening Peak	Off Peak		Weekday	Weekend
Post Construction	-0.180*** (0.004)	-0.019*** (0.001)	Post Construction	-0.068*** (0.002)	-0.032*** (0.002)
R2	0.487	0.431	R2	0.630	0.409
Num.Obs.	15070	48035	Num.Obs.	45054	18051
Baseline Hourly Speed	52	66	Baseline Hourly Speed	62	64
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 8: Comparison of Average Hourly Speed before and after HOV lane addition on I-405 at Cahuenga vehicle detector on US 101 over observed data only.

	Evening Peak	Off Peak		Weekday	Weekend
Post Construction	-0.248*** (0.007)	-0.047*** (0.002)	Post Construction	-0.112*** (0.003)	-0.052*** (0.004)
R2	0.636	0.476	R2	0.723	0.492
Num.Obs.	8482	27417	Num.Obs.	25482	10417
Baseline Hourly Speed	50	66	Baseline Hourly Speed	61	65
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 9: Statistical analysis of observed and imputed data for I-405 hourly flows (left) and speeds (right) regressed over the evening peak period (2pm-9pm, weekdays) and off peak period hours (all other times) with continuous time variables.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	0.125*** (0.008)	0.224*** (0.009)	Post Construction	-0.416*** (0.015)	-0.004 (0.004)
Cont. Time	0.000 (0.000)	-0.001*** (0.000)	Cont. Time	0.003*** (0.000)	-0.000 (0.000)
Cont. Time Post-Construction	-0.000 (0.000)	0.002*** (0.000)	Cont. Time Post-Construction	-0.004*** (0.000)	-0.000*** (0.000)
R2	0.378	0.895	R2	0.501	0.424
Num.Obs.	18781	60094	Num.Obs.	18781	60094
Baseline Hourly Flow	7955	4978	Baseline Hourly Speed	52	66
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 10: Statistical analysis of only observed data for I-405 hourly flows (left) and speeds (right) regressed over the evening peak and off peak periods with continuous time variables.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	0.069*** (0.009)	0.236*** (0.011)	Post Construction	-0.467*** (0.016)	-0.021*** (0.005)
Cont. Time	0.001*** (0.000)	-0.001*** (0.000)	Cont. Time	0.003*** (0.000)	0.000*** (0.000)
Cont. Time Post-Construction	-0.001*** (0.000)	0.001*** (0.000)	Cont. Time Post-Construction	-0.004*** (0.000)	-0.001*** (0.000)
R2	0.367	0.898	R2	0.504	0.432
Num.Obs.	15070	48035	Num.Obs.	15070	48035
Baseline Hourly Flow	8046	5013	Baseline Hourly Speed	52	66
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 11: Statistical analysis of observed and imputed data for US 101 hourly flows (left) and speeds (right) regressed over the evening peak period (2pm-9pm, weekdays) and off peak period hours (all other times) with continuous time variables.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	-0.105*** (0.022)	0.147*** (0.013)	Post Construction	-0.284*** (0.015)	-0.104*** (0.004)
Cont. Time	0.001*** (0.000)	-0.001*** (0.000)	Cont. Time	-0.000 (0.000)	0.001*** (0.000)
Cont. Time Post-Construction	-0.001*** (0.000)	0.002*** (0.000)	Cont. Time Post-Construction	0.000 (0.000)	-0.002*** (0.000)
R2	0.178	0.657	R2	0.592	0.405
Num.Obs.	18781	60094	Num.Obs.	18781	60094
Baseline Hourly Flow	6517	4521	Baseline Hourly Speed	50	62
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Table A - 12: Statistical analysis of only observed data for US 101 hourly flows (left) and speeds (right) regressed over the evening peak and off peak periods with continuous time variables.

