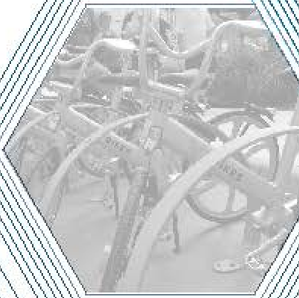

Evaluation of Adaptive Ramp Metering on I-80 in the San Francisco Bay Area

Anurag Pande

FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

EVALUATION OF ADAPTIVE RAMP METERING ON I-80 IN THE SAN FRANCISCO BAY AREA

FINAL PROJECT REPORT

by

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Sponsorship
CTEDD, MTC, and Cal Poly College of Engineering

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16. Abstract

Adaptive ramp metering (ARM) is a critical component of smart freeway corridors under an active traffic management portfolio. While improving capacity through smart corridors and application of proactive traffic management solutions is less costly and easier to deploy than freeway widening, conversion to smart corridors still represents a sizable investment for public agencies. However, in the U.S. there have been limited evaluations, of smart corridors in general and ARM in particular, based on real operational data. This project examined recent Smart Corridor implementation on I-80 in the Bay area based on travel time reliability measures, efficiency measures, and based on user opinion survey. As such, the evaluation represents the most complete before/after evaluation of such systems. The study section is 19 miles long and extends between the Carquinez Bridge at Crockett at its east end and the San Francisco-Oakland Bay Bridge at its west end. The reliability measures include buffer index, planning time, and measures from the literature that account for both skew and width of the travel time distribution. For efficiency, the ratio between VMT/VHT is estimated for the I-80 corridor. All before-after comparisons are contextualized through similar measures from another Bay area corridor I-680, which did not go through a Smart Corridor Implementation. The measures are estimated for the entire corridor as well as corridor segments upstream of a bottleneck that historically have the worst measures of reliability. User-opinion survey conducted as part of the project involved 626 completed and usable survey responses covering a wide yet representative demographic of users. The representative survey was ensured using a induced exposure approach adopted from traffic safety literature. The results show that the marginal improvements in freeway operations based on reliability and efficiency are underappreciated by the users.

17. Key Words: Adaptive Ramp Metering, ITS, Travel time reliability, Smart Corridors, INRIX data, PeMS Data, User-survey, Induced Exposure.

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Chapter 1: Introduction

Smart corridors that implement various ITS technologies are key component of addressing congestion issues especially in regions where freeway expansion is not a feasible option. Interstate 80 (I-80) is a transcontinental freeway connecting the two major metropolitan areas of San Francisco and New York City. Through San Francisco bay area in northern California, the freeway serves as a heavily-traveled corridor connecting the San Francisco Bay Area with Sacramento. In the Bay Area, the 19-mile section between the Carquinez Bridge and the I-80/I-580/I-880 interchange (near the San Francisco-Oakland Bay Bridge) is one of the most congested and heavily traveled corridors in the region with over 270,000 vehicles per day. The freeway ranges in width from 4 to 5 lanes per direction, including a High Occupancy Vehicle (HOV) lane in effect during peak commute times and requiring 3 or more persons per vehicle. The California Department of Transportation (Caltrans) estimates there are 4 to 5 collisions and 16,000 vehicle-hours of delay each day. Furthermore, an estimated 25% of congestion is incident-related (Caltrans, 2017).

This research analyzes a new adaptive ramp metering system implemented on this 19-mile section, including its effects on travel time reliability. Additionally, new measures of travel time reliability are analyzed using data from the study corridor. As noted by the Federal Highway Administration (FHWA), many drivers either adjust their schedules or budget extra time to allow for traffic delays but are less tolerant of unexpected delays. This makes travel time reliability an important performance measure to consider.

1.1. Ramp Metering Overview

First implemented in 1963 on Chicago's Eisenhower Expressway, ramp metering is now a widely used active traffic management technique. Ramp metering regulates on-ramp flows before/during congestion, breaks up platoons, and smoothly converts multiple on-ramp lanes to one. It is generally considered to be one of the most cost-effective freeway management strategies (Mizuta et al, 2014).

Ramp Metering Strategies

There are three primary methods for determining metering rates, each requiring different infrastructure investments (DKS Associates, 2010). With Fixed Time ramp metering, the rate is programmed by time-of-day based on historical patterns. Typically used in locations with predictable traffic conditions, the equipment required for this strategy is the simplest but does not allow for any optimization based on actual traffic conditions. As a result, meter violation rates are typically the highest when using a Fixed Time strategy. For example, on a day when congested conditions end earlier than usual, a Fixed Time meter would continue using a restrictive metering rate, causing unnecessary delay and emissions at the ramp and likely resulting in user frustration.

With Local Traffic Responsive ramp metering, freeway mainline detectors in the vicinity of the ramp determine its metering rate. The controller utilized pre-defined relationships between freeway flow and ramp demand. Ramps are treated as discrete units rather than as part of a system. Violation rates are more reasonable with this strategy because it responds in an intelligent way to current conditions by, for example, using a higher metering rate when freeway flow is lower. This strategy can utilize a predictive algorithm which anticipates the onset of freeway congestion and proactively adjusts the metering rate.

With Adaptive Ramp Metering (ARM), an algorithm calculates the optimal metering rate in real time for each ramp along a corridor, often with an ultimate goal of controlling a bottleneck. While similar to Local Traffic Responsive ramp metering, ARM uses a virtual intelligence engine to deploy a response strategy based on modeled conditions. In addition to managing recurring congestion, ARM can manage freeway incidents by using more restrictive metering upstream of the incident and less restrictive metering downstream.

An ARM system operates by detecting traffic speed and volume immediately upstream and downstream of the on-ramp, as well as the on-ramp traffic volume. It also communicates with ramp metering nodes at upstream locations to determine the volume and speed of freeway traffic approaching the on-ramp. The system then coordinates the regulation of on-ramp traffic along the corridor to prevent the loss of freeway capacity. Metering rates are adjusted based on conditions on the freeway upstream of the on-ramp, conditions on the freeway at the on-ramp, and conditions on the on-ramp itself.

The ARM system is controlled from a traffic operations center, where the controllers can be remotely overridden or reprogrammed. ARM necessitates the most complex hardware and software of the three ramp metering strategies. Requirements include detectors upstream and downstream of the ramps, a communication medium, and a central computer linked to the ramps. The detector technologies must measure vehicle volume, occupancy, and speed. A downstream detector may also be used as the upstream detector for the next location in cases where ramps are spaced relatively close together. The typical detector requirements for ARM are shown schematically in Figure 1.

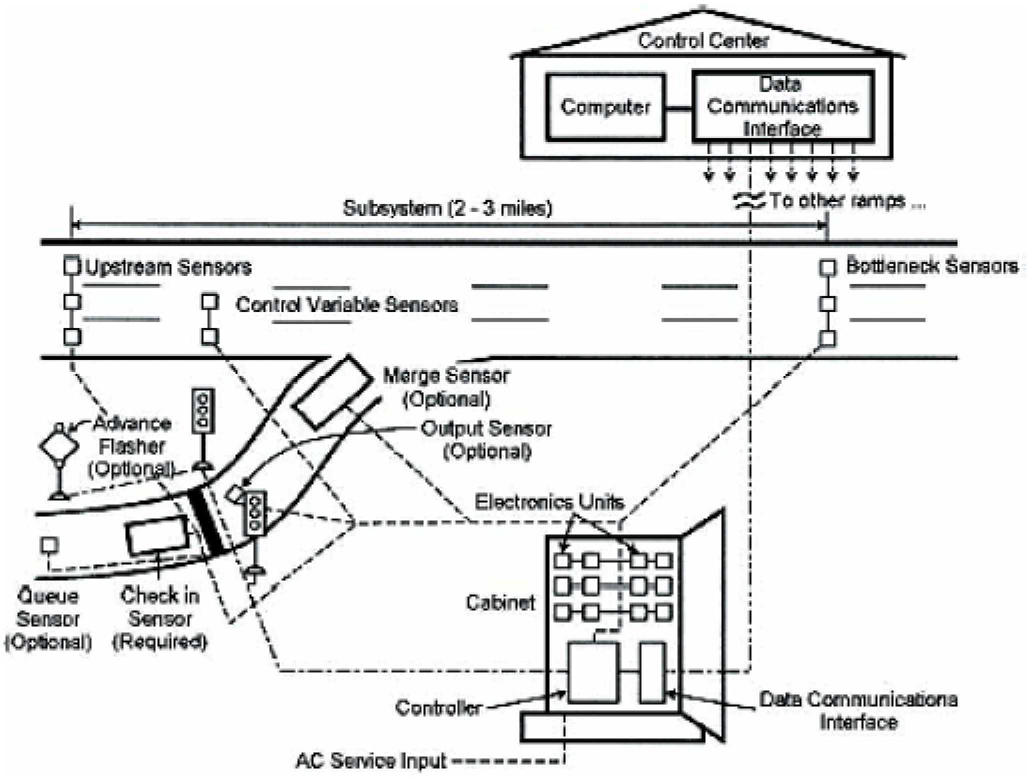


Figure 1 ***Typical Detector Requirements for Adaptive Ramp Metering (DKS Associates, 2010)***

All three of these ramp metering strategies can be made responsive to queues spilling back onto local streets. Queue length detectors can be implemented at the upstream end of the on-ramp to alert the ramp meter when the queue is about to spill into the local cross street. The ramp meter then adjusts its rate or turns off.

Ramp Metering in California

The California Department of Transportation (Caltrans) states in their Ramp Metering Design Manual (Caltrans, 2016) and in their Ramp Metering Development Plan (Caltrans, 2016) that they are committed to using ramp metering as an effective traffic management strategy. Caltrans considers ramp metering to be an integral strategy for reducing congestion, reducing travel times, and increasing safety. Ramp metering is used to maintain efficient operations by keeping freeways operating at or near capacity, thus optimizing the transportation system for travelers. Caltrans uses ramp metering as a part of a coordinated and integrated traffic management system. They use it in consistency with their goal of maximizing capacity while providing good stewardship of public investment and minimizing environmental impacts.

Motivation and Context

For numerous reasons, freeway widening would have been a poor choice for the study corridor. Much of the freeway right-of-way is physically constrained by fully developed communities or by environmentally sensitive areas bordering San Francisco Bay. The estimated cost to widen would have been cost prohibitive, in the hundreds of millions of dollars (Caltrans Press Conference, 2016). Regardless of cost, freeway widening would likely have been politically unpopular as well as ineffective over time. The congested nature of this corridor means that adding capacity would have likely induced even more demand, such as from choice transit users or from drivers who currently shift their trips to off-peak periods.

Traditional demand management strategies, such as HOV lanes and park and ride lots, already existed along the corridor. In fact, the HOV lanes already required three or more occupants per vehicle, rather than the typical two or more. With collision rates as much as twice the statewide average, there were also concerns over safety, secondary collisions, and resulting additional congestion. An Active Traffic Management (ATM) system was identified as the best solution for the corridor, addressing recurring congestion as well as incidents and being a sustainable transportation infrastructure investment. The project goals for the ATM system were to optimize corridor performance, provide real-time information to users, improve travel time reliability, improve access for first-responders, and reduce secondary collisions and their related congestion.

The ultimate project, called the I-80 SMART Corridor, was a collaboration of multiple agencies and was constructed in phases over several years at a cost of $79 million. Most project elements came online during summer 2016. While the ARM component of the project is the focus of this research, the I-80 SMART Corridor also includes several other Intelligent Transportation System (ITS) components such as variable advisory speed signs, lane use signs, and traffic information boards. The project extends to local streets as well, specifically the parallel arterial San Pablo Avenue, with traffic signal management and “Trailblazer” signs which direct detouring vehicles back onto the freeway after bypassing a major incident.

Even though ramp metering has been used throughout California and the San Francisco Bay Area for decades, the study corridor was historically never included under a ramp metering system due to complicated political and institutional concerns. With ARM instrumentation installed and operational along the study corridor, it has become the first Bay Area corridor to utilize ARM rather than Local Traffic Responsive ramp metering. The project construction work included installing ramp meters on 43 on-ramps in total, plus “end of queue” detectors and, in a few instances, preferential HOV lanes.

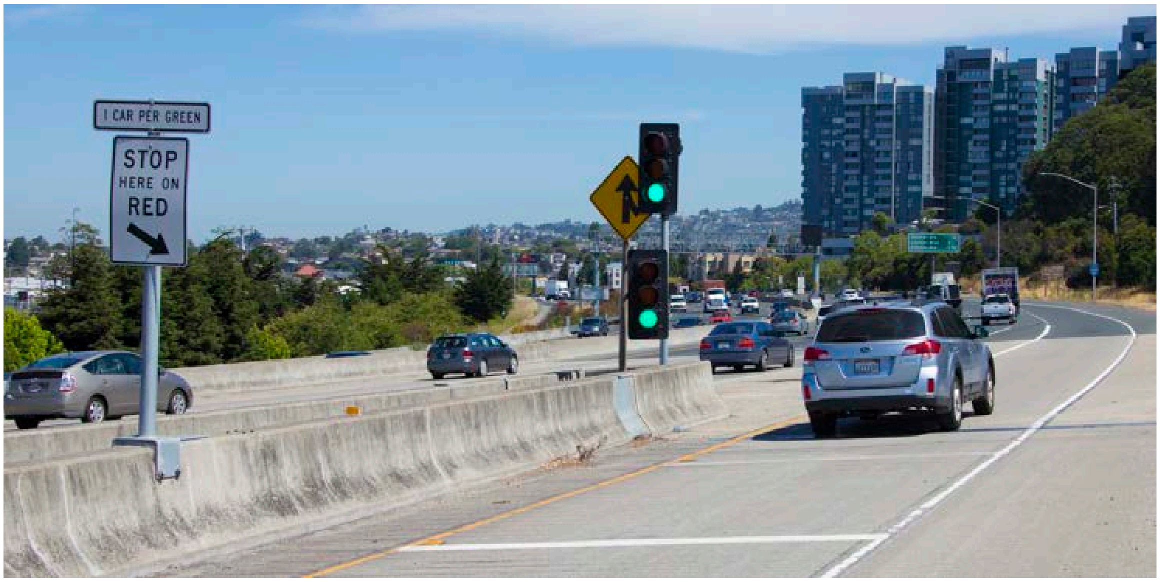


Figure 2 ***Typical single lane metered on-ramp on I-80 SMART Corridor (Caltrans Press Conference, 2016)***

The ramp meters were first activated in August 2016, with Local Traffic Responsive ramp metering. The ARM system of operation began in April 2017 (Low, 2017). All traffic operations for the project corridor, including the ARM system, are controlled from the Caltrans/California Highway Patrol Traffic Management Center in Oakland.

For this project the investigators in consultation with the local sponsor determined two ways the performance to evaluate performance of the ARM system implemented as part of the Smart Corridor:

- User perceptions and opinions will be collected through a targeted online survey. Questionnaire topics include travel characteristics, driving habits, system perspectives, demographics, and qualitative comments.
- System's operational performance was estimated using parameters such as average speed, average travel time, and most critically Travel Time Reliability. Data from INRIX and Caltrans PeMS will be utilized to estimate these parameters before and after implementation of the project.

Organization of the Report

The chapter following this Introduction provides a review of literature on Adaptive Ramp Metering, System Performance and Travel Time Reliability, and Corridor user surveys. Chapter 3 details the source of the data, the scope of the study area, and the methodologies used for estimating operational performance before and after implemetation of ARM. Chapter 4 provides results from the User opinion Survey. Chapter 5 draws conclusions on the effectiveness of the Adaptive Ramp Metering system as well as on the future technology transfer activities for the project.

Chapter 2: Literature Review

This literature review covers studies looking at general effectiveness of ramp metering, studies looking specifically at adaptive ramp metering, and various studies of travel time reliability measures.

Ramp Metering Effectiveness

Implementing ramp metering has been found to be a worthwhile investment and has resulted in benefits including increased speeds, reduced travel times, reduced collisions, and reduced emissions (Mizuta et al, 2014) (Ahn et al, 2007) (Haj-Salem and Papageorgiou, 1995) (Kang and Gillen, 1999).

Despite these benefits, the public often perceives ramp meters as an unnecessary impediment, resulting in the systems being unpopular. One extreme debate over ramp metering involved a legislatively mandated “ramp meter holiday” in the Twin Cities of Minneapolis and St. Paul, Minnesota. Ramp meters had been in use since 1969 to optimize freeway safety and efficiency, though their effectiveness was being questioned following increases in congestion and meter wait times. For the test, the ramp meters were shut off for eight weeks so that their effectiveness could be tested.

The legislature’s authorized study (Cambridge Systematics, 2001) found numerous benefits from ramp metering in the metro area. The use of ramp metering resulted in a 22% savings in freeway travel time and a 14% increase in freeway throughput. Throughout the system, collisions increased by 26% without ramp metering. Considering the entire congestion management system, the benefit/cost ratio was determined to be 5:1. Traveler surveys showed an increased appreciation for ramp metering after the shut-off though also support for modifications, including shortened wait times. Another study of the shutoff (Levinson and Zhang, 2006) investigated several performance measures with and without the ramp meters. It was found that the ramp meters were particularly helpful for long trips relative to short trips. Another finding was that the ramp meters reduced travel time variation. The authors recommended a more refined ramp control algorithm which explicitly considers ramp delay.

Adaptive Ramp Metering

One of the first tests in California of adaptive ramp metering (Pham et al, 2002) occurred in Los Angeles County and found increases in mainline speed, decreases in travel time, and reductions in freeway delay compared to the existing local mainline responsive strategy. The most benefits occurred when using a combined global and local ramp metering strategy. In a simulation model of adaptive ramp metering on the I-405 freeway in southern California (Chu et al, 2004) it was found that adaptive ramp metering can reduce freeway congestion effectively compared to fixed-time control. It was also found that ramp metering becomes less effective under incident scenarios with severe traffic congestion.

A study of a newly deployed adaptive ramp metering system in Portland, Oregon (Ahn et al, 2007) found mixed results, with an increase in freeway delay possibly being traded for lower on-ramp delay. A study in Australia (Papamichail et al, 2010) found that a coordinated ramp metering strategy led to a significant increase in throughput and reduction of travel times compared with the previous metering system.

A simulation model of an adaptive system in Minnesota (Xin et al, 2004) found that freeway performance was compromised in favor of reducing ramp delays. A Dutch coordinated ramp metering algorithm was simulated and found to outperform non-coordinated metering (Yuan et al, 2009). Another coordinated ramp metering algorithm was implemented in Germany and showed promising results (Bogenberger et al, 2002).

Travel Time Reliability

Most of the studies involving field evaluations of ramp metering in the U.S. have focused on measures of on-ramp delays, mainline delays, fuel consumption, and/or resulting emissions. This research will instead focus on assessing the effects of ramp metering on measures of travel time reliability. Several relevant studies of travel time reliability are examined below in detail.

Assessments of Traditional Measures

In some of the earliest research into travel time reliability measures for use as practical performance measures, Lomax, Schrank, Turner, and Margiotta (2003) grouped measures into three broad categories based on differences in communication and calculation: Statistical Range, Buffer Time Measures, and Tardy Trip Indicators. The study recommended the following measures: Percent variation, Misery Index, and Buffer Time Index.

Pu (2011) compared numerous reliability measures and explored their mathematical relationships. It was found that the coefficient of variation, instead of the standard deviation, is a good proxy for several other measures. It was found that, especially in cases where travel time distributions are heavily skewed, the average-based buffer index or average-based failure rate is not always appropriate. In these cases, the author recommends the median-based buffer index or failure rate (percent of on-time arrival).

New Measure Based on Width and Skew of Travel Times

Van Lint, Van Zuylen, and Tu (2008) challenged existing travel time reliability measures, based predominantly on variance of travel times, and propose a new measure based on both width and skew. Their research included an empirical investigation of a 19 km study segment on the A20 freeway in The Netherlands with a free flow travel time of around 11 minutes.

First, a schematic overview of factors influencing the distribution of travel times was presented (shown below in Figure 3). The authors note that the list is not exhaustive.

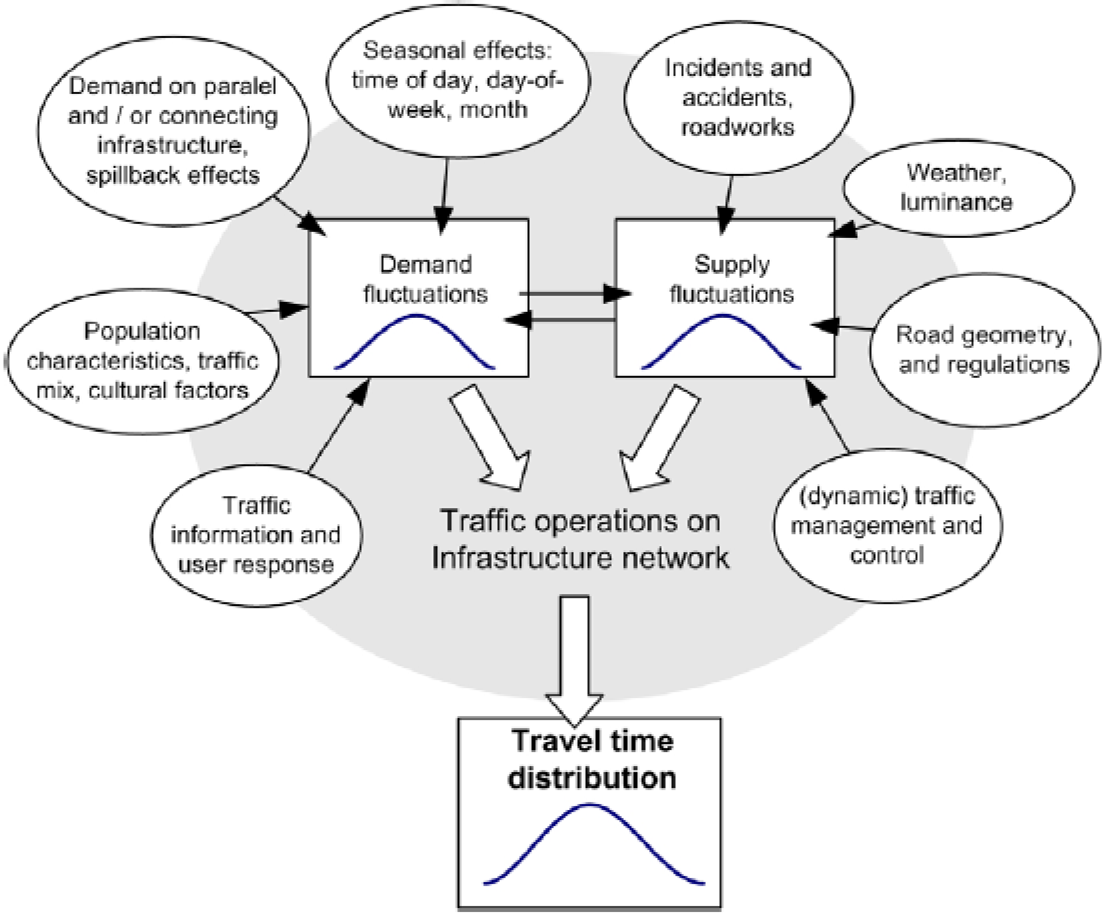


Figure 3 ***Factors Influencing the Distribution of Travel Times (Van Lint et al, 2008)***

Their empirical investigation which followed supported the claim that heavy skewing in travel distributions can have substantial economic consequences. For example, in 2002 close to 350,000 travelers traversed the study segment on Thursday afternoons between 5:00 and 6:00 pm. It was found that the 5% most delayed travelers had encountered more than 25 minutes of delay, amounting to more than 17,000 travelers incurring at least 7,200 hours of delay in total. Similarly, approximately 7,500-8,000 hours of delay had been incurred by the 50% least delayed travelers. Therefore, the authors argue, this left-skewed travel time distribution is extremely undesirable, especially since extremely long delays are likely to have much more serious consequences than modest delays. They conclude that not only the variance should guide reliability discussions, but also the skewness.

A new measure for travel time reliability based on both width and skew was derived, called UIr. The measure incorporates two new percentile-based indicators for width and skew that are insensitive to outliers. UIr can be interpreted as the likelihood of incurring a very bad travel time, relative to the median.

It was shown that all travel time reliability measures are highly inconsistent, even commonly used indicators such as the misery index and the buffer time index. Furthermore, choosing between measures and setting thresholds is subject to debate without objective and quantitative criteria such as economic or societal costs.

Assessment of New Measure

Bhouri, Aron, and Kauppila (2012) assessed travel time reliability of hard shoulder running on the A4-A86 motorway in France, particularly the reliability indicators. The study segment is 3 km in length. The authors stated that a smaller planning time increases driver satisfaction. Even if Planning Time does not decrease, a smaller Buffer Time implies greater reliability.

The authors then addressed the lambda-var and lambda-skew indicators proposed by Van Lint et al. (2008), used to measure respectively the width and the skew of a travel time distribution. They report the lambda-var indicator is robust for both reliability and congestion. However, the lambda-skew indicator was found to have a weakness since the travel time in non-congested traffic, used in the calculation, was determined largely by the roadway's automatic speed control systems. The authors concluded that UIr was therefore not an effective indicator, since it incorporates lambda-skew.

Effects of Ramp Metering Strategy

Bhouri, Haj-Salem, and Kauppila (2013) evaluated the ramp metering on the A6W motorway in France by studying the impacts on traffic and travel time reliability. Their focus was on reducing daily uncertainty in travel times to provide travelers with greater consistency. The evaluation used measurements of traffic volume, occupancy rate, and speed in addition to estimated travel time. The paper compared the reliability and travel time impacts of two different freeway ramp metering strategies: ALINEA, a local strategy which maintains freeway density around the critical value, and CORDIN, a coordinated strategy.

Four traffic indices were considered: Total Time Spent (TTS), expressed in vehicles times hours; Total Travel Distance (TTD), expressed in vehicles times kilometers; Mean Speed, defined as TTD/TTS; and Travel Time, calculated using the real speed measurements of consecutive measurement stations. Congestion mapping of iso-occupancy curves in space and time was drawn using the loop detector occupancy measurements and the real data collection time slice of 6 minutes. Several reliability measures were considered: Standard Deviation and Coefficient of Variation; Buffer Time and Planning Time; Misery Index; and Probabilistic indicators.

The field test site comprised five on-ramps with a total motorway length of about 20 km. Traffic flow, occupancy rate, and speed measurement stations were available at roughly 500 m spacing intervals. The three strategies (No Control, ALINEA, and CORDIN) were applied over alternate weeks for a period of about 16 months. Data was then extracted from the traffic management system database and screened to discard major detector failures, atypical traffic patterns (weekends and holidays), and significant traffic incidents. Demand variation impacts were minimized by averaging the selected days for each strategy.

The evaluation results for the traffic indices, examining the period of 6:00-11:00 am, showed CORDIN performed better than ALINEA. Both metering strategies improved TTS and TTD compared to No Control. Using the congestion mapping, the quantitative results of the TTS indices were qualitatively confirmed. The CORDIN strategy was found to give better results for Total Travel Time.

Studying travel time variability, both ALINEA and CORDIN were found to reduce the average travel time and the travel time variability, with no significant differences between the resulting daily variabilities of the two. Depending on the measure used, both metering strategies reduced travel time variability by 24-37%. For both, the Planning Time was reduced by about 14 minutes. Since the mean travel time only improved by 3-4 minutes with metering, the authors argued that the reduced travel time variability, evidenced by the Planning Time, is the main improvement from the user perspective.

SURVEY LITERATURE REVIEW

Surveys are a common tool used to collect feedback and public opinions in transportation. They have been used to examine public opinions about new policies as well as for before-and-after comparisons (e.g., (Bhouri et al, 2013), (Chu et al, 2004)). Video-based surveys have been used to estimate levels of service (LOS) based on perceptions of users of multiple specific rural freeway corridors (Papamichail et al, 2010). In the rural freeway corridor study, target participants were randomly selected from Alachua County (FL) residents, university students, administrative staff, and professionals. The sample of 126 recipients was not weighted (Papamichail et al, 2010). In Houston, Texas a combination of mail-out and phone questionnaire surveys targeted carpoolers, bus riders, and van-poolers who use the freeway high-occupancy vehicle (HOV) system. The purpose of the survey was to examine the user views of longer operating hours for HOV and high-occupancy toll (HOT) lanes in the Houston metropolitan area.

Lee and Pino (2012) examined the effectiveness of web-based and phone surveys and noted the changing patterns of landline and cell phone usage. These changing patterns have increased the cost and decreased the effectiveness of phone surveys due to low response rate. Web-based surveys have received significant attention recently because of these issues with phone surveys. Viggiano et al. (2014) noted that a web survey was feasible and effective in collecting detailed information from a large sample at very low cost. Cobanoglu et al. (2001) found that web-based survey responses can be collected more quickly than mail-out survey responses and at lower cost. In addition, the response rate for web-based surveys tends to be significantly higher than for mail-out surveys, with no difference in the quality of the data. One issue that Cobanoglu et al. identified was it can be difficult for a web-based survey to reach a representative sample of the population under consideration.

A common technique to address the challenge of a representative sample is to weigh the sample based on demographics of the study area obtained from the American Community Survey data of the US Census Bureau. However, the approach may not be really effective for targeting a population of automobile users on the I-80 corridor. Devarasetty et al. (Low, 2017) noted this challenge in their online survey of Katy Freeway users in Houston, Texas. They noted the demographics from an older 2003 survey mailed to the travelers observed on the Katy Freeway may resemble the target demographics more closely. The 2008 Katy Freeway survey (see Patil et al.) for details of the survey) was also an online survey.

Nikolaidou and Papaioannou (2017) noted that a variety of member characteristics makes social media tools such as Facebook and Twitter suitable for many different applications. This diversity in the user composition is also precisely the element that makes it a potentially effective tool for transport data collection. For web-based surveys conducted via social media, responses need to be validated to ensure the respondents didn’t illogically fill out the survey.

Conclusions from the Literature Review

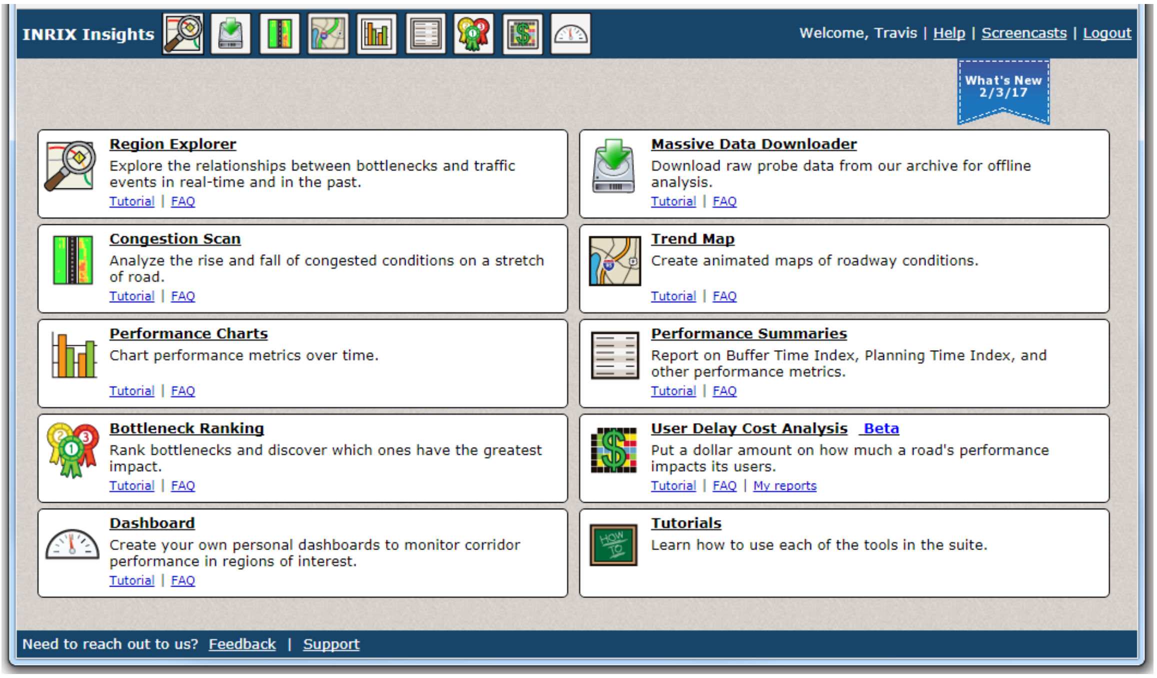
Several previous studies of Adaptive Ramp Metering were simulation based. In this study, we examine the effectiveness from a user perspective. Therefore, travel time reliability is the performance measure in this study since system users typically plan for expected delays but are less tolerant of unexpected delays.

The impact of Adaptive Ramp Metering as part of Smart Corridor implementation on Travel Time Reliability has not been thoroughly studied in the U.S. context. This is important since the driver population and cultural differences may have effects on system compliance and therefore effectiveness.

Operations Analysis: Travel time reliability and Efficiency

Data Source

Data for this research has been obtained from INRIX Insights (see Figure XX) using probe vehicle data. INRIX Insights provides data fields for speed, travel time, and several user-oriented travel time reliability measures. Data is available down to one-minute granularity. INRIX Insights provides additional data visualization and retrieval tools which allow for the analysis of bottlenecks, traffic incidents and events, and the cost of delays. The suite of tools is meant to allow agencies to support operations, planning, analysis, research, and performance measures generation. The focus is providing effective information on metrics that departments of transportation can use to communicate with the public or decision-makers.



Region Explorer
Explore the relationships between bottlenecks and traffic events in real-time and in the past.
Tutorial | FAQ

Massive Data Downloader
Download raw probe data from our archive for offline analysis.
Tutorial | FAQ

Congestion Scan
Analyze the rise and fall of congested conditions on a stretch of road.
Tutorial | FAQ

Trend Map
Create animated maps of roadway conditions.
Tutorial | FAQ

Performance Charts
Chart performance metrics over time.
Tutorial | FAQ

Performance Summaries
Report on Buffer Time Index, Planning Time Index, and other performance metrics.
Tutorial | FAQ

Bottleneck Ranking
Rank bottlenecks and discover which ones have the greatest impact.
Tutorial | FAQ

User Delay Cost Analysis Beta
Put a dollar amount on how much a road's performance impacts its users.
Tutorial | FAQ | My reports

Dashboard
Create your own personal dashboards to monitor corridor performance in regions of interest.
Tutorial | FAQ

Tutorials
Learn how to use each of the tools in the suite.

*Figure 4: **Screenshot of INRIX Insights***

Research Scope

While the I-80 SMART Corridor project encompasses both directions of the freeway, only the eastbound direction of I-80 was selected for this research. This is because a portion of the westbound direction had already been equipped with lane use signs that could potentially confound the effects of the adaptive ramp metering. The analysis corridor begins at the Powell Street eastbound off-ramp, just after the I-80/I-580/I-880 interchange, and ends at the Pomona Street eastbound on-ramp, just before the Carquinez Bridge, for a total distance of 19 miles. The extent of the project corridor is shown in Figure 5.

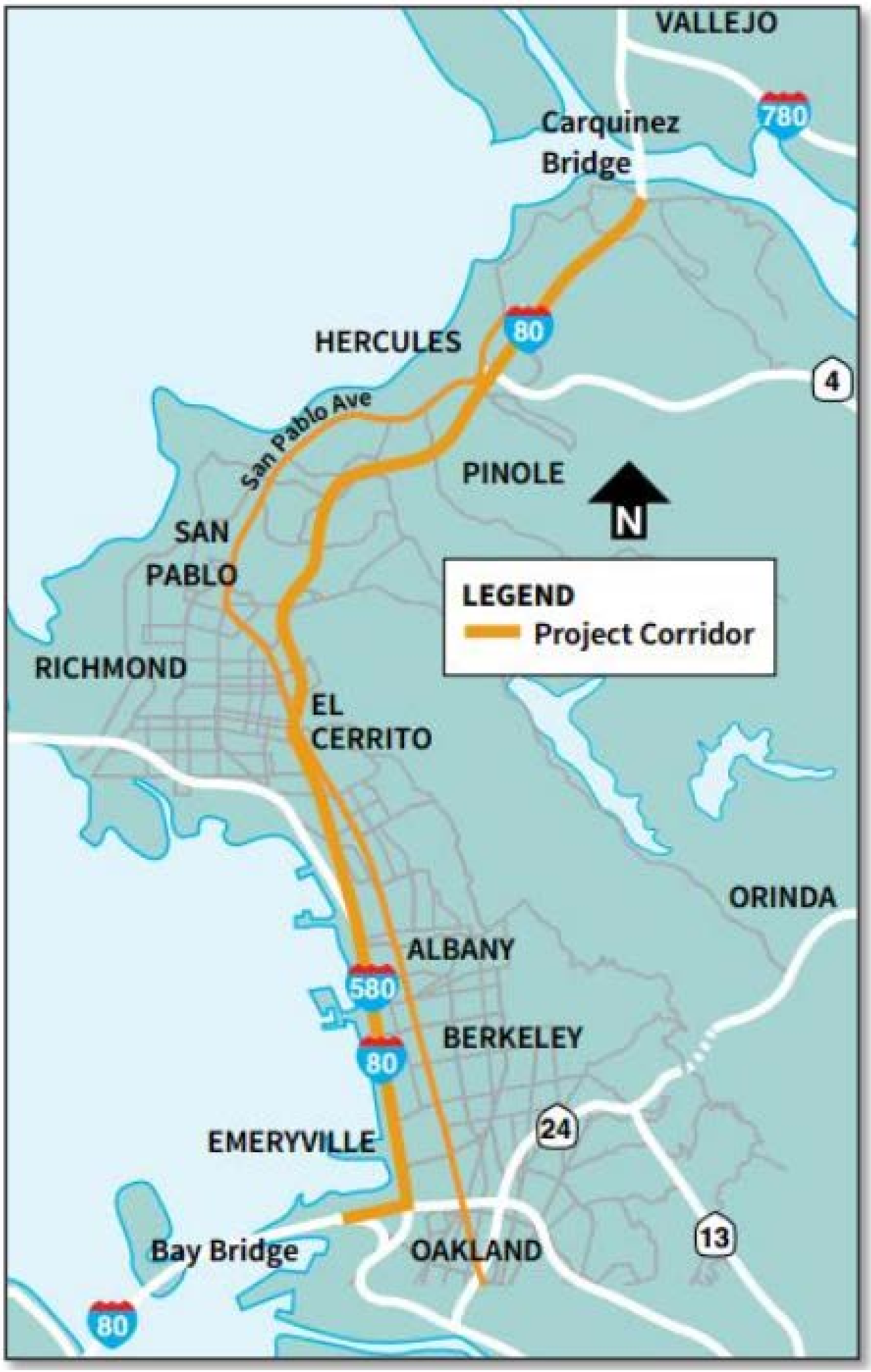


Figure 5: ***19-mile Smart corridor project map (courtesy of Caltrans, 2017).***

To capture the most typical commute congestion patterns, the data analyzed in this research is from mid-week (Tuesdays, Wednesdays, and Thursdays). Data is analyzed during the month of

May from each of the years 2011 through 2017, inclusive. The month of May generally captures travel patterns before the summer travel season but is after the months with the most rain.

During the month of May 2017, Adaptive ramp metering was activated from 6:00 AM to 6:00 PM. At all other times, local traffic responsive metering was activated as needed. During the month of May in all prior years (including 2016), no ramp metering was deployed.

Measures of Reliability

Travel time reliability was chosen as the broad class of measure for the before-after evaluation since this class of measures appears to relate well to the way in which users make their travel decisions. As mentioned previously, while many drivers either adjust their schedules or budget extra time to allow for recurring traffic delays, they tend to be less tolerant of unexpected delays.

Traditional Measures

Mean travel time, standard deviation, and variance are the fundamental statistics that reveal freeway corridor performance. In addition, the buffer methods for quantifying travel time reliability address the additional travel time that users should account for, due to the travel time variability on their route, to arrive on time. Buffer Time (BT) is defined as the extra time a user should add to the mean travel time in order to arrive on time 95% of the time, computed as the difference between the 95th percentile travel time (T_{95}) and the mean travel time (M). Buffer Index (BI) is defined as the ratio between the Buffer Time and the mean travel time. It is calculated as:

$$BI = \frac{T_{95} - M}{M} \dots Eq. 1$$

The Buffer Index is useful for users to assess how much extra travel time should be allowed to account for daily uncertainty in travel conditions. For example, if the mean travel time is 20 minutes and the Buffer Index is 40%, then the Buffer Time equals 8 minutes. Therefore, to ensure on-time arrival with 95% certainty, the user should allow 28 minutes for the trip which averages 20 minutes (Bhouri et al, 2013).

Planning Time (PT) is another frequently used reliability measure. It is defined as the total travel time needed to ensure an on-time arrival 95% of the time, or simply the 95th percentile travel time (T_{95}). The Planning Time Index (PTI) is defined as the 95th percentile travel time divided by free-flow travel time (T_{ff}):

$$PTI = \frac{T_{95}}{T_{ff}} \dots Eq. 2$$

For example, if the free flow travel time is 15 minutes and the Planning Time Index is 1.60, then users should plan 24 minutes of total travel time to ensure on-time arrival with 95% certainty. The buffer methods use the 95th percentile value of the travel time distribution as a reference for their definitions. As a result, they more explicitly account for the extreme values of travel time delay (Bhouri et al, 2013). Travel Time Index (TTI) is the travel time represented as a percentage of the free-flow travel time.

Measures Accounting for the Skew and the Width of Travel Time Distribution

As discussed in the Literature Review, Van Lint et al. (2008) proposed new measures for assessing travel time reliability by analyzing day-to-day travel time distributions and characterizing by width and skew, with wider and/or more skewed distributions resulting in less reliable travel times. These measures have not been applied in the U.S. yet. They proposed a measure for skew, λ_{skew}, defined as the ratio of the distance between the 90th and 50th percentile travel times and the distance between the 50th and 10th percentile travel times:

$$\lambda_{skew} = \frac{T_{90} - T_{50}}{T_{50} - T_{10}} \dots Eq. 3$$

In general, as λ_{skew} increases the probability of experiencing extreme travel times increases, relative to the median. If $\lambda_{skew} > 1$ then the users with greater delay lose more time than the users with less delay gain, with respect to the median travel time. Van Lint et al. also proposed a measure for width, λ_{var}, defined as the distance between the 90th and 10th percentile travel times relative to the median:

$$\lambda_{var} = \frac{T_{90} - T_{10}}{T_{50}} \dots Eq. 4$$

Large values of λ_{var} indicate the travel time distribution has a large width, relative to its median. Van Lint et al. combined λ_{var} and λ_{skew} to derive a travel time reliability measure based on both skew and width, called the Unreliability Indicator (UI_r):

$$UI_r = \frac{\lambda_{var} ln(\lambda_{skew})}{L_r} \ldots Eq. 5$$

L_r represents the route length. The purpose of dividing by the route length is to determine travel time unreliability per unit length, avoiding location specificity. In this research, we have proposed substitute measures that may potentially be used since they may be readily derived from the INRIX data. The next chapter provides details of specific evaluation metrics and evaluation of spatio-temporal trends to evaluate the early evidence of effectiveness of ramp metering strategies.

ANALYSIS AND RESULTS

The analysis involves examination of long-term trends in travel time reliability measures from the year 2011 through 2017. Potentially confiding factors that may affect travel time reliability, including trends in aggregate travel demand and incident counts are also examined. It should be noted that 2017 was the first year that Smart Corridor project, which primarily involves ARM on the EB corridor under consideration in this study, was implemented on I-80.

Demand

Traffic volumes at several points along the study corridor from 2011 to 2015 (the most recent year with traffic census data available) show a pattern of generally increasing demand, as shown in Table 1. These increasing demand volumes provide context to travel time reliability measures discussed in this research.