	Evening Peak	Off Peak		Evening Peak	Off Peak
Post Construction	0.630** (0.252)	0.391*** (0.082)	Post Construction	-0.335*** (0.079)	-0.101*** (0.025)
Cont. Time	-0.009*** (0.003)	-0.004*** (0.001)	Cont. Time	0.001 (0.001)	0.001*** (0.000)
Cont. Time Post-Construction	0.009*** (0.003)	0.005*** (0.001)	Cont. Time Post-Construction	-0.001 (0.001)	-0.002*** (0.000)
R2	0.128	0.598	R2	0.636	0.477
Num.Obs.	8482	27417	Num.Obs.	8482	27417
Baseline Hourly Flow	6517	4521	Baseline Hourly Speed	50	66
Month FE	Yes	Yes	Month FE	Yes	Yes
Weekday FE	Yes	Yes	Weekday FE	Yes	Yes
Hour FE	Yes	Yes	Hour FE	Yes	Yes
* p < 0.1, ** p < 0.05, *** p < 0.01			* p < 0.1, ** p < 0.05, *** p < 0.01		

Freeway Removals in the United States

Table A - 13: Characteristics of all completed freeway removal projects in the United States.

Project Name (Location)	Conversion Type	Construction (Years)	Traffic Outcomes	Removal Reason(s)	Source
Harbor Drive (Portland, OR)	Four-lane freeway → riverfront park	1974-1978	-9.6% traffic (nearby roads and bridges)	Anti-freeway Urban/Economic redevelopment Political support Local community Air pollution Reduce traffic Alternative route Academic support	Seattle Urban Mobility Plan (2008) Khalaj et al. (2020)
Westside Highway (New York City, NY)	Elevated six-lane freeway → six/eight lane boulevard	1977-2001	-53% traffic (corridor)	Anti-freeway Safety Costs Structural damage Political support Local community Academic support	Billings & Garrick (2013) Khalaj et al. (2020)
Cypress Freeway (Oakland, CA)	Elevated eight-lane freeway → six-lane freeway relocation	1989-1998	-23%-32% traffic (corridor) +26%-220% traffic (adjacent freeways)	Earthquake damage Structural aging Safety Costs Political support Businesses Relocation	Figure 18 & Figure 19 Khalaj et al. (2020)
Park East Freeway (Milwaukee, WI)	Elevated six-lane freeway → four-lane boulevard	2001-2008	-40% traffic (corridor) +4% traffic (local streets) -6% traffic (adjacent freeways)	Political support Anti-freeway Costs Urban/Economic redevelopment Physical barrier Low traffic Safety Business support Structural aging/damage Local community Academic support	Billings et al (2013) Khalaj et al. (2020)
Embarcadero Freeway (San Francisco, CA)	Double-deck freeway → six lane boulevard	1988-2008	-50% traffic (corridor) +44% traffic	Earthquake damage Professional support Local community Political support Safety	Billings et al (2013) Khalaj et al (2020)

			(local streets) +2% traffic (adjacent freeway)	Low traffic Business support Costs Academic support	
Niagara Scenic [Robert Moses] Parkway (Niagara Falls, NY)	Four-lane freeway → two-lane road	Removed in 2001	-	Urban redevelopment Physical obstacle Political support Local community Academic support	Khalaj et al (2020)
VA 110 (Arlington County, VA)	Unknown	Removed in 2004	-	“Security concerns”	Khalaj et al (2020)
Central Freeway (San Francisco, CA)	Elevated four-lane, two level freeway → four-lane boulevard	1996-2008	-33% traffic (corridor) -17% traffic (local streets) -10% traffic (adjacent freeways)	Economic development Earthquake damage Professional support Local community Political support Safety Low traffic Academic support	Billings et al (2013) Khalaj et al. (2020)
Riverfront Parkway (Chattanooga, TE)	Four-lane parkway → Two-lane road	Removed 2005	Sentiment of reduced congestion	Low traffic Urban/Economic redevelopment Physical obstacle Air pollution Costs Public benefit	Khalaj et al (2020) Billings & Garrick (2013)
Central Artery I-93 (Boston, MA)	Elevated six-lane freeway → Underground tunneled 8-10 lane freeway & surface boulevard/park	1991-2007	-62% vehicle-hours	Anti-freeway Design flaws Reduce traffic Safety Business support Political support Urban redevelopment	(MassDOT, n.d.) Khalaj et al. (2020)
I-195 (Providence, RI)	Elevated freeway → new development (relocation?)	Removed 2010	TBD	Relocation Urban redevelopment Structural aging Costs	Khalaj et al (2020)
Alaskan Way Viaduct SR 99 (Seattle, WA)	Elevated six-lane freeway → Surface boulevard and four-lane tunnel	2011-2019	-16% traffic (corridor)	Earthquake damage Safety Costs	(WSDOT, n.d.) Khalaj et al. (2020)
Crosstown Expressway	Elevated freeway →	Removed 2012	TBD	Structural aging Safety	Khalaj et al (2020)