Table 1: I-80 Traffic Volumes

	AADT		
Year	West of Ashby	West of Pinole Valley	West of Pomona
2011	264,000	184,000	111,000
2012	270,000	185,000	112,000
2013	270,000	185,000	112,000
2014	277,000	189,000	116,000
2015	270,000	188,000	118,000

Spatial Analysis with Increasing Travel Distance Upstream of the Bottleneck

I-80 segments immediately upstream of the Pinole Valley Road bottleneck had some of the worst travel time reliability. The subsequent analysis of travel time unreliability focused on segments upstream of this bottleneck. Using the Pinole Valley Road interchange as the downstream end-point, the segment length was increased by the distance to the previous upstream on-ramp in a sequential manner. Figure 6 shows a schematic diagram depicting three such segments as an illustration.

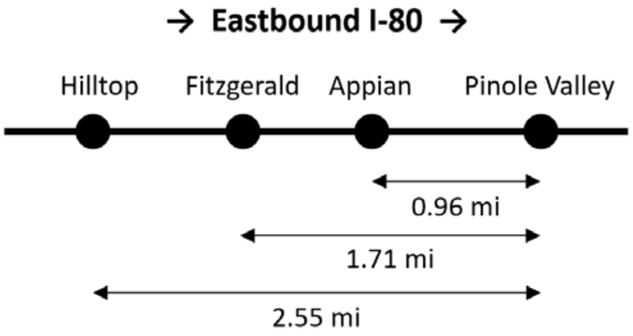


Figure 6: Three upstream segments closest to Pinole Valley Road bottleneck (Low, 2017)

NOTE: As the adaptive ramp metering on the I-80 was officially started in April 2017, this study wished to showcase the data in a yearly format where one could notice a trend starting at the beginning of the graph rather than towards the middle. Thus, all graphs showcase data points that take into account data gathered from April of the year displayed to March of the following year. In other words, the data point for segment 1 in the year 2014 is calculated using the data gathered from April 2014 to March 2015.

Graph 1 displays the average efficiency by segment for the full segment lengths of the I-80 and I-680 freeways as well as the I-680 segment length that stretched from Treat Blvd to Sycamore Valley Road. One can see that of these three freeway segments, regardless of length or peak hour, appear to lose efficiency as time progresses. From 2016 to 2017, however, the I-680 segments actually begin to improve while the I-80 segments continue to drop in efficiency. This is the complete opposite effect we had originally hypothesized. (Several research studies have been conducted and concluded that adaptive ramp metering does benefit travel times and traffic flow of freeways. This particular result may be an outlier or have been influenced by a factor that was not accounted for in the data analysis).

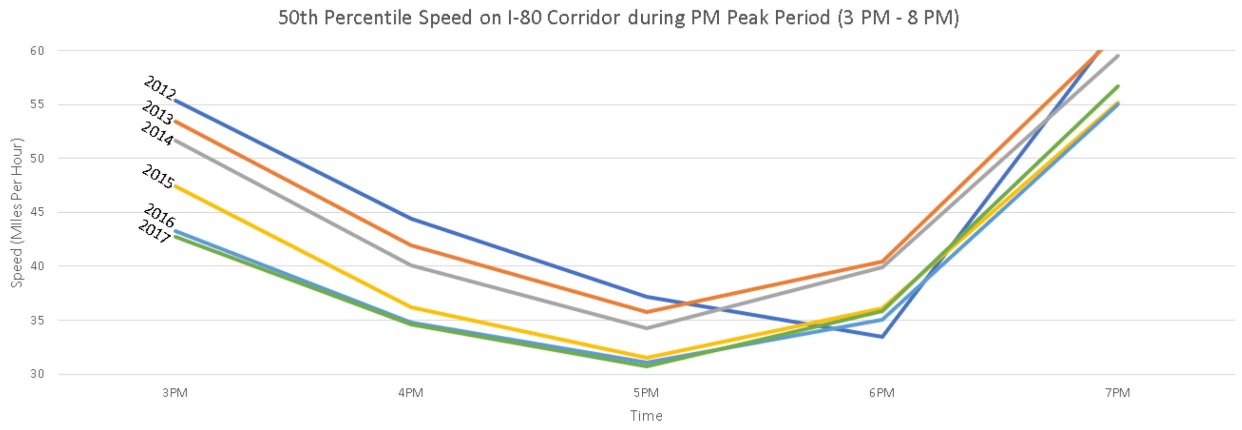
Graph 2 shows the average efficiency by segment for the I-80 in the eastbound direction during the PM peak hour. One can see that as the segment decreases in length, the efficiency of said segment also gradually decreased. This trend holds a strong correlation as time goes on and also reveals a change in difference between the longest and shortest segments analyzed. In 2015, where use of the freeway appears to have peaked within the study's time range, the difference in efficiencies between the longest and shortest segments was approximately 10. In contrast, the lowest difference in efficiencies was about 5.3.

Graph 3 shows similar parameters as Graph 2 with the exception that Graph 3's data is collected and analyzed from the westbound direction during the AM peak hour. The difference in efficiencies across all segment lengths in this graph is noticeably smaller than with the eastbound direction. In addition, there is a slight but noticeable improvement in efficiency in segments 1 through 7 after the adaptive ramp metering began operating. On the other hand, the "Entire" segment lengths and segments 8 through 10 little or even negative results.

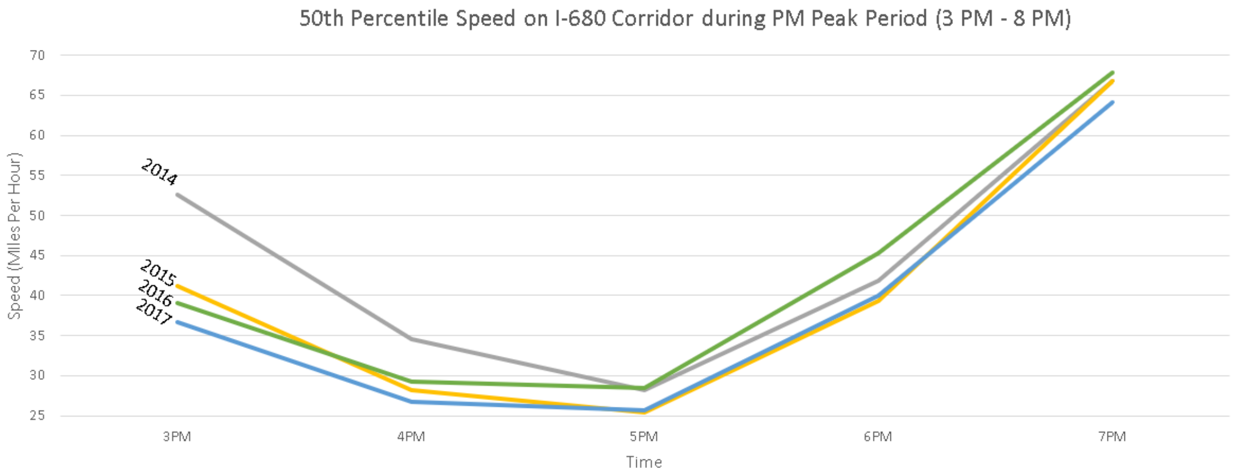
<u>Median Speed</u>

Time Variation

Graph 1.1

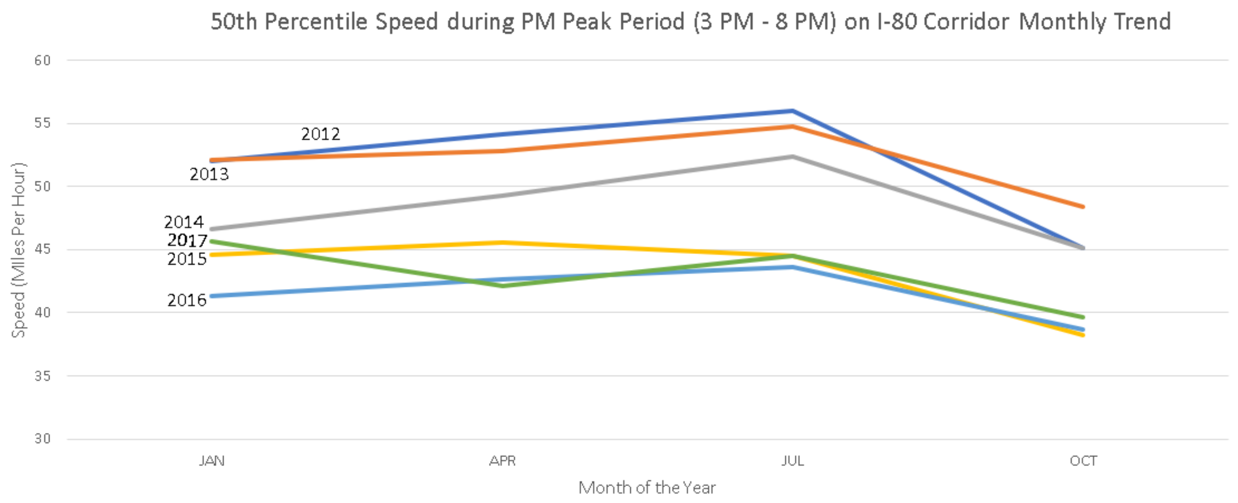

50th Percentile Speed on I-80 Corridor during PM Peak Period (3 PM - 8 PM)
Speed (Miles Per Hour)
60
55
50
45
40
35
30
2012
2013
2014
2015
2016
2017
3PM
4PM
5PM
6PM
7PM
Time

Graph 1.2

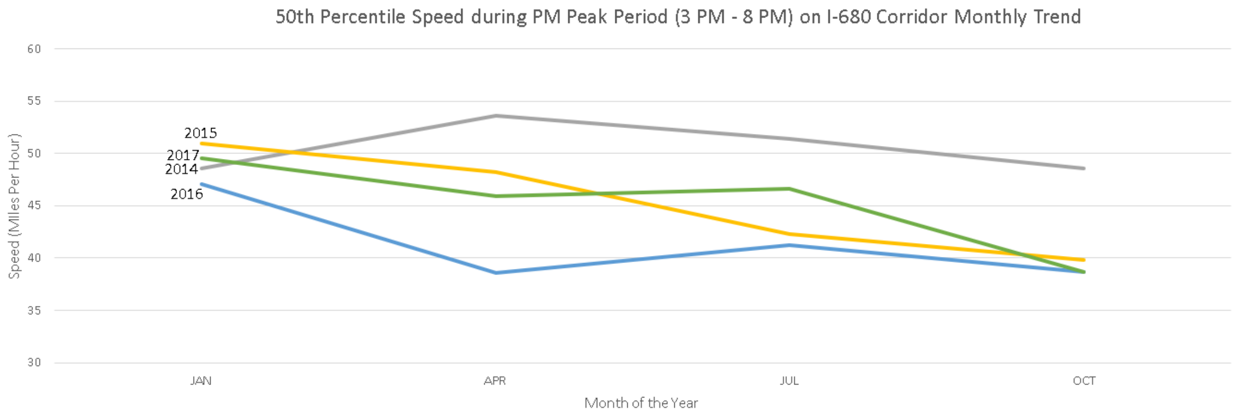

50th Percentile Speed on I-680 Corridor during PM Peak Period (3 PM - 8 PM)
Speed (Miles Per Hour)
70
65
60
55
50
45
40
35
30
25
2014
2015
2016
2017
3PM
4PM
5PM
6PM
7PM
Time

Monthly Variation

Graph 1.3

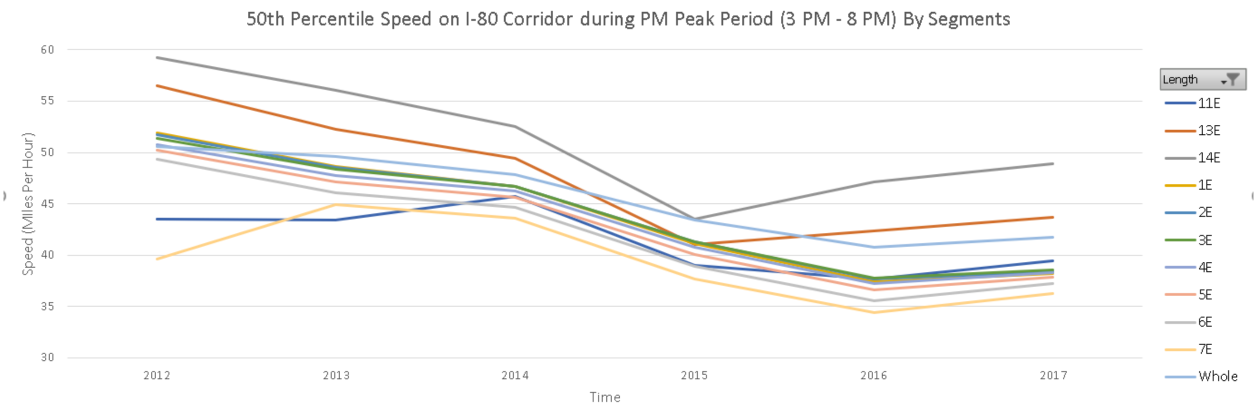


Graph 1.4

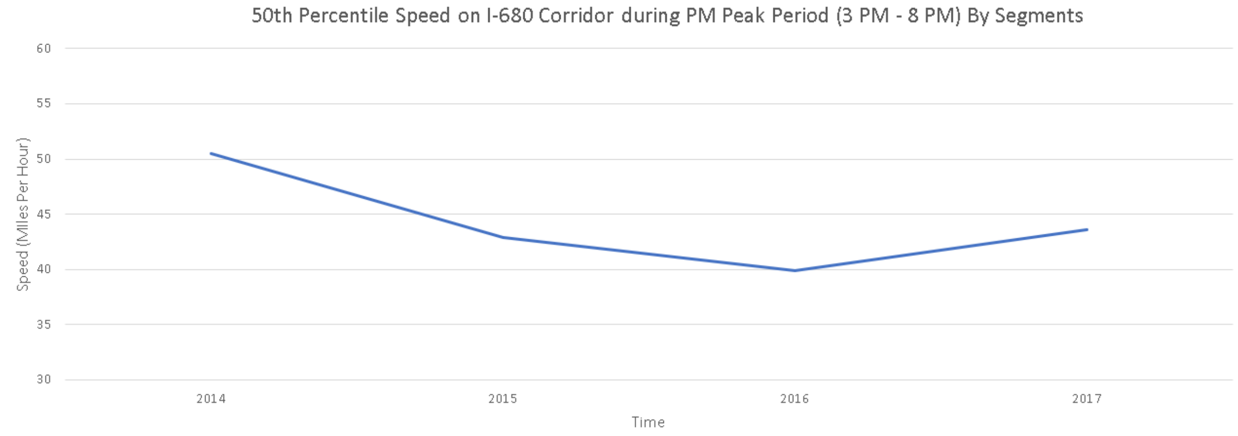


Segment Variation

Graph 1.5



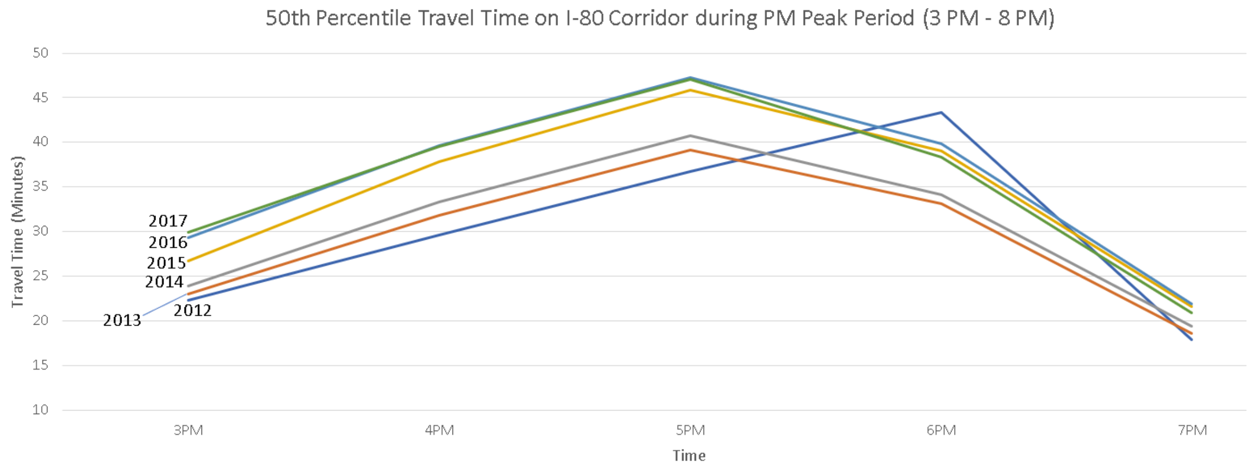
Graph 1.6



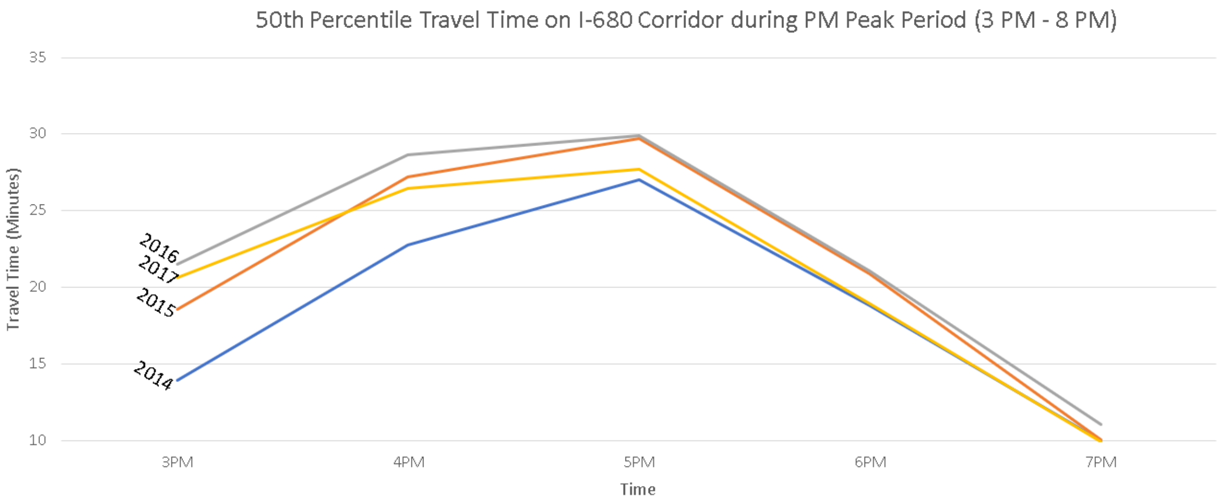
50th Percentile Travel Time

Time Variants

Graph 2.1

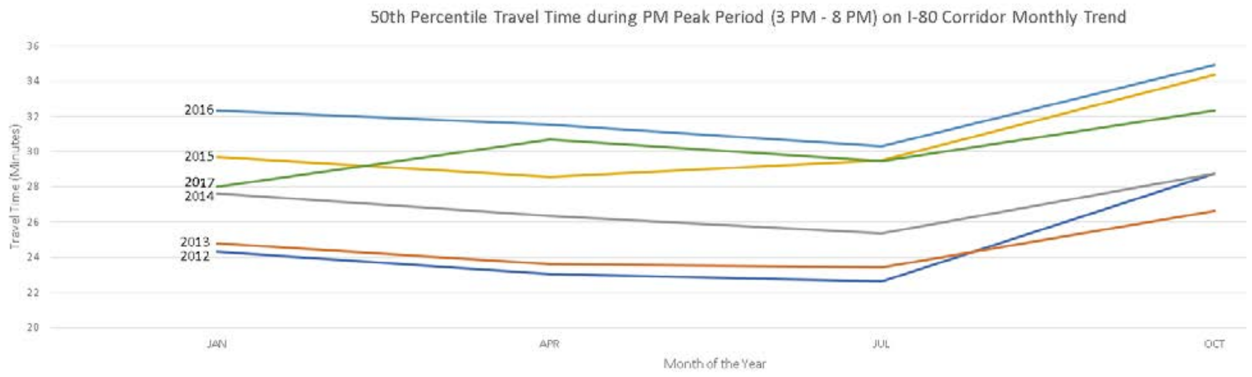


Graph 2.2

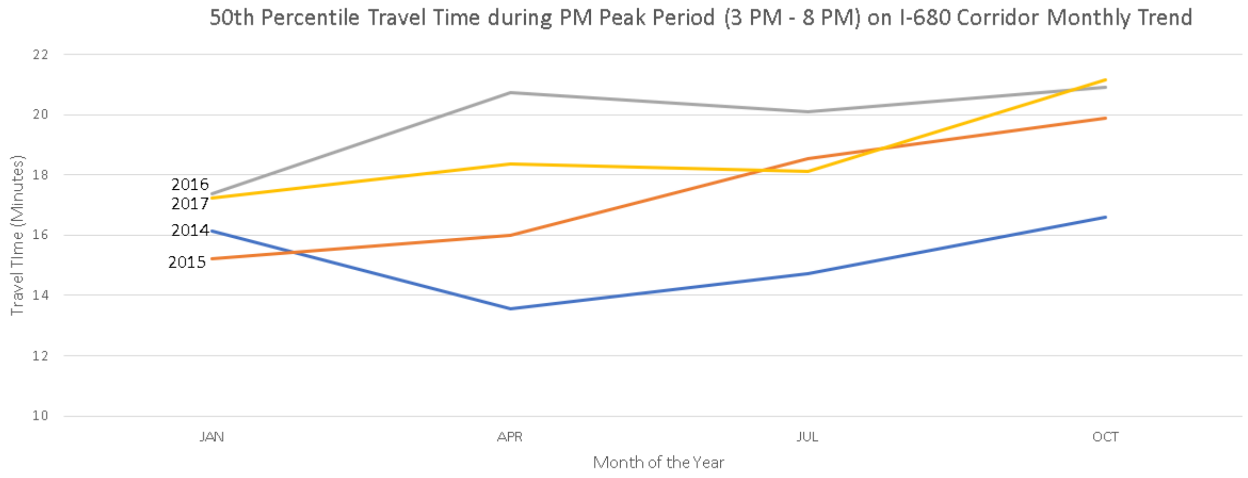


Monthly Variation

Graph 2.3

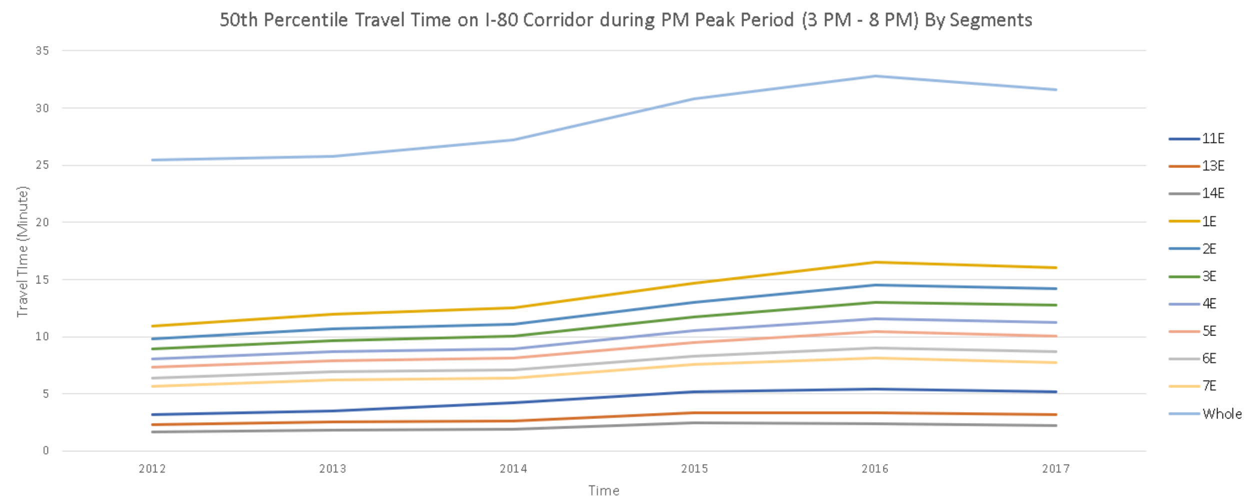


Graph 2.4

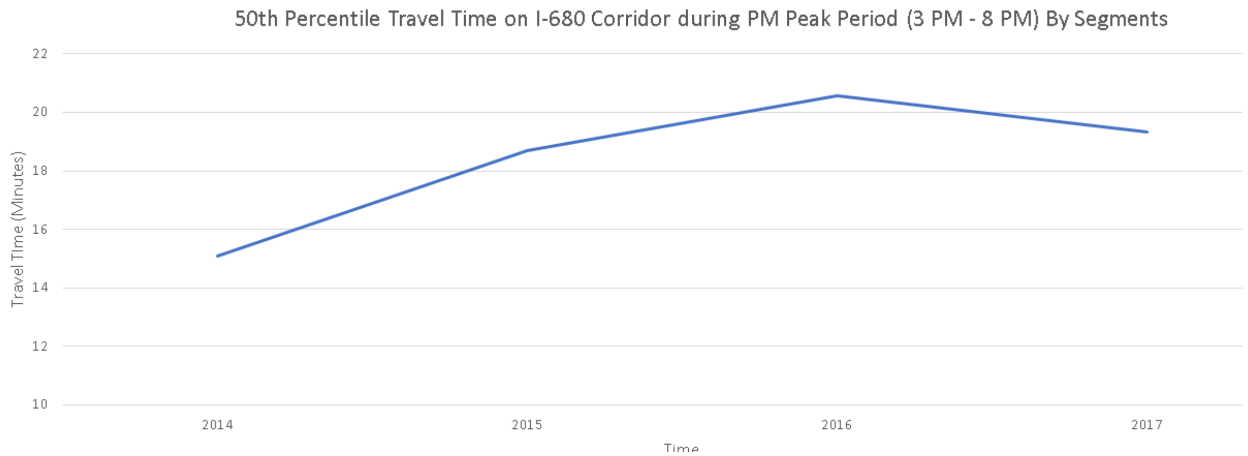


Segment Variation

Graph 2.5


50th Percentile Travel Time on I-80 Corridor during PM Peak Period (3 PM - 8 PM) By Segments
Travel Time (Minute)
35
30
25
20
15
10
5
0
2012
2013
2014
2015
2016
2017
Time
11E
13E
14E
1E
2E
3E
4E
5E
6E
7E
Whole

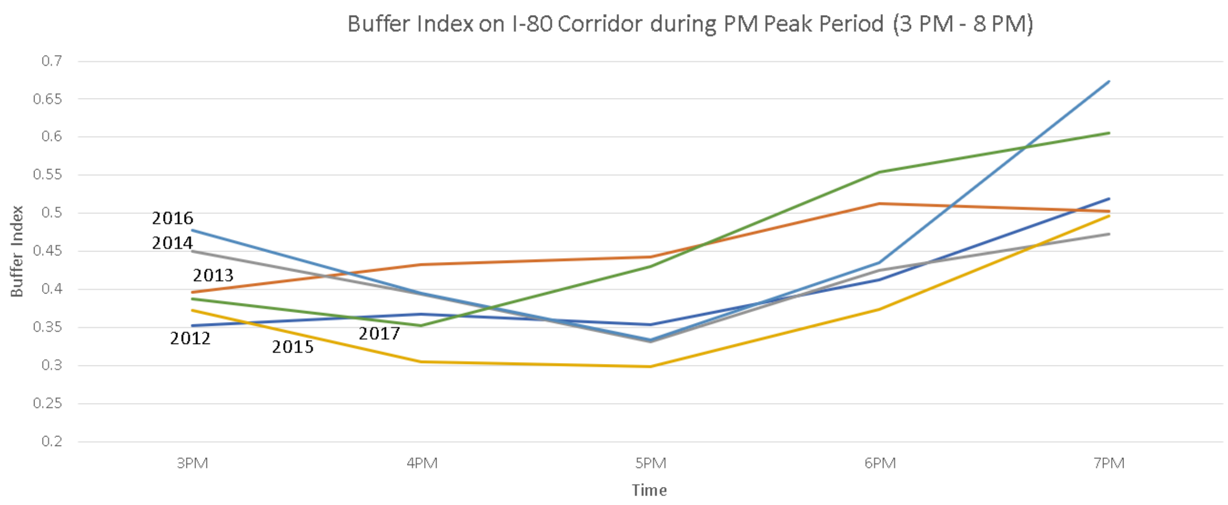
Graph 2.6


50th Percentile Travel Time on I-680 Corridor during PM Peak Period (3 PM - 8 PM) By Segments
Travel Time (Minutes)
22
20
18
16
14
12
10
2014
2015
2016
2017
Time

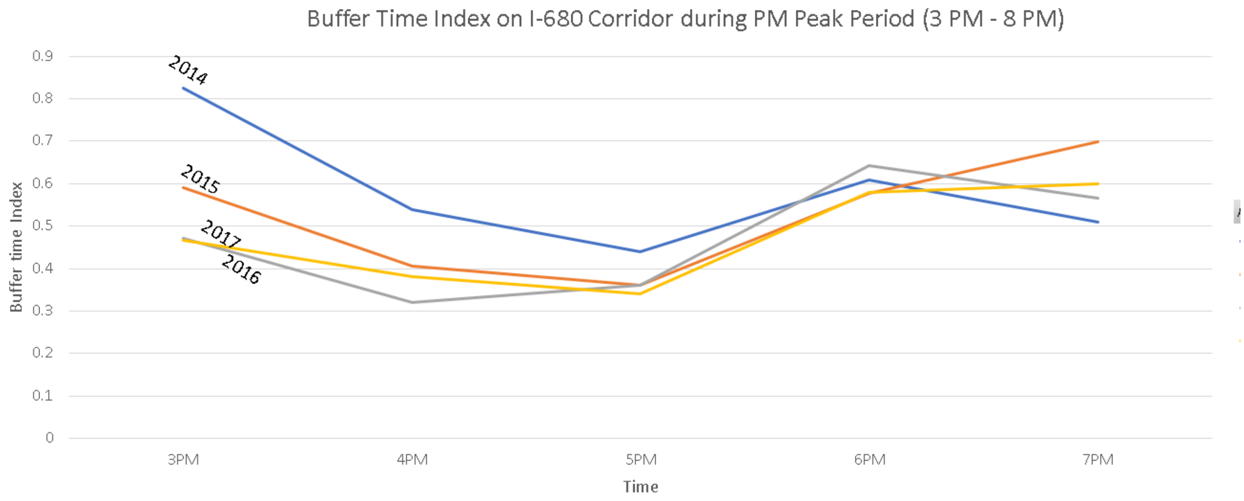
Buffer Index

Time Variant

Graph 3.1

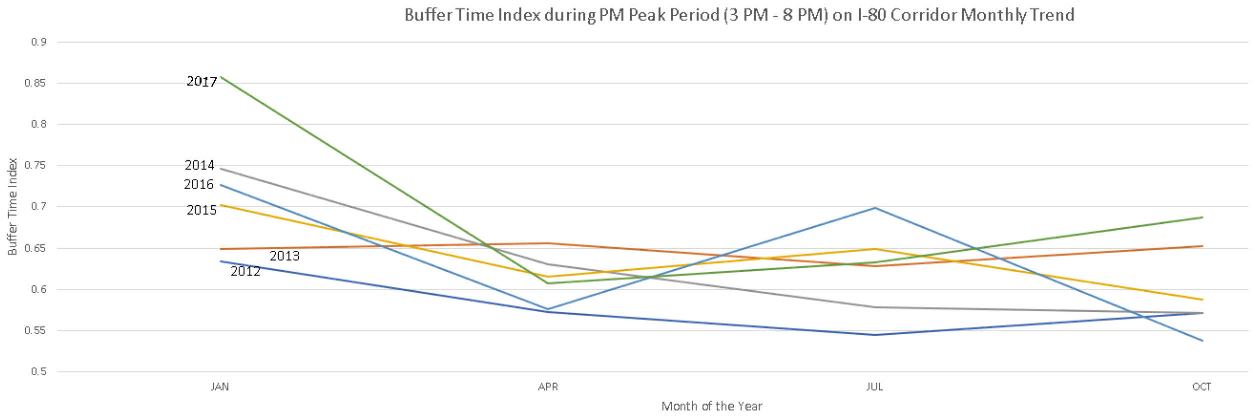


Graph 3.2

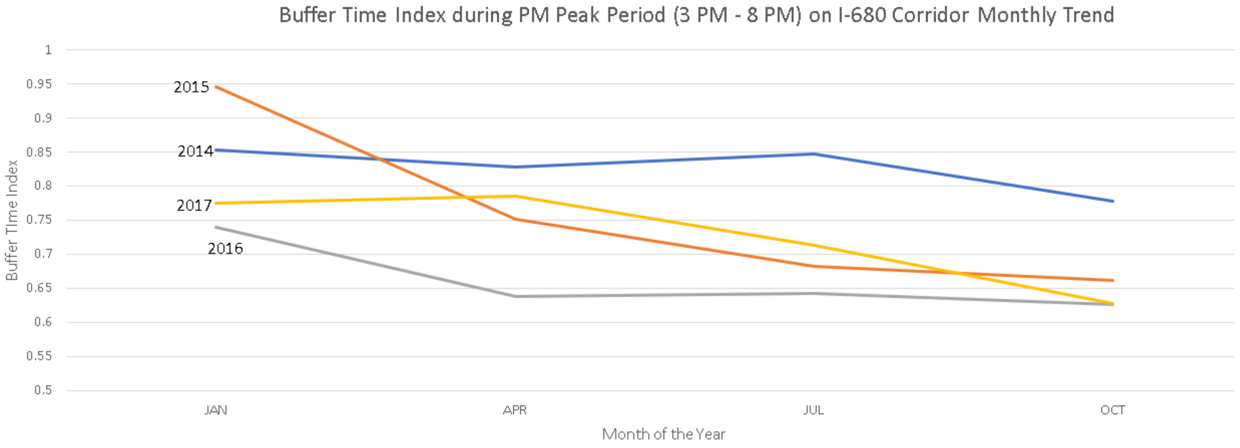


Monthly Variant

Graph 3.3

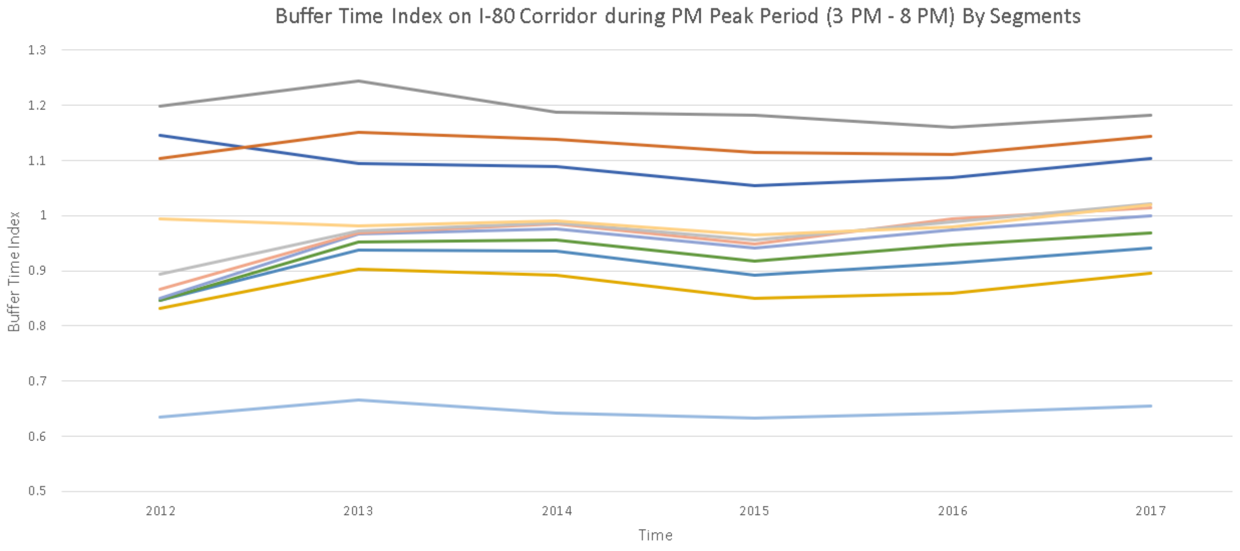


Graph 3.4

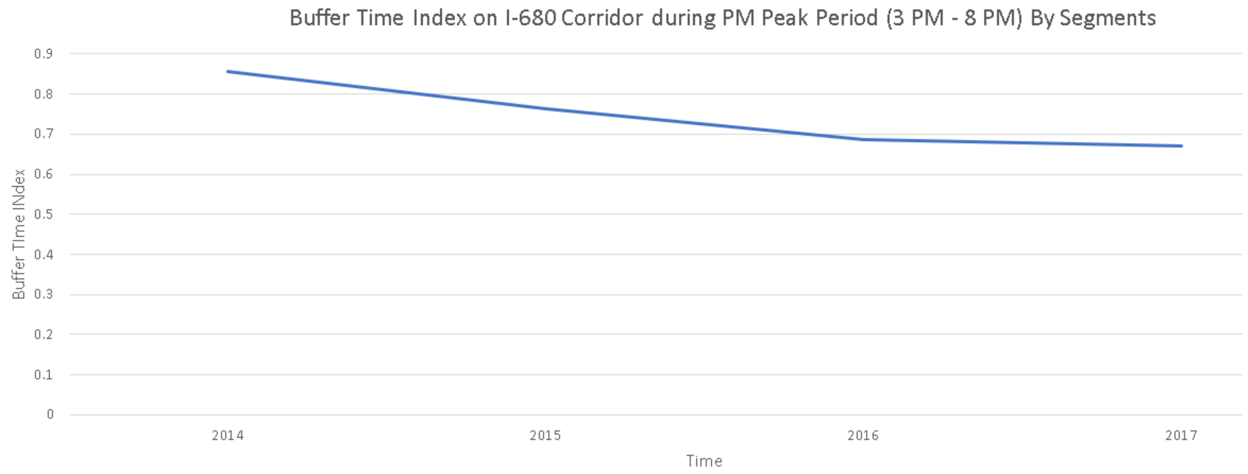


Segment Variant

Graph 3.5



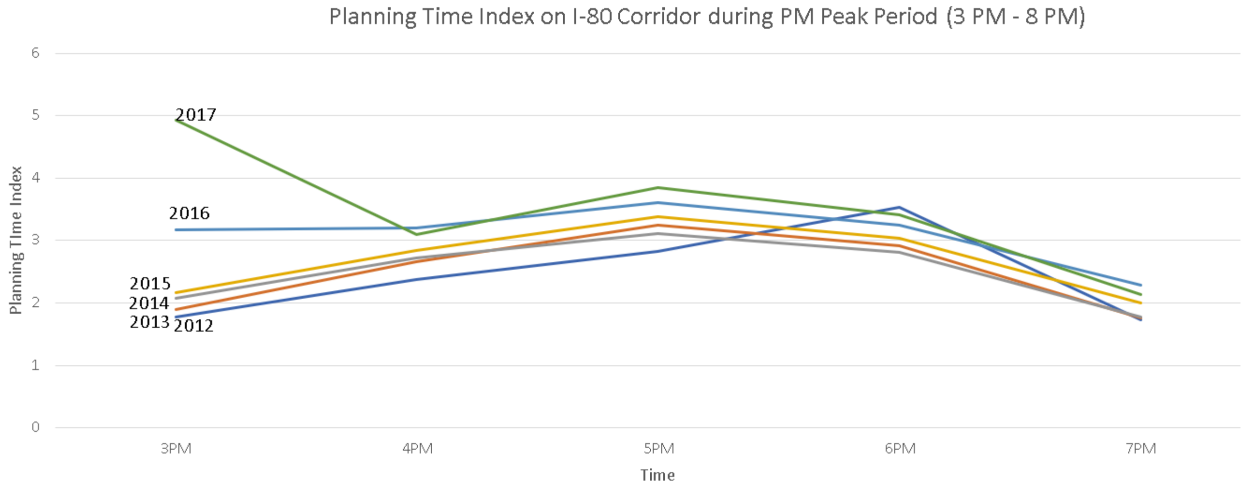
Graph 3.6



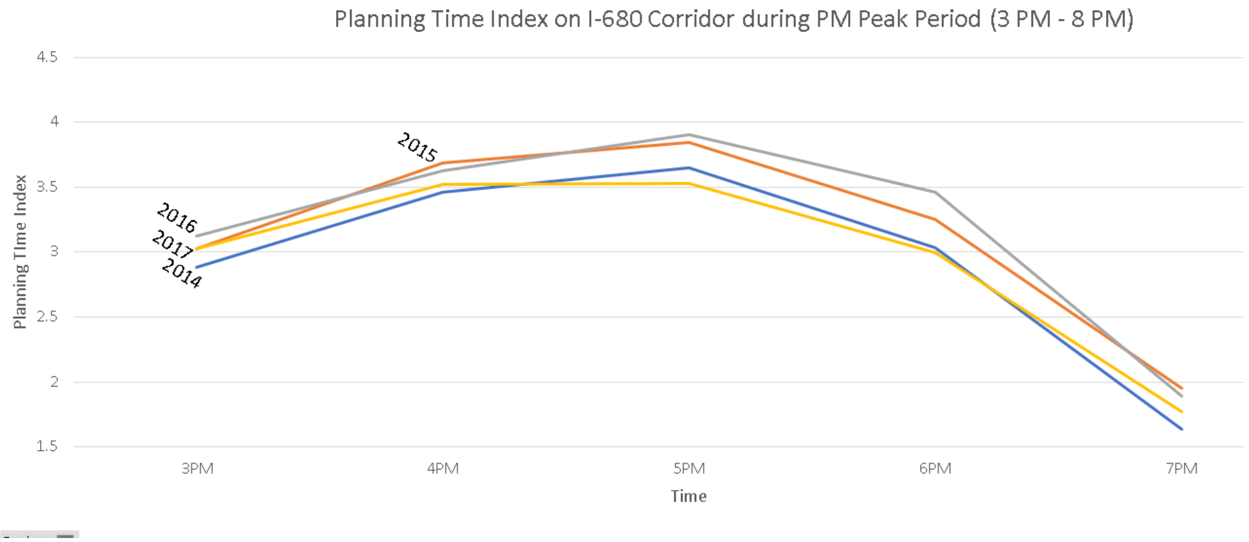
Planning Time Index

Time Variant

Graph 4.1

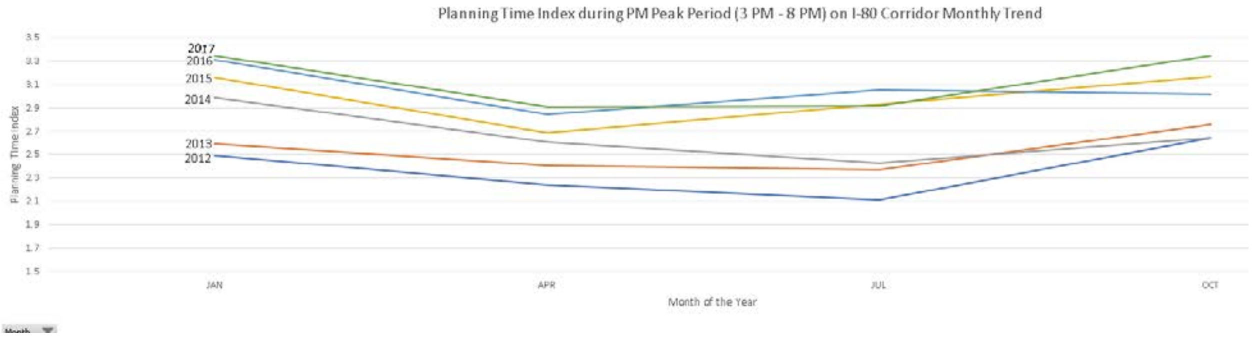


Graph 4.2

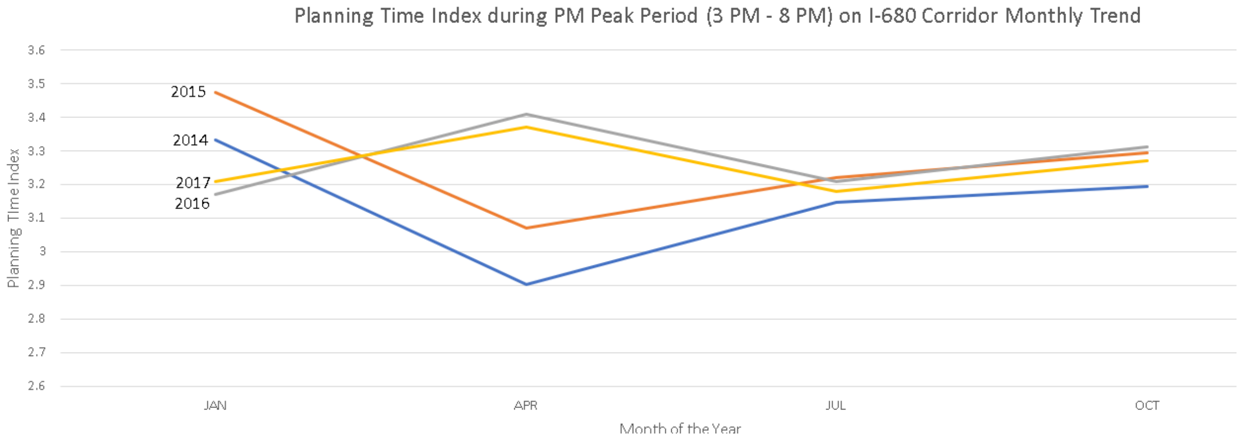


Monthly Variant

Graph 4.3

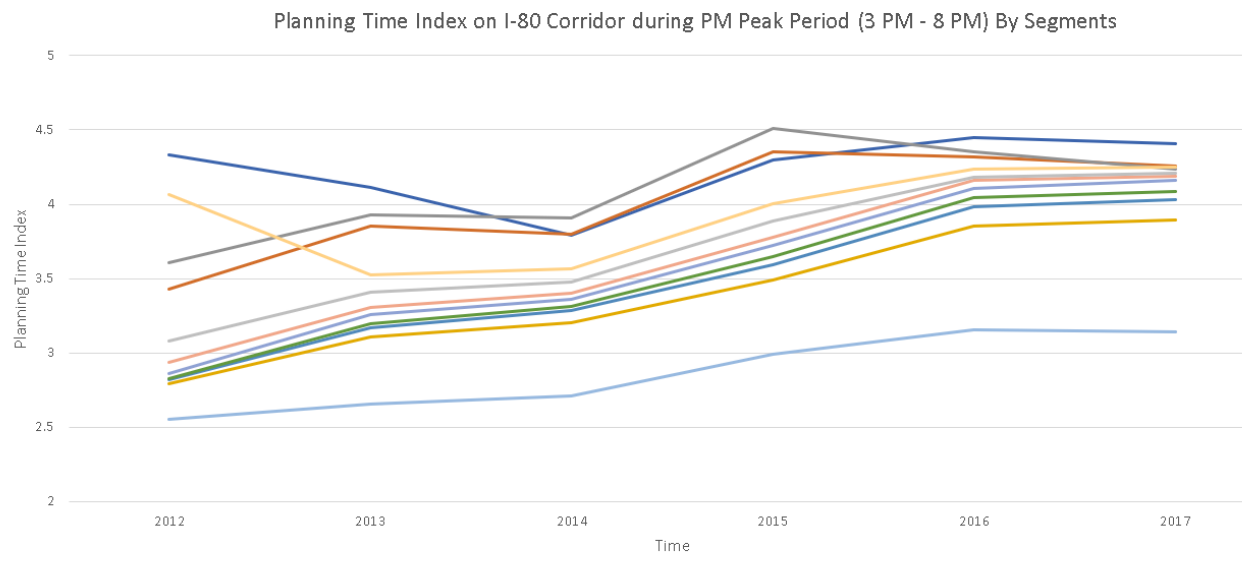


Graph 4.4

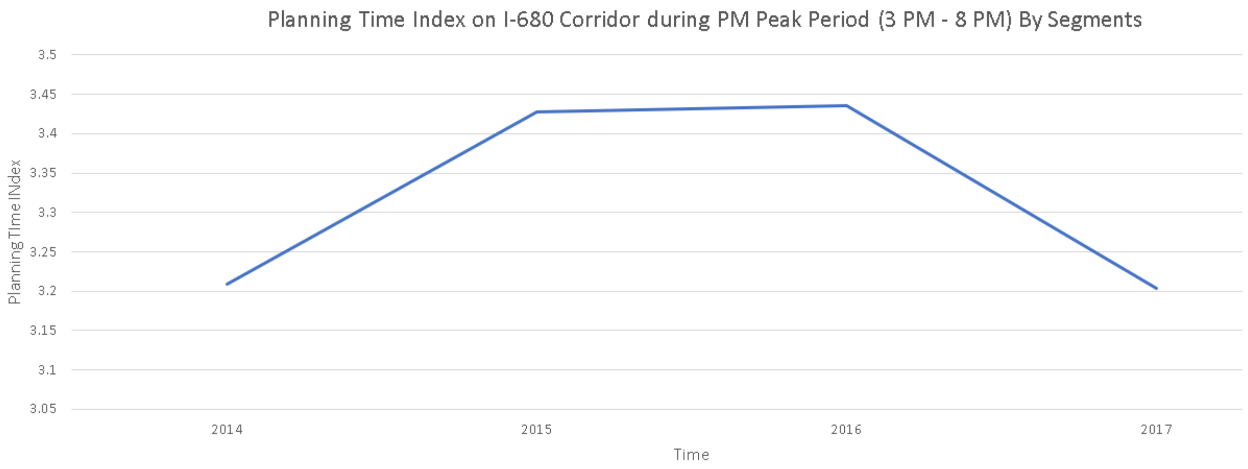


Segment Variant

Graph 4.5



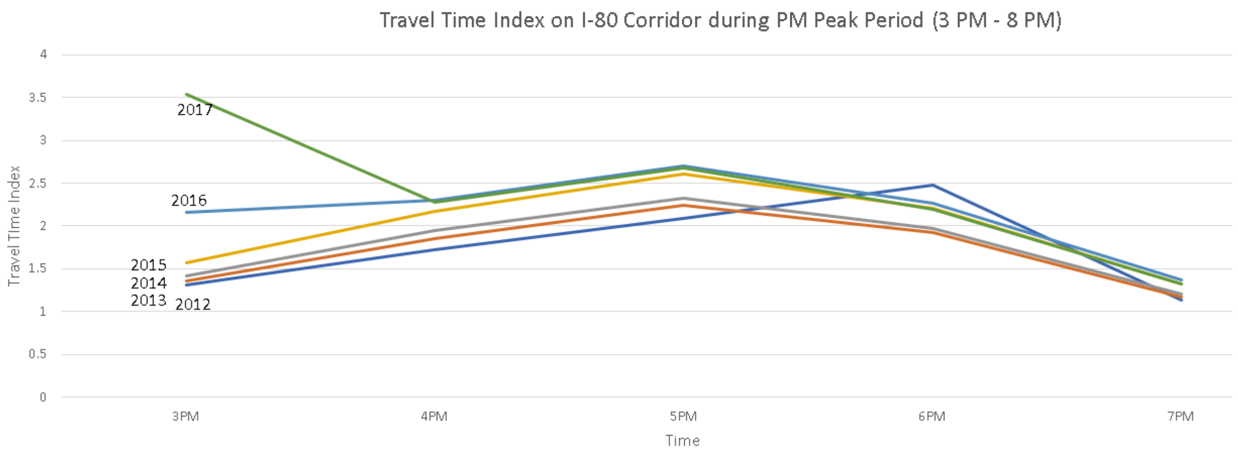
Graph 4.6



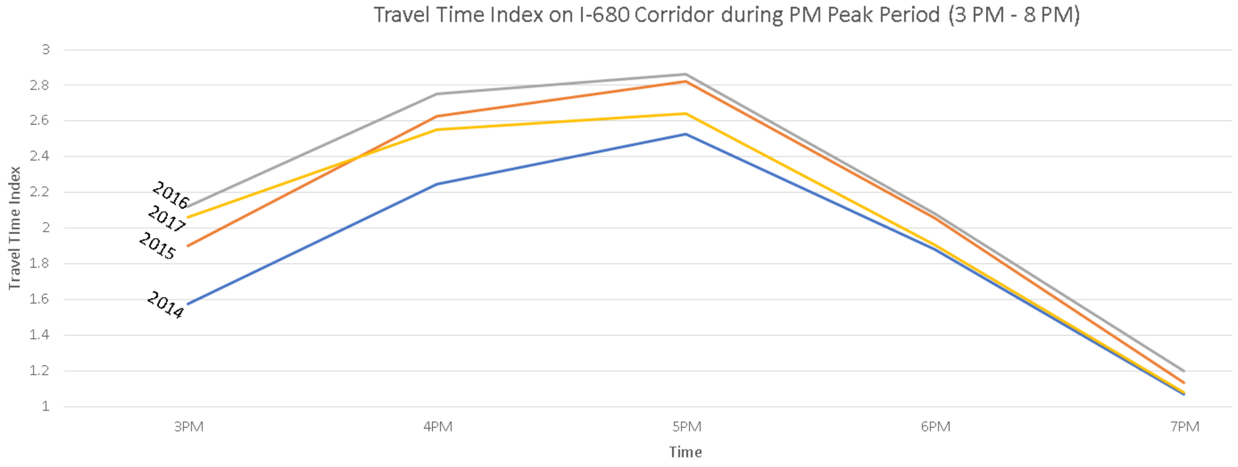
Travel Time Index (Based on Average Travel Time) Index

Time Variant

Graph 5.1

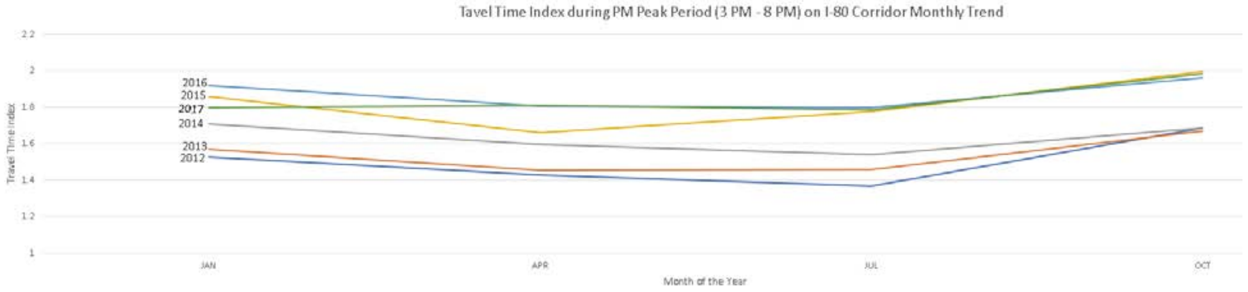


Graph 5.2

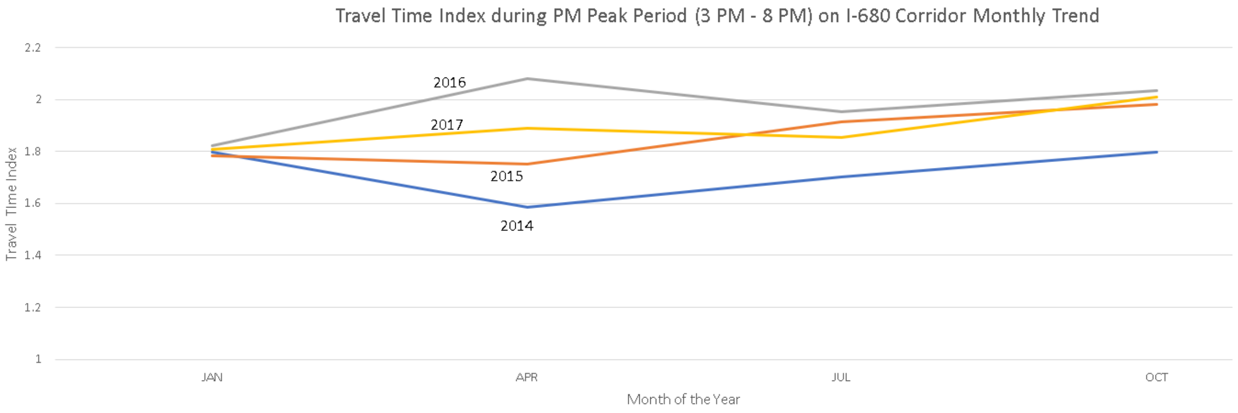


Monthly Variant

Graph 5.3

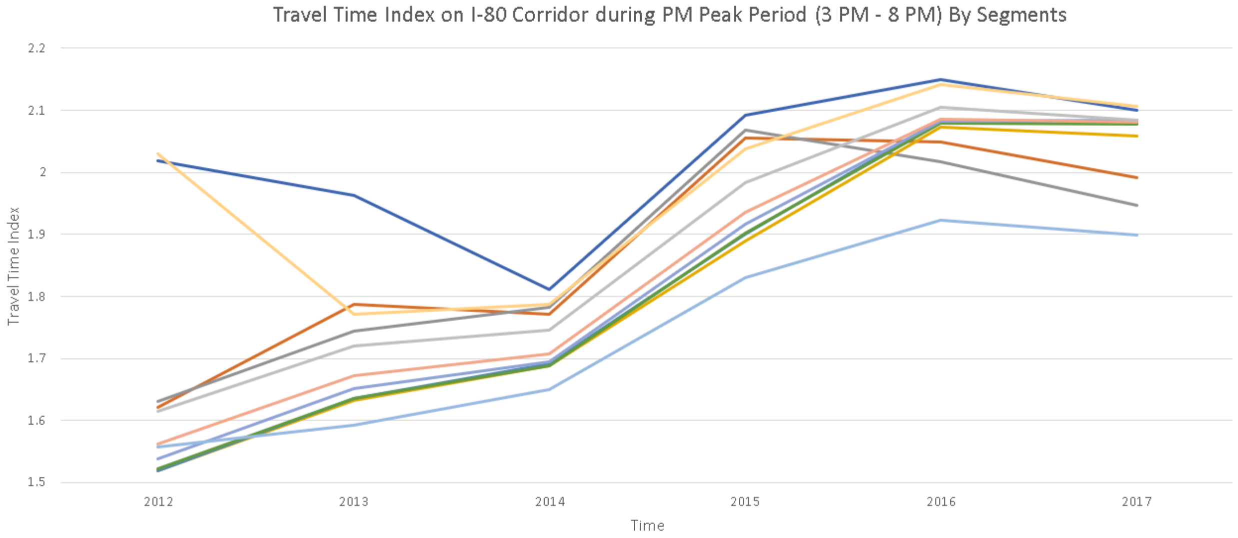


Graph 5.4

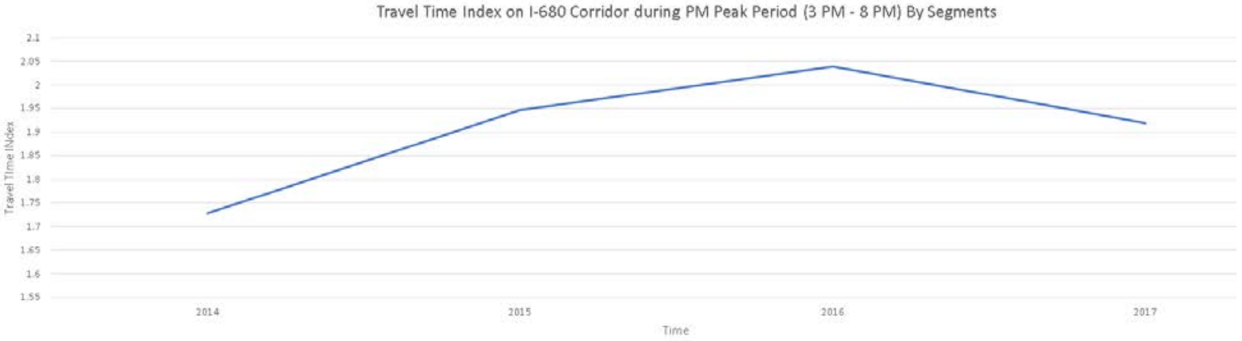


Segment Variant

Graph 5.5



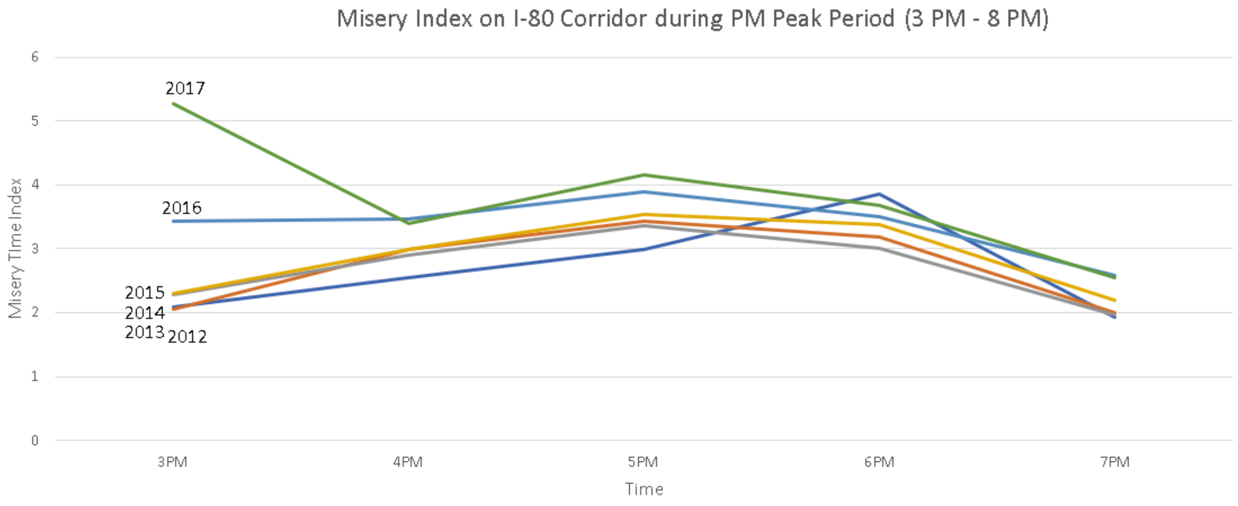
Graph 5.6



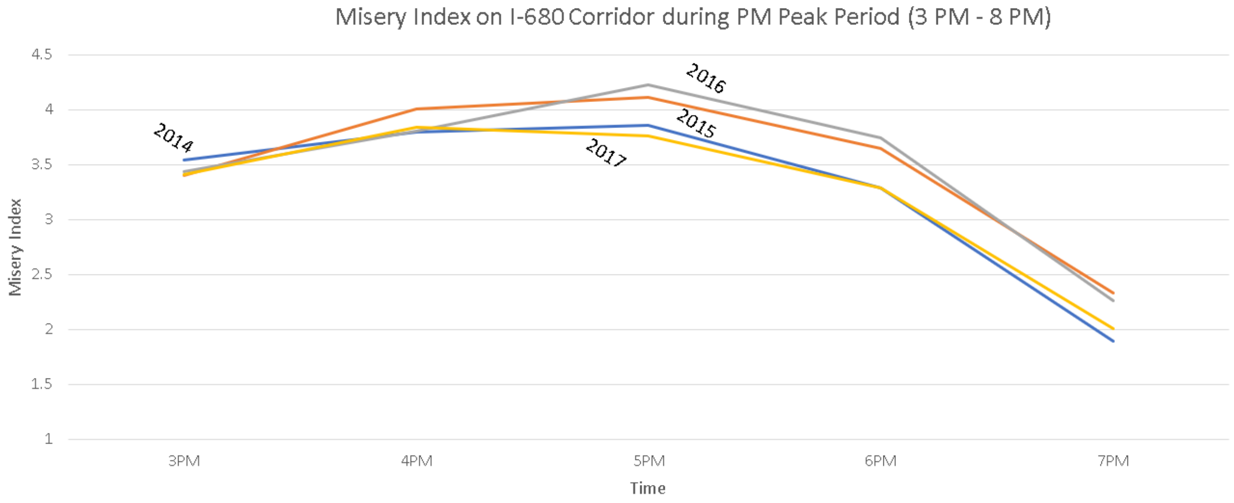
Misery Index

Time Variant

Graph 6.1

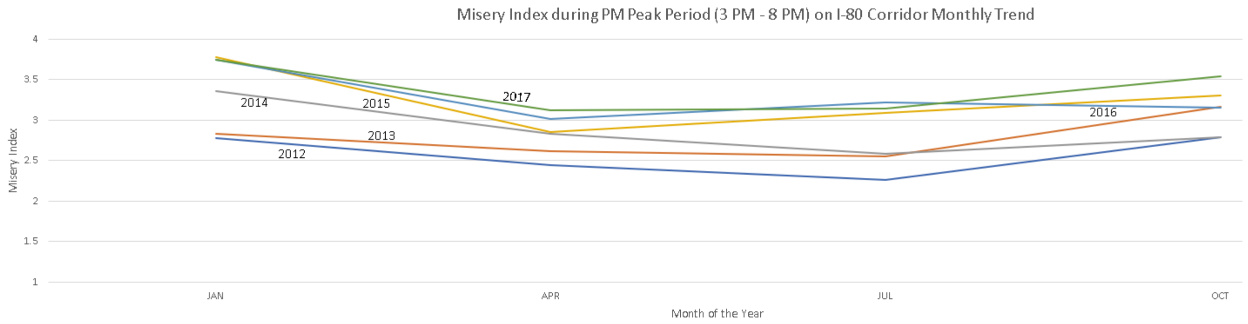


Graph 6.2

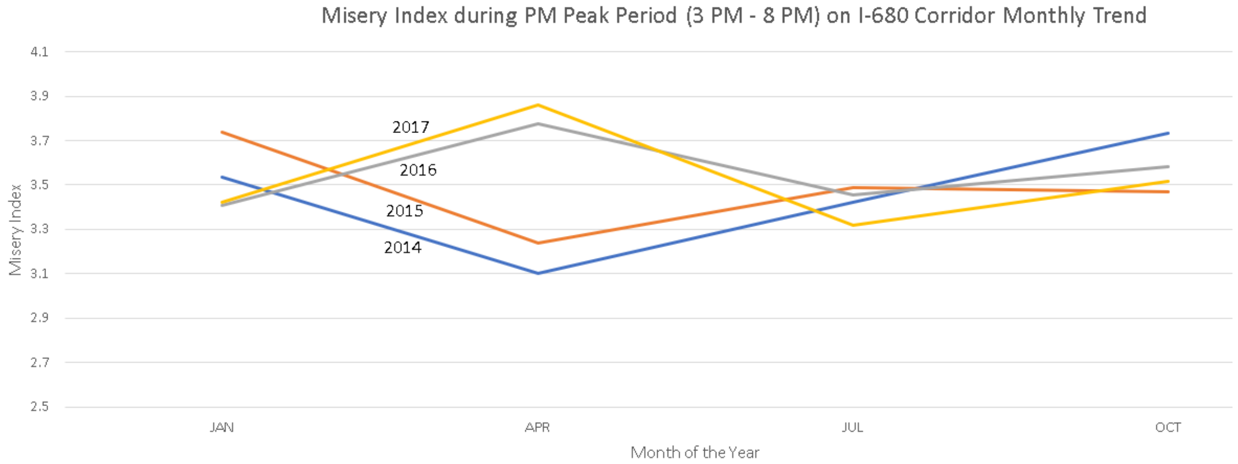


Monthly Variant

Graph 6.3

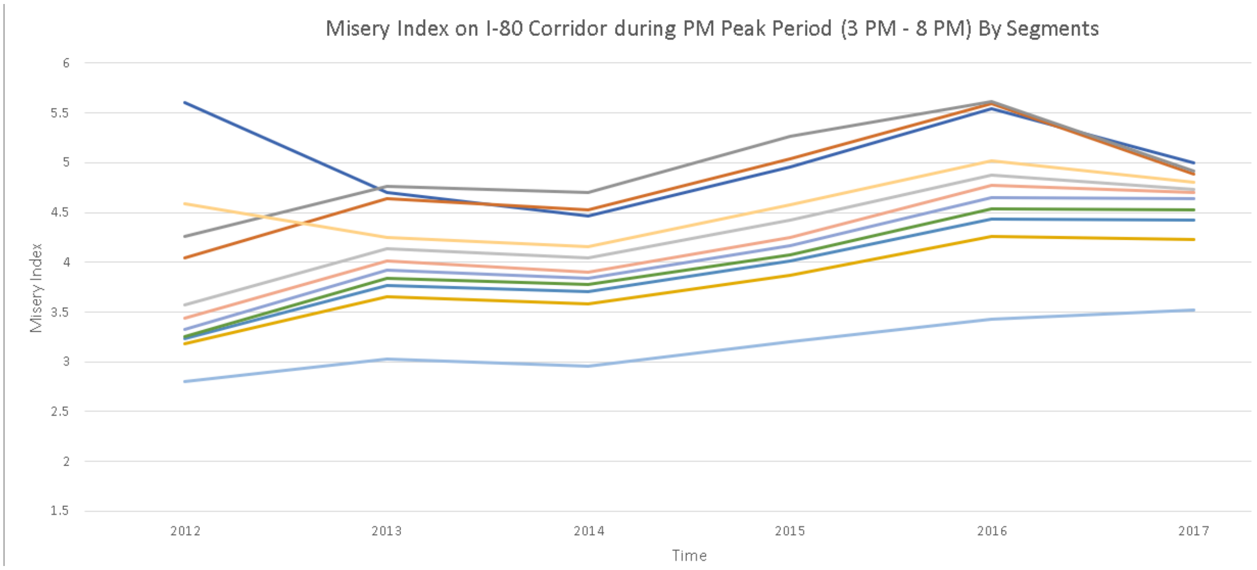


Graph 6.4

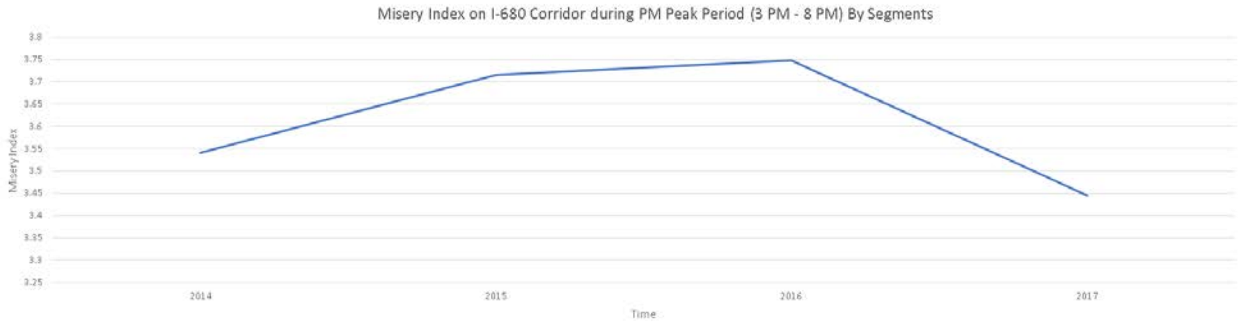


Segment Variant

Graph 6.5



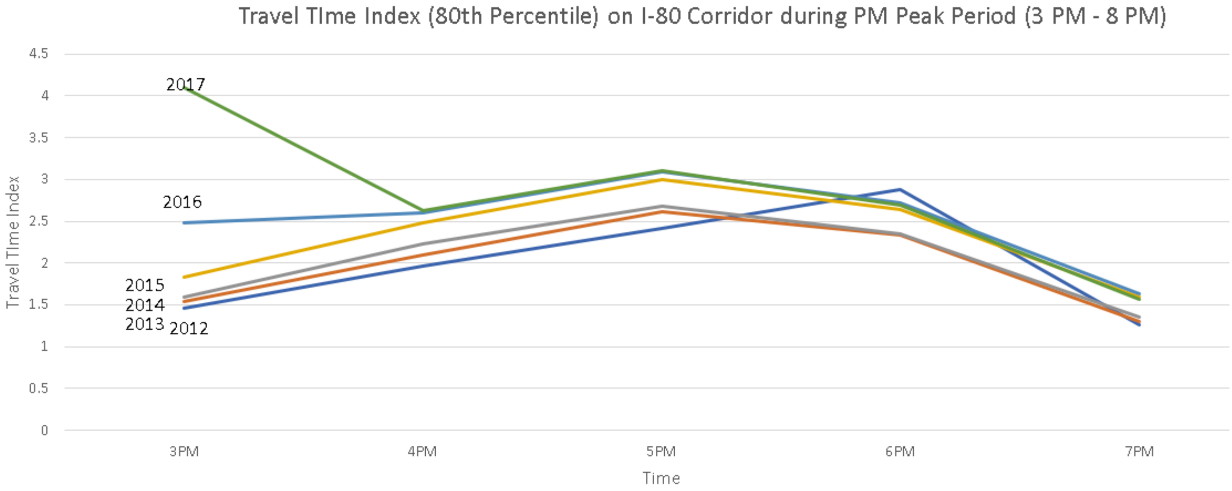
Graph 6.6



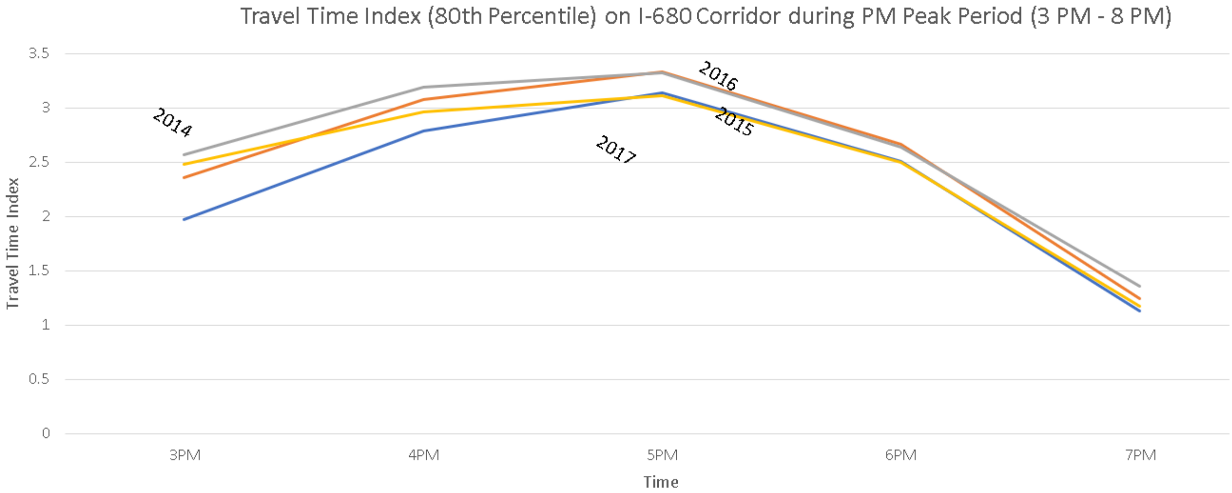
Travel Time Index (Based on 80th Percentile Travel Time)