(Oklahoma City, OK)	Surface boulevard			Costs Relocation	
East-West Expressway (Baltimore, MD)	Elevated freeway → new development	Removed 2012	TBD	Public benefit Urban redevelopment	Khalaj et al (2020)
Inner Loop East (Rochester, NY)	Four/six-lane freeway → two-lane boulevard	2013-2019	+200% traffic (corridor) +10-20% traffic (local streets) +49-67% ped & bike	Low traffic Political support Urban/Economic redevelopment Physical obstacle Structural aging	Pugh (2024)

Volume/Capacity Calculations – I-405

Table A - 14: I-405 Skirball/Mullholand Aggregated Hourly Data (September – November)

	2004*		2018*		2025**	
	Free Flow Speed (mph)	Truck Prop (%)	Free Flow Speed (mph)	Truck Prop (%)	Free Flow Speed (mph)	Truck Prop (%)
Lane 1	75.3	0.0	75.6	0.0	71.8	0.0
Lane 2	72.7	0.0	73.0	0.0	68.6	0.0
Lane 3	70.6	2.5	71.0	10.1	64.5	7.0
Lane 4	67.7	8.2	66.3	11.5	61.6	8.3
Lane 5	63.0	24.8	62.9	14.3	60.1	9.6
Lane 6 (HOV)	-	-	63.6	0.0	63.6	0.0
Average	69.9	7.1	68.7	6.0	65.3	4.2

*100% Observed; **0% Observed

Pre-Expansion 2004 Calculation:

Capacity:

Average total free flow speed	69.9 mph
Average total truck proportion	7.1%
Number of lanes	5

$$Capacity = \frac{(2,200 + 10 \times (\min(70, 69.9) - 50))}{1 + \frac{7.1}{100}} \times 5$$

$$Capacity = \frac{2396}{1.071} \times 5 = 11,200$$

Volume:

Peak Hour Flow – estimated from 5-minute flow data (100% observed, 0% imputed)

9,491 veh/hour (9/2/2004 18:35-19:35)

$$\frac{V}{C} = \frac{9,491}{11,200} = 0.85$$

Post-Expansion 2018 Calculation:

Capacity:

Average total free flow speed	68.7 mph
Average total truck proportion	6.0%
Number of lanes	6

$$Capacity = \frac{(2,200 + 10 \times (\min(70, 68.7) - 50))}{1 + \frac{6.0}{100}} \times 6$$

$$Capacity = \frac{2387}{1.060} \times 6 = 13,500$$

Volume:

Peak Hour Flow – estimated from 5-minute flow data (89% observed, 11% imputed)

10,274 veh/hour (9/7/2018 18:50-19:50)

$$\frac{V}{C} = \frac{10,274}{13,500} = 0.76$$

Post-Expansion 2025 Calculation:

Capacity:

Average total free flow speed	65.3 mph
Average total truck proportion	4.2%
Number of lanes	6

$$Capacity = \frac{(2,200 + 10 \times (\min(70, 65.3) - 50))}{1 + \frac{4.2}{100}} \times 6$$

$$Capacity = \frac{2353}{1.042} \times 6 = 13,550$$

Volume:

Peak Hour Flow – estimated from 5-minute flow data (0% observed, 100% imputed)

9,236 veh/hour (9/4/2025 7:10-8:10)

$$\frac{V}{C} = \frac{9,236}{13,550} = 0.68$$

Volume/Capacity Calculations – I-880

Cypress Freeway/I-880 pre-earthquake (8 lanes):

$$(1000 + 20 \times 50) \times 8 = 16,000 \text{ veh/hours}$$

I-980 & I-880 post-earthquake (6 lanes):

$$(1000 + 20 \times 50) \times 6 = 12,000 \text{ veh/hours}$$

I-580 (10 lanes):

$$(1000 + 20 \times 50) \times 10 = 20,000 \text{ veh/hours}$$

Capacity (lane-miles):

Cypress Freeway/I-880 pre-earthquake:

$$1.5 \text{ miles} \times 8 \text{ lanes} = 12 \text{ lane-miles}$$

I-880 Replacement Freeway:

Segment Replacement + Western Connector (Bay Bridge) + Northern Connector (Emeryville)

$$2.5 \text{ miles} \times 6 \text{ lanes} + 1.3 \text{ miles} \times 4 \text{ lanes} + 1.4 \text{ miles} \times 4 \text{ lanes} = 25.8 \text{ lane-miles}^*$$

* numbers from (Goff, et al., 1998)

$$(25.8 - 12) / 12 \times 100 = 115\% \text{ increase in lane-mile capacity}$$

Peak Period Speed Calculations – I-405

Table A - 15: I-405 Skirball/Mullholand Aggregated Hourly Data (September – November).