Time Variant

Graph 7.1

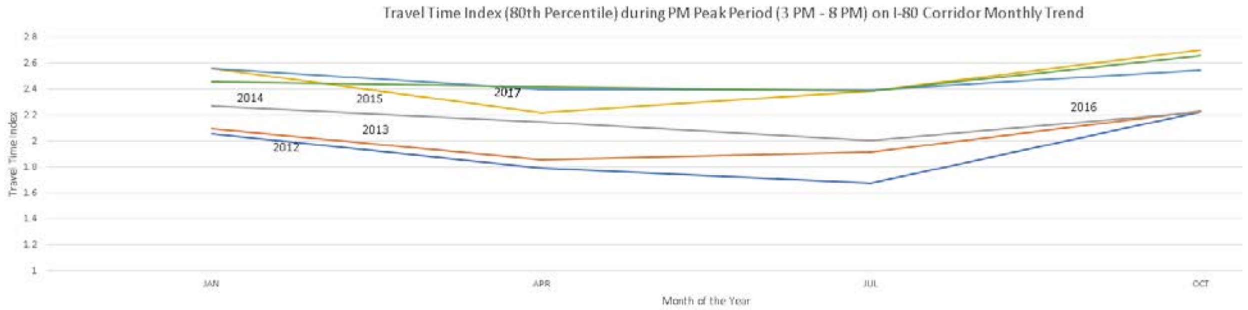


Graph 7.2

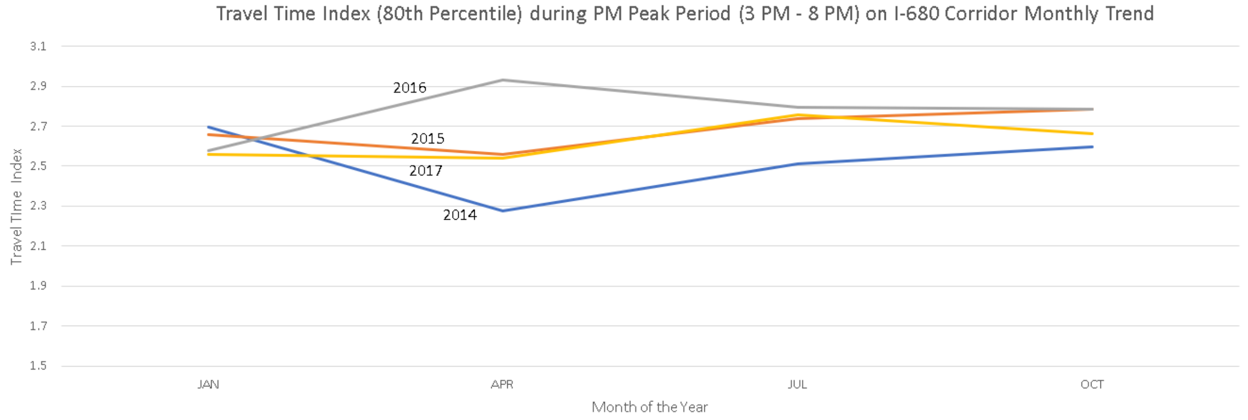


Monthly Variant

Graph 7.3

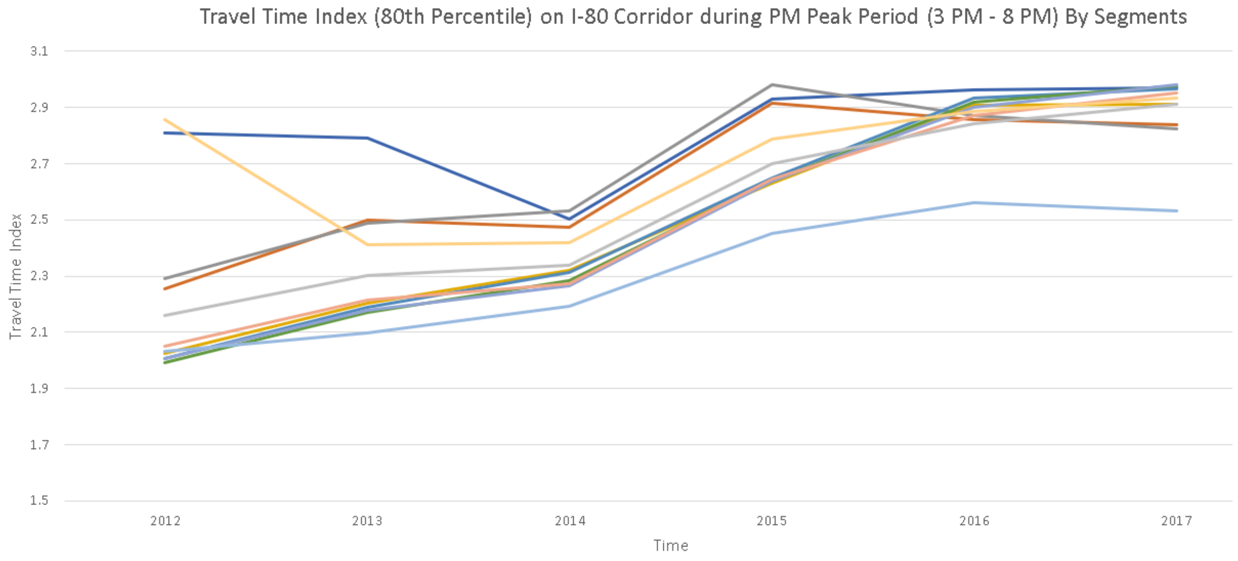


Graph 7.4

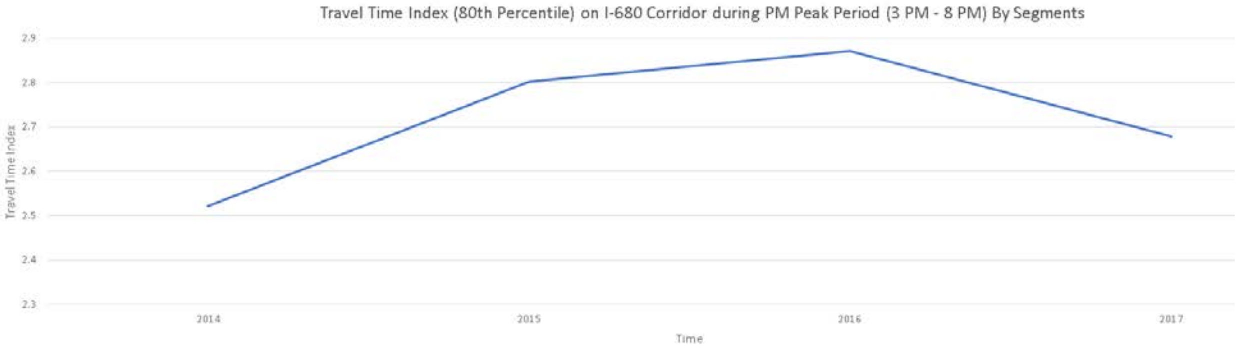


Segment Variant

Graph 7.5



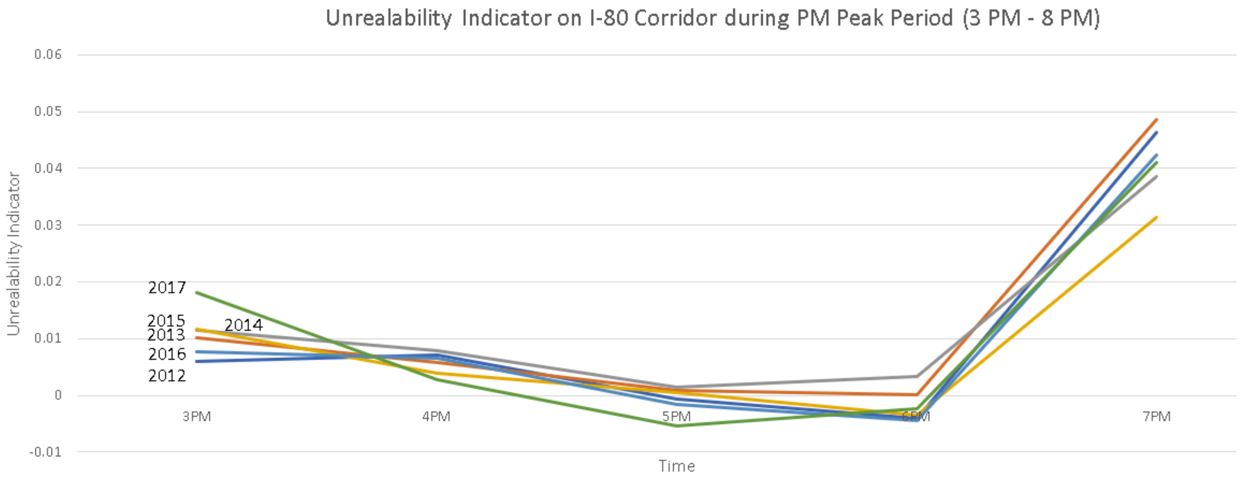
Graph 7.6



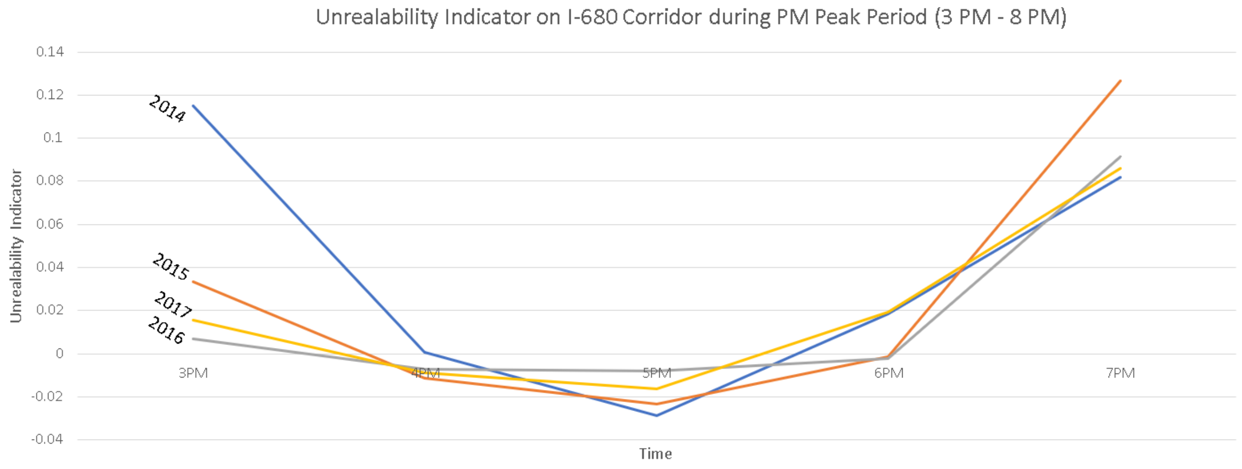
Unreadability Indicator

Time Variant

Graph 8.1

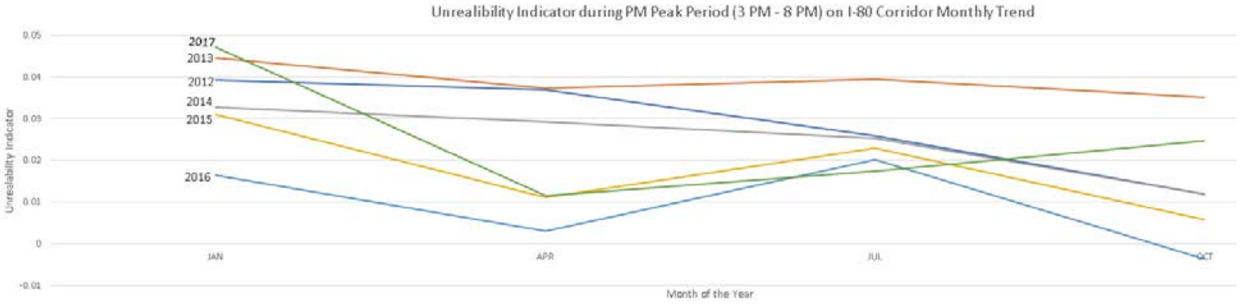


Graph 8.2

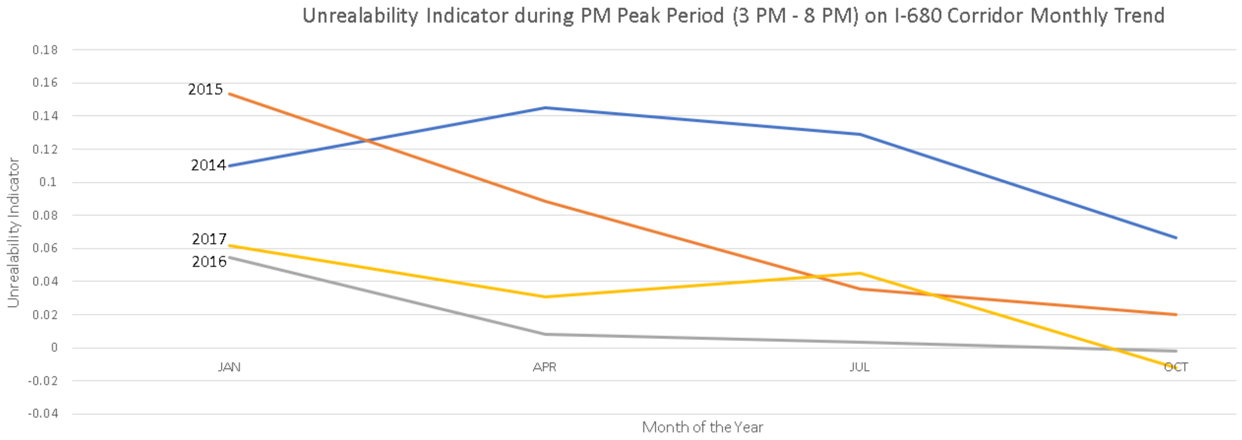


Monthly Variant

Graph 8.3

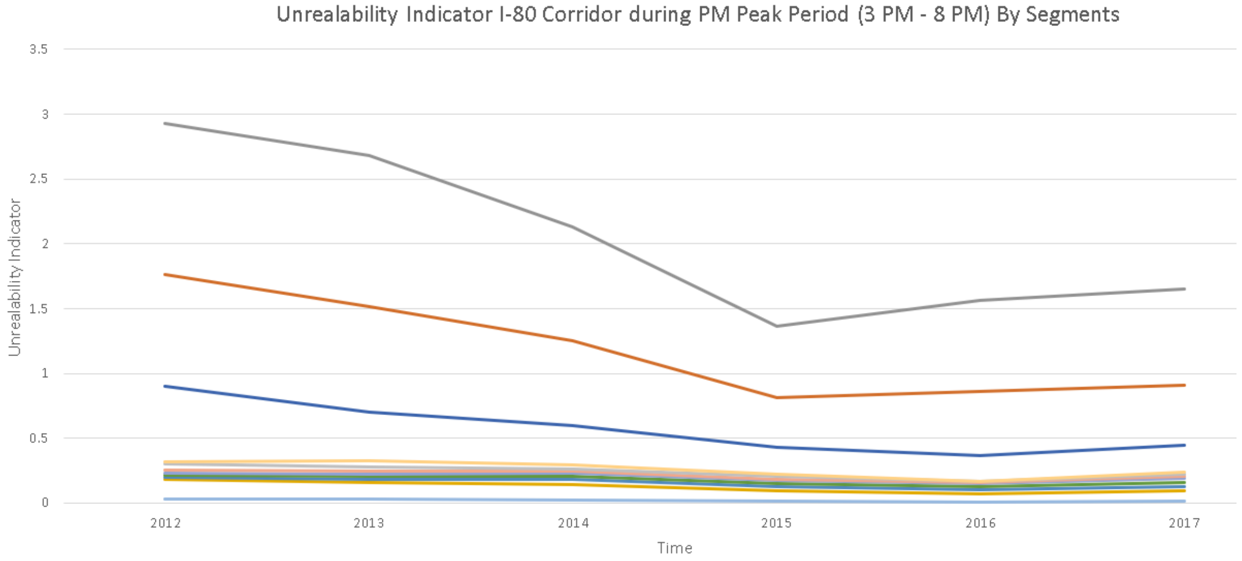


Graph 8.4

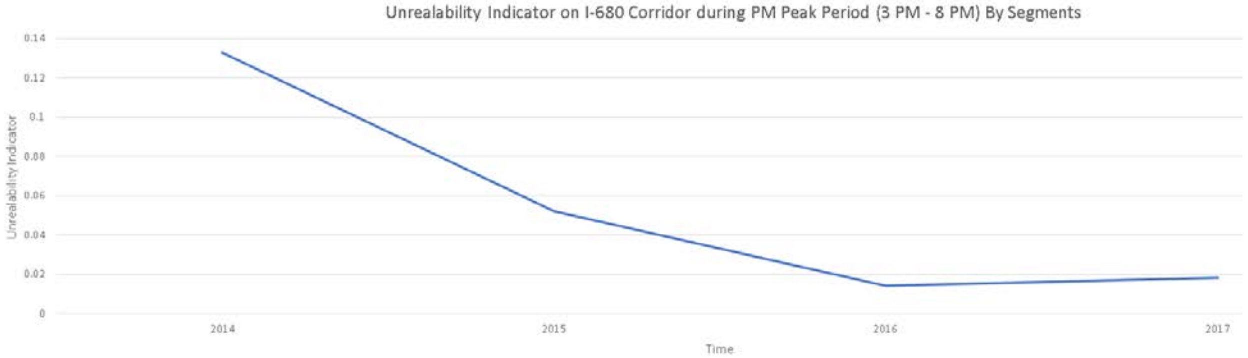


Segment Variant

Graph 8.5



Graph 8.6



User-Survey Analysis

I-80 Adaptive Ramp Metering User Satisfaction Survey

Introduction

Cal Poly, San Luis Obispo partnered with the Metropolitan Transportation Commission to conduct an online survey to evaluate user perceptions and acceptance of the Adaptive Ramp Metering (ARM) implemented on Interstate 80 (I-80) in Alameda and Contra Costa Counties of California. The study section is 19 miles long and extends between the Carquinez Bridge at Crockett at its east end and the San Francisco-Oakland Bay Bridge at its west end. The survey targeted only those who use this section of I-80. Motorists must be 18 or older to participate in the survey.

There were 626 completed and usable survey responses covering a wide yet representative demographic of users. This summary of responses is based on the survey data weighted initially to reflect the age and gender profile of “not-at-fault” motorists recorded from collision reports. The information about composition of driver population on I-80 was deduced using the induced exposure concept proposed by Stamatiadis and Deacon (1997). The induced exposure method uses not-at-fault drivers involved in crashes as a measure of exposure. The concept assumes that at-fault drivers generally belong to a certain group that is prone to commit driving errors while “not-at-fault” drivers represent a random sample of the road user population. We therefore derived sampling weights for cohorts of drivers stratified by age group and gender to reflect each cohort’s representation in the driver population. Further scrutiny revealed a disproportionately high participation of the college-educated in the survey compared to the general population of the area. A second stage weighting adjusted for the distribution of educational level of respondents to match the distribution in the 2016 American Community Survey of the US Census. Appendix 1 has additional details on weighting of survey data.

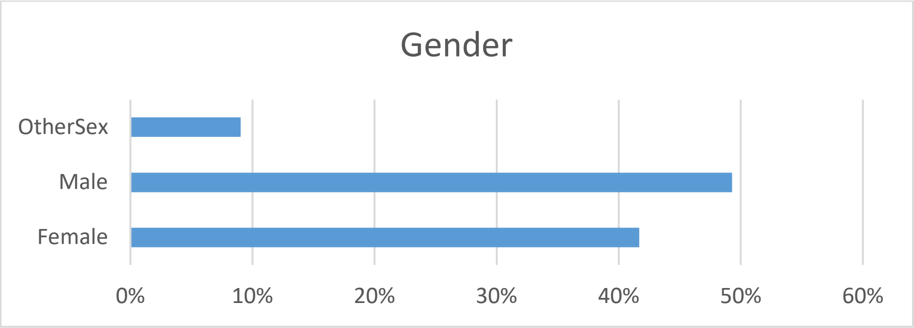
Demographic Profile of Respondents

Examination of the demographic profile of survey respondents revealed a true-to-life distribution of the population in terms of gender and age. This reflects even penetration of outreach to demographic groups.

Gender

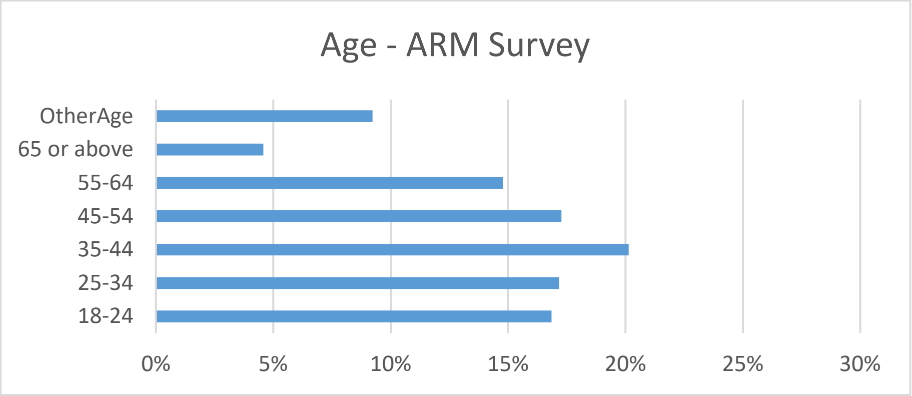
Respondents were well balanced by gender with nearly half (49%) of them male. The survey indicated 42% of females compared to 40% among the “not-at-fault” driving population. It is notable, however, that the 2016 American Community Survey (ACS) of the US Census for the

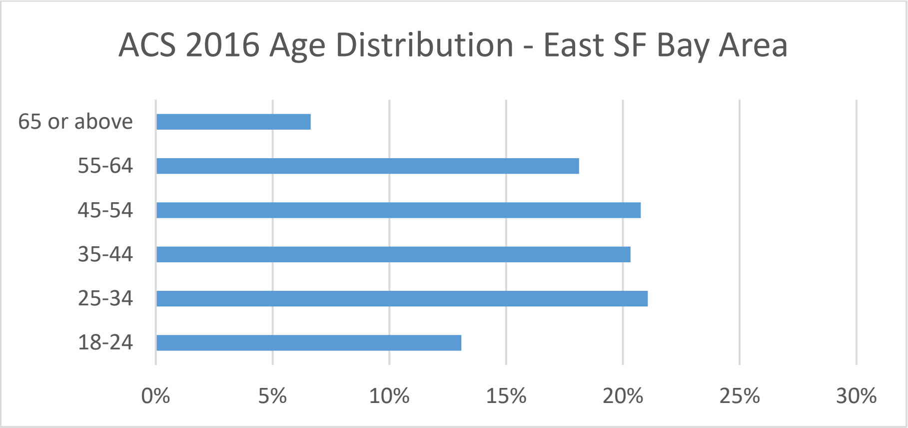
San Francisco Bay Area showed 51% female population of adults (aged 18 and higher), some of whom were not drivers.



Age

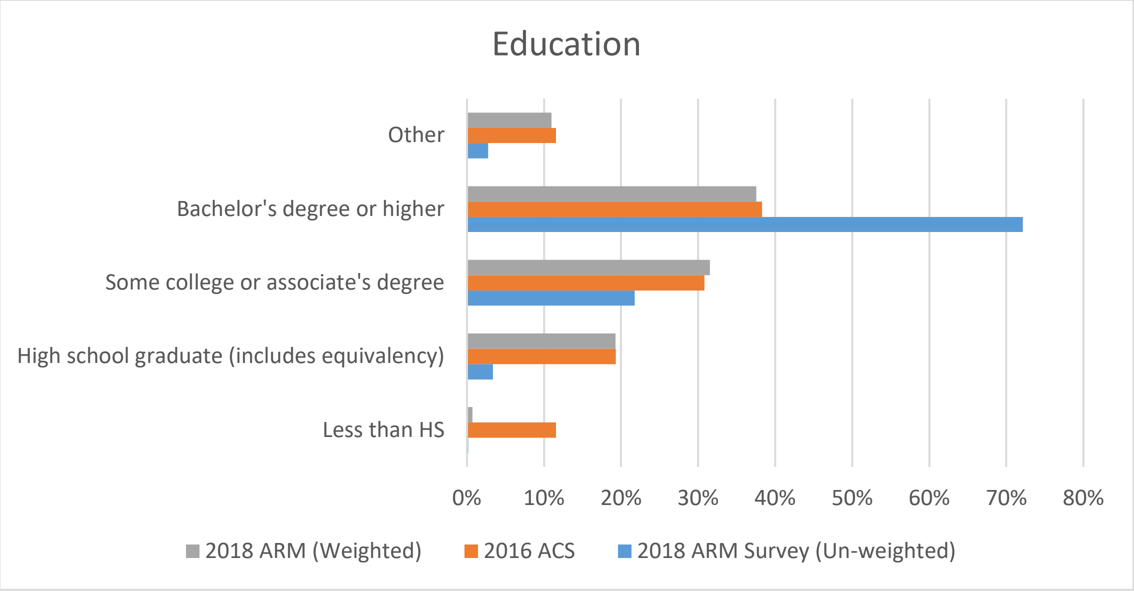
The distribution of respondents by age was fairly normal in shape. The distribution was also quite representative of the 2016 American Community Survey of the US Census for the general population.





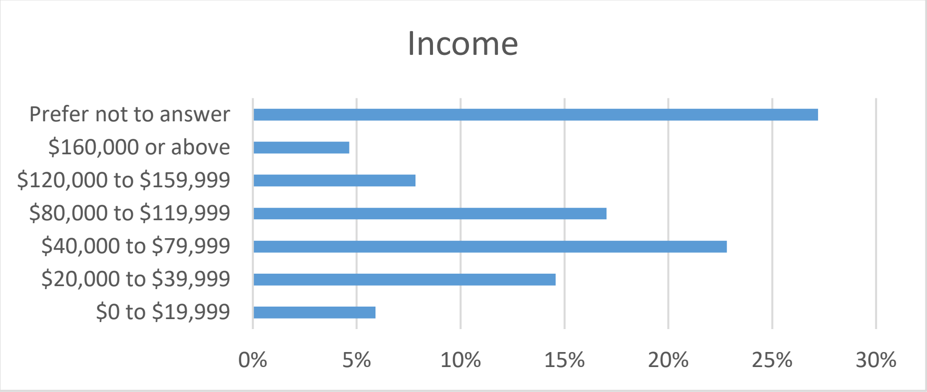
Education

Without correction for education bias, respondents were predominantly college-educated. The 72% respondents with college degrees was five and a half times the 13% in the 2016 ACS of the US Census for the East Bay (Alameda, Contra Costa and Solano Counties) and nearly double that of the San Francisco Metropolitan Area (at 42%). While his implies a more-than-averagely educated group of respondents, correction for education bias among respondents yielded a total of 38% with college degrees, which is close to the value for the San Francisco Metropolitan Area.



Income

Excluding more than a quarter (27%) of respondents who did not answer the income question, the rest were heavily concentrated in the lower and upper mid-income categories; 21% reported incomes below $40,000 a year and 13% reported incomes above $120,000 a year. The distribution was also consistent with the distribution of incomes in the US.

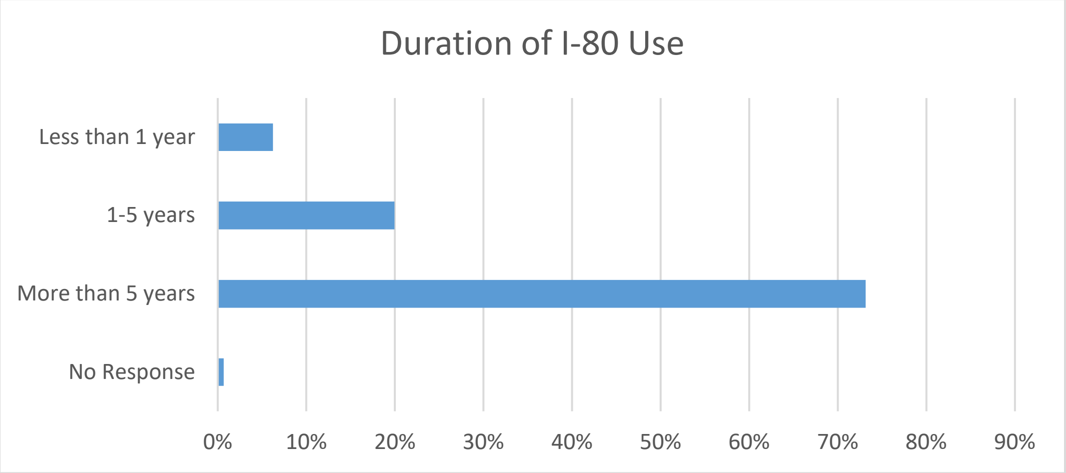


I-80 Use Profile of Respondents

In terms of use, survey respondents were both long-term and habitual users of I-80. This suggests that respondents have had the opportunity to observe travel conditions without and with the ramp metering improvements. This profile of respondents gave strong validity to the information collected.

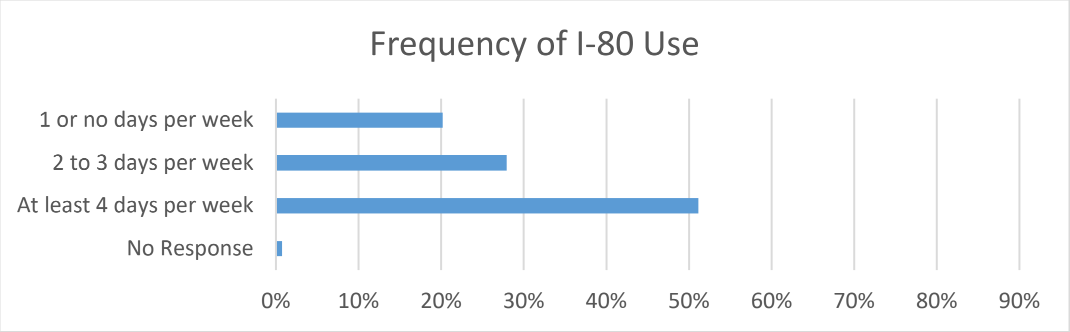
Duration of I-80 Use

Respondents were long-term users with 73% having used it for more than 5 years and 20% having used it for 1 year to 5 years.



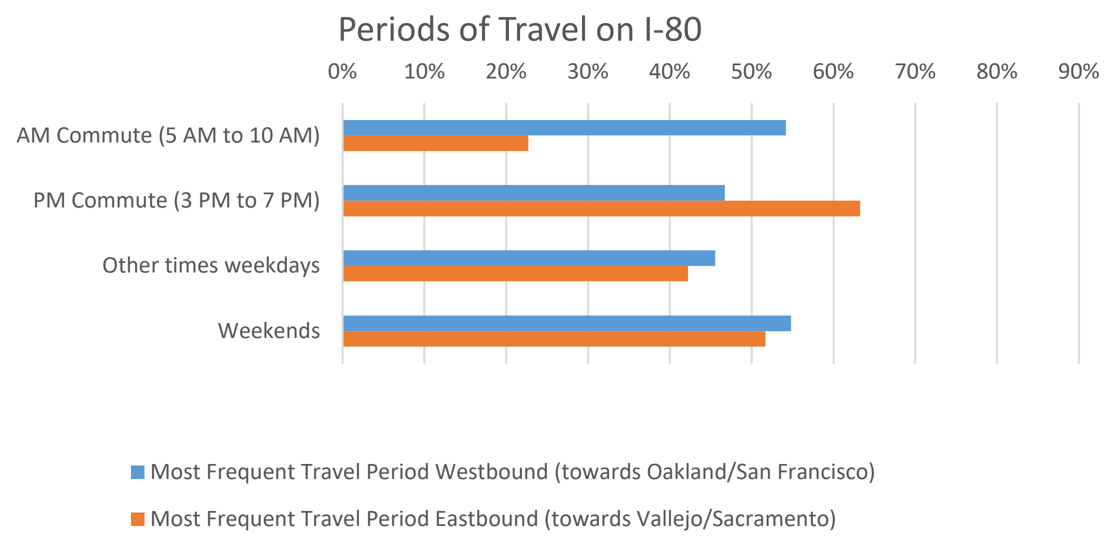
Frequency of I-80 Use

Most respondents were habitual users of I-80 with 51% using it for at least 4 days a week and 28% for 2 days or 3 days a week.



Periods of Travel on I-80

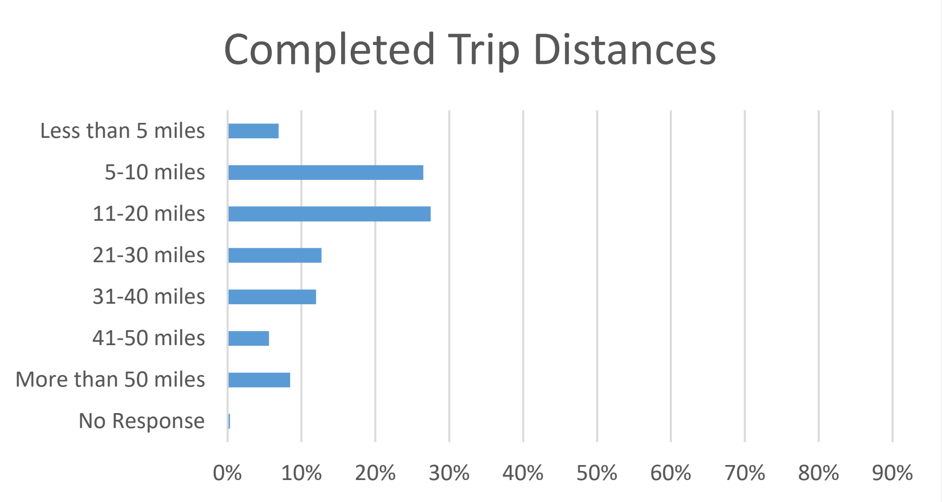
Respondents used I-80 habitually during varied periods of the day throughout the week. Responses confirmed the known phenomenon of concentrated travel westbound toward Oakland/San Francisco in the morning and eastbound in the afternoon. But it is interesting to note almost equally heavy use of the freeway during the off-peak and on weekends. This again lends validity to the observations of survey respondents.



NB: *Multiple responses permitted to each question*

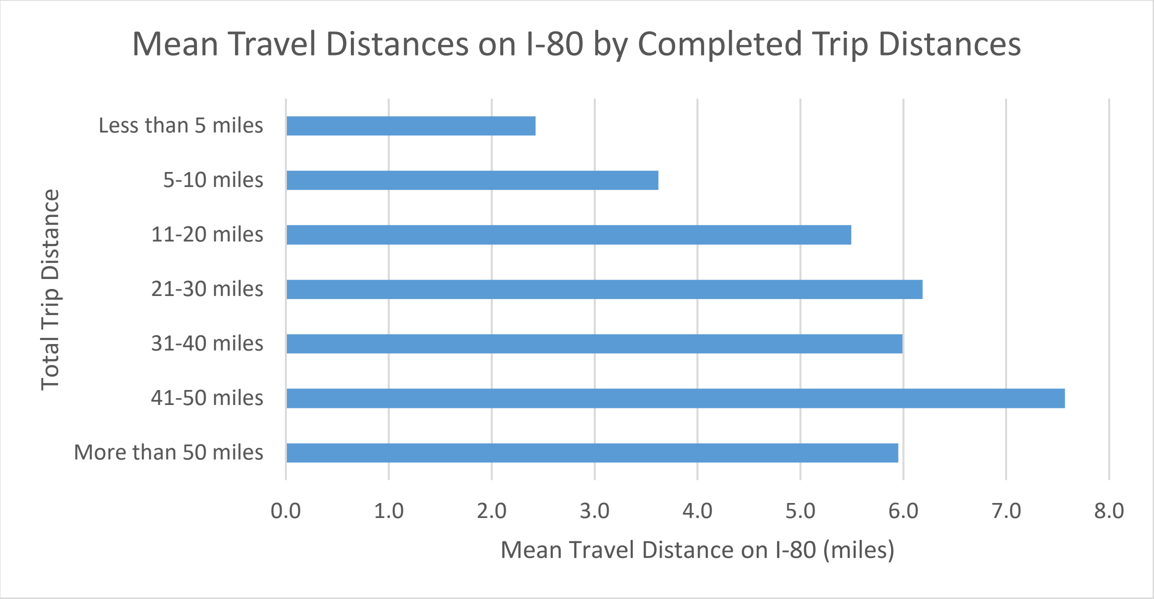
Total Completed Trip Distances including I-80

The profile of respondents reveals that the most common completed trip distances of motorists using I-80 were between 5 miles and 20 miles (54%).



Travel Distances on I-80

Respondents spent varying proportions of the completed trip distances on the I-80 SMART corridor. Out of the average completed trip distance of approximately 20 miles, respondents spent an average of 5.04 mile on I-80, which is 25% of the mean of total trip distances. Individual proportions differed widely with a standard deviation of 5.45 around the mean distance on I-80. It is interesting to note the consistencies among total trip distances and travel distance on I-80. As trip distances increased, mean travel distance on I-80 also increased while proportions of trip distance spent on I-80 fell. The user responses to the question about total trip distance were also consistent with the on and off ramps reported by the users. It provided credibility to the responses obtained and avoids the potential problem of illogically filled out web surveys.

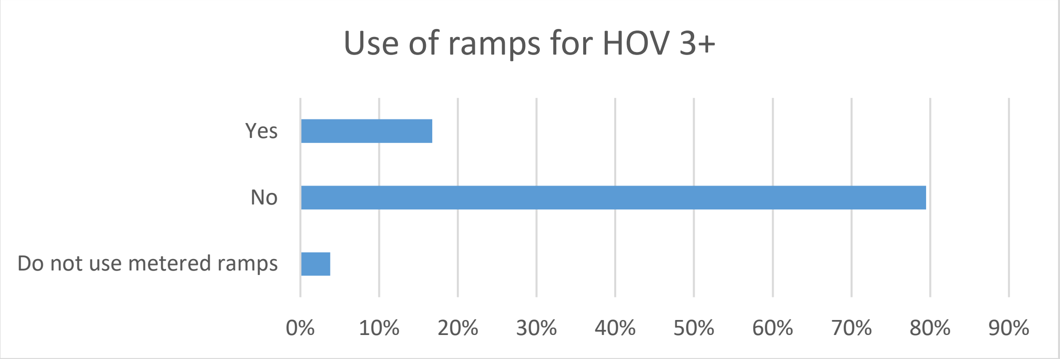


Distribution of Ramp Use along I-80

Respondents were widely distributed across the nearly two dozen ramps in each direction of the study section. There are 43 ON-ramps in both directions of the study section. As expected, there were concentrations of users at major ramps between I-80 and other major highways (e.g. I-80 and CA 4) and at ramps which serve major employment centers (e.g. University Avenue). Appendix 2 includes charts showing distribution of ramp use by direction.

Use of Ramp Meters Designated for "HOV 3+"

Three out of four respondents (79%) did not use the priority ramps for high occupancy vehicles (HOV 3+). This is the segment of motorists typically controlled by the ramp meters. This characteristic again lends credence to the user responses about the adaptive ramp meters.

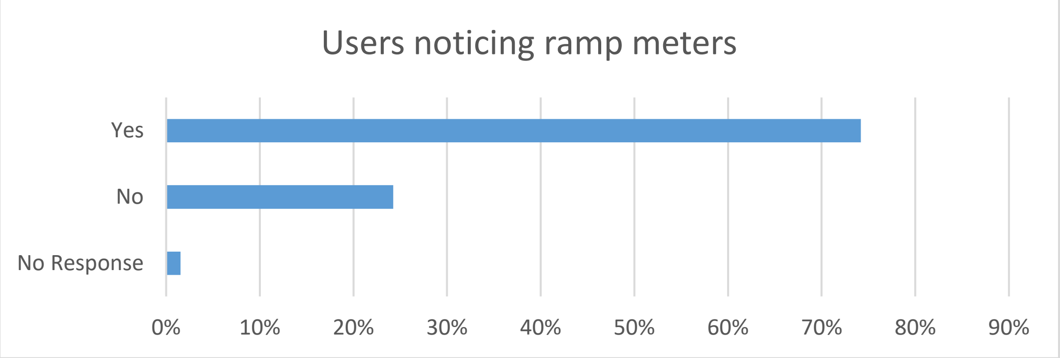


Awareness of Adaptive Ramp Meters

Most survey respondents were aware of the change to an adaptive ramp metering system. This revelation supports the validity of their sentiments about expected results from the ramp metering project.

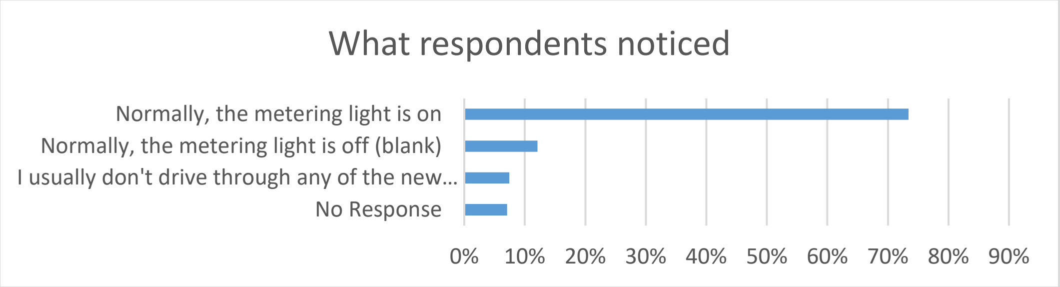
Users notice of ramp meters

Nearly three quarters (74%) of survey respondents confirmed having noticed the change to the ramp meters.



What respondents noticed

Consistent with noticing the change, 73% of respondents reported that the metering signals were “normally on” when they were getting onto I-80.



Drilling a little further, the majority of all those who noticed a change to the ramp meters indicated that the meters were on (63%) seven times as often as those who indicated the meters were off (9%). Even those who did not notice the change confirmed that the meters were on (10%) three times more often than off (3%) when using the study section of I-80.

What noticed		**Notice of change**		
	No Response	**No**	**Yes**	**Total**
No Response	1%	6%	0%	7%
I usually don't drive through any of the new ramp meters on this section	0%	5%	3%	7%
Normally, the metering light is off (blank)	0%	3%	9%	12%
Normally, the metering light is on	1%	10%	63%	73%
All Respondents	2%	24%	74%	100%

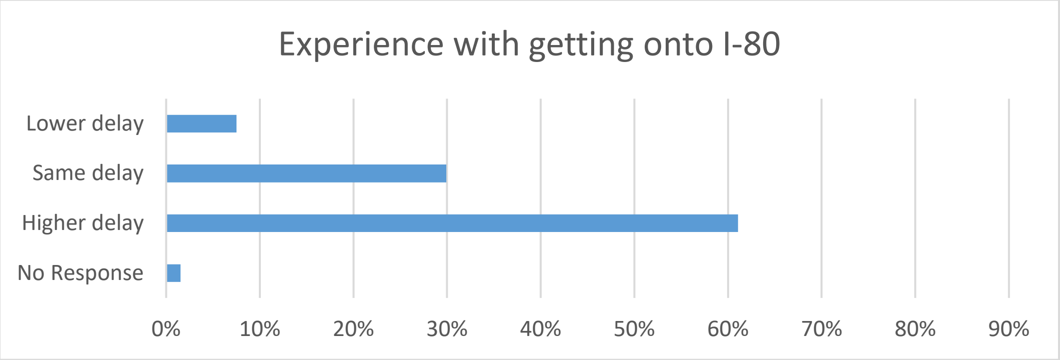
User Experiences of Survey Respondents

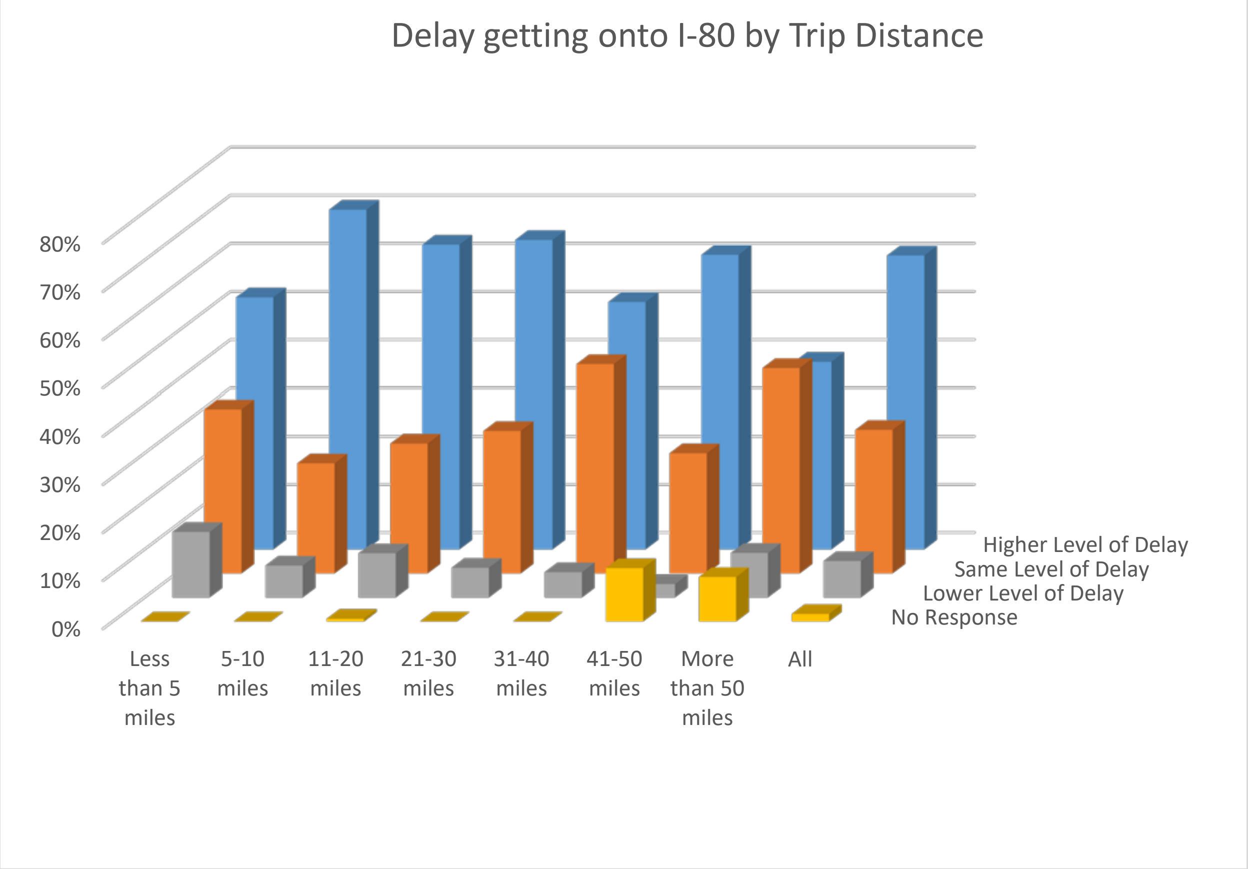
The majority of survey respondents have not registered improvements in delay associated with travel on I-80. Less than 10% reported any reduction in delay due to the adaptive ramp metering project.

Experience with getting onto I-80

Three out five respondents (61%) reported higher delays when getting onto I-80 with the new ramp meters while additional 30% reported experiencing the same level of delay.

Digging a little deeper, examination of reported user experience by completed trip distance revealed some variability. Chi-Square tests indicate that differences were statistically significant although patterns were not clearly defined.

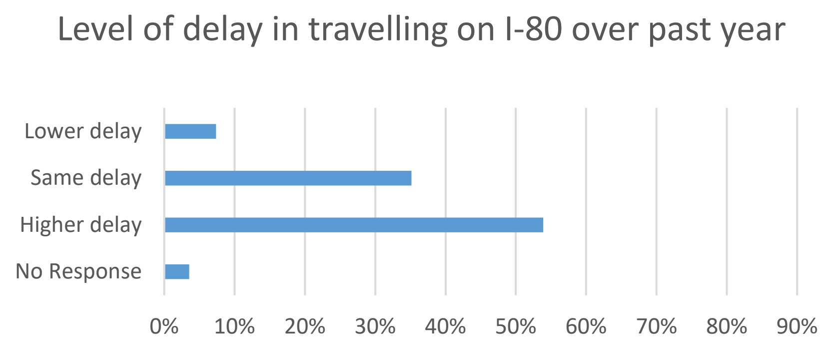




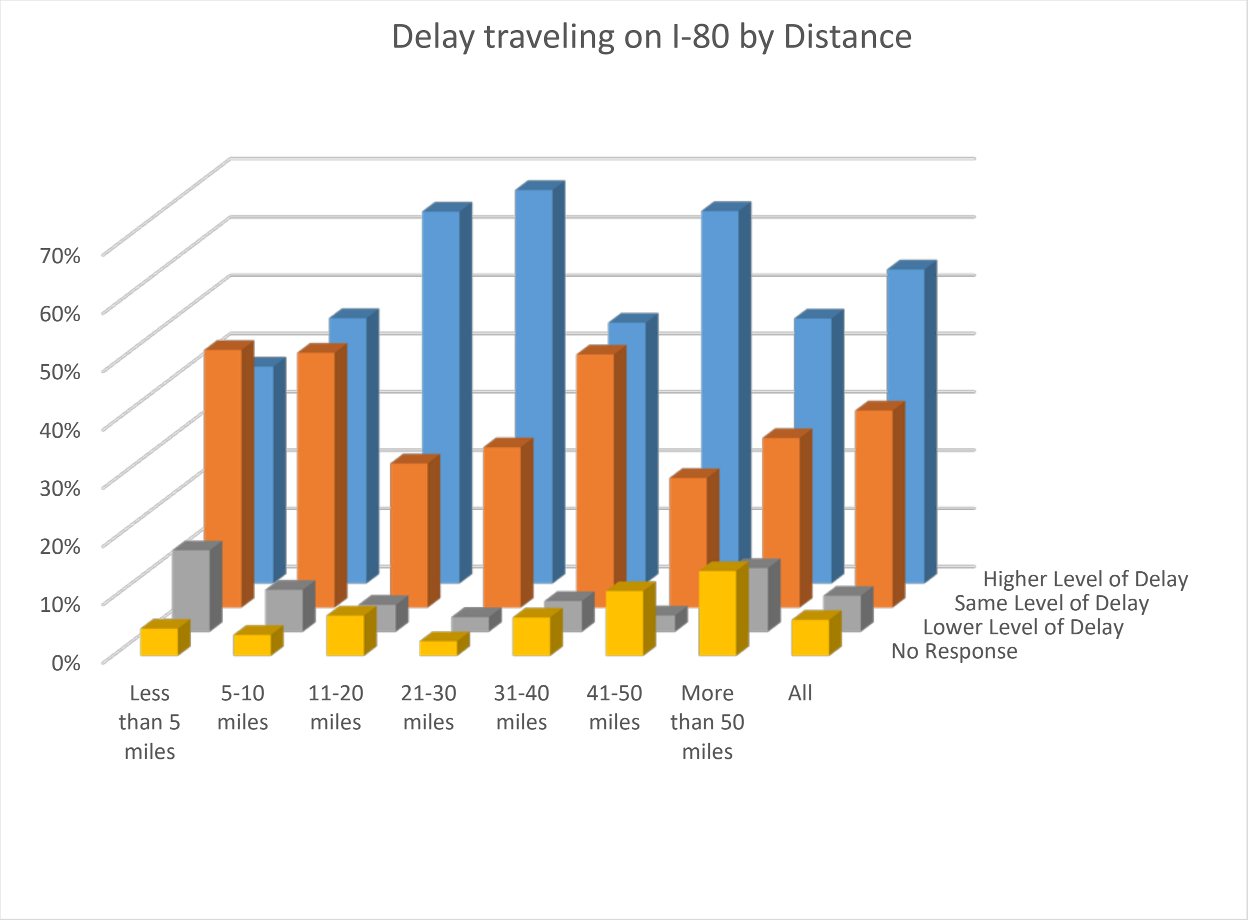
Level of delay in travelling on I-80 over past year

Similar to level of delay getting onto I-80, nearly 3 out of 5 respondents (56%) reported higher delay traveling on I-80 within the past year when the new ramp meters were installed while additional 36% reported experiencing the same level of delay on the mainline.

Examination of reported user experience by completed trip distance revealed some variability in level of delay while travelling on I-80. Chi-Square tests revealed that differences were statistically significant.

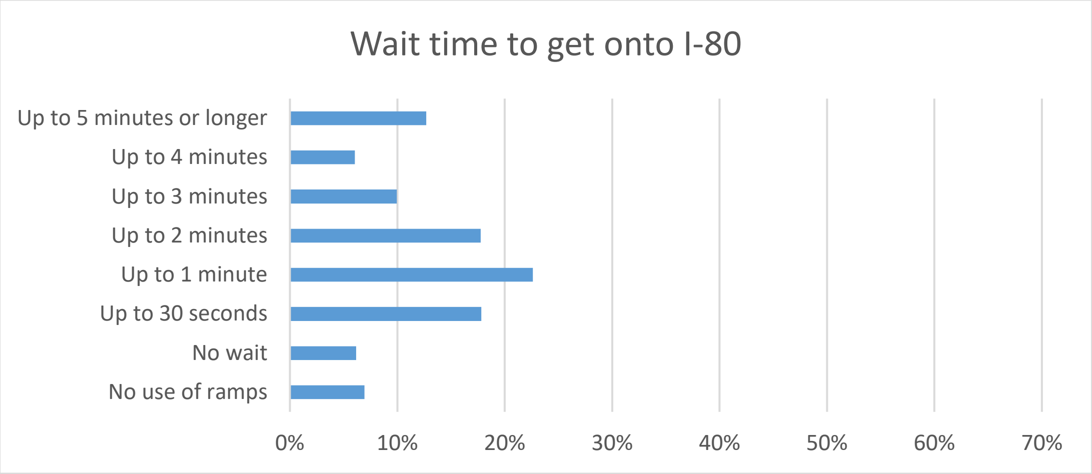


NB: *Multiple responses permitted to the question*



Wait time to get onto I-80

Respondents indicated relatively short wait times at ramp meters with 59% concentrated in the wait times between 30 seconds and 2 minutes. The average wait times were approximately 1 minute long even though a noticeable 13% waited for 5 minutes or longer.

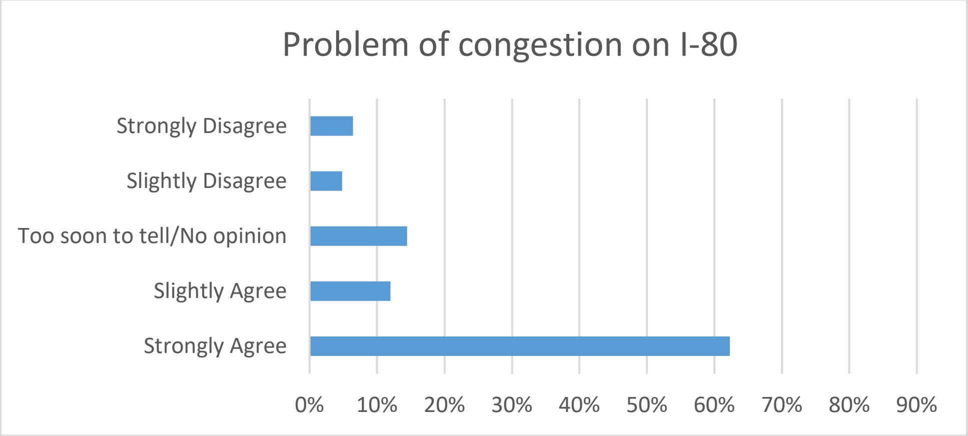