Average Peak Period Speed (mph)			
	2004*	2018*	2025**
Lane 1	48.5	48.8	51.8
Lane 2	49.0	44.1	49.1
Lane 3	48.0	42.6	45.7
Lane 4	50.4	38.9	44.2
Lane 5	48.9	41.7	44.2
Lane 6 (HOV)	-	43.3	62.3
Average	49.0	43.2	49.6
*100% Observed; **0% Observed			

R Script for Regression Models

Below is a sample script to create peak and off peak fixed effects regression models with indicator and continuous time controls for I-405. A similar process was followed for other data subsets.

```
#Initiate packages
library(ggplot2)
library(tidyverse)
library(viridis)
library(fixest)
library(modelsummary)
library(lubridate)

#Create post construction indicator
ConsolidatedData$post_event <- as.integer(as.Date(ConsolidatedData$Datetime) >=
as.Date("2014-05-23"))

#Specify off peak and evening peak
ConsolidatedData <- ConsolidatedData %>%
  mutate(period = case_when(
    numeric_hour >= 14 & numeric_hour <= 21 ~ "evening peak",
    TRUE ~ "offpeak"), period = factor(period))

#Create continuous time variables
event_date <- as.Date("2014-06-01")

#Continuous time by month
ConsolidatedData$time <- interval(
  min(ConsolidatedData$Datetime),
  ConsolidatedData$Datetime
) %/% months(1) + 1

#Counting months since intervention
ConsolidatedData$time_after_event <- pmax(
  0, interval(event_date, ConsolidatedData$Datetime) %/% months(1))

#Create data subsets
df_subweekday <- ConsolidatedData %>%
  filter(!Weekday %in% c("Sat", "Sun"))
df_subweekend <- ConsolidatedData %>%
  filter(Weekday %in% c("Sat", "Sun"))
df_subpeak <- df_subweekday %>% filter(numeric_hour %in% 14:21)
df_suboff <- bind_rows(
```

```

df_subweekday %>% filter(!(numeric_hour %in% 14:21)),
df_subweekend)

#Write fixed effects regression formula for I-405 flows
#Run model over evening peak hours only
model.peak <- feols(log(totalI405 + 1) ~ post_event + time + time_after_event| Month +
Weekday + numeric_hour,
                    cluster = ~ Datetime, data = df_subpeak)
baseline_mean.peak <- mean(df_subpeak$totalI405[df_subpeak$post_event == 0],
                          na.rm = TRUE)

#Run model over off peak hours only
model.off <- feols(log(totalI405 + 1) ~ post_event + time + time_after_event| Month + Weekday
+ numeric_hour,
                  cluster = ~ Datetime, data = df_suboff)
baseline_mean.off <- mean(df_suboff$totalI405[df_suboff$post_event == 0],
                         na.rm = TRUE)

## Continuous time variable models (off peak and peak)
msummary(list("Evening Peak" = model.peak, "Off Peak" = model.off),
          stars=c('*'=1, '**'=.05, '***'=.01), statistic = "{std.error}"),
          gof_map = c("r.squared", "nobs"),
          add_rows = data.frame(
            term = c("Baseline Hourly Flow", "Month FE", "Weekday FE", "Hour FE"),
            model.6 = c(round(baseline_mean.peak,0), "Yes", "Yes", "Yes"),
            model.7 = c(round(baseline_mean.off,0), "Yes", "Yes", "Yes")
          ),
          coef_map = c(
            "post_event" = "Post Construction", "time" = "Cont. Time", "time_after_event" = "Cont.
Time Post-Construction"))

```

Below is a sample script for removing imputed data rows and keeping only observed data rows for I-405. A similar process was followed for US 101.

```

#Filter out missing data rows
ObservedData <- ConsolidatedData %>%
  filter('I405 ML Observed' == 100)

```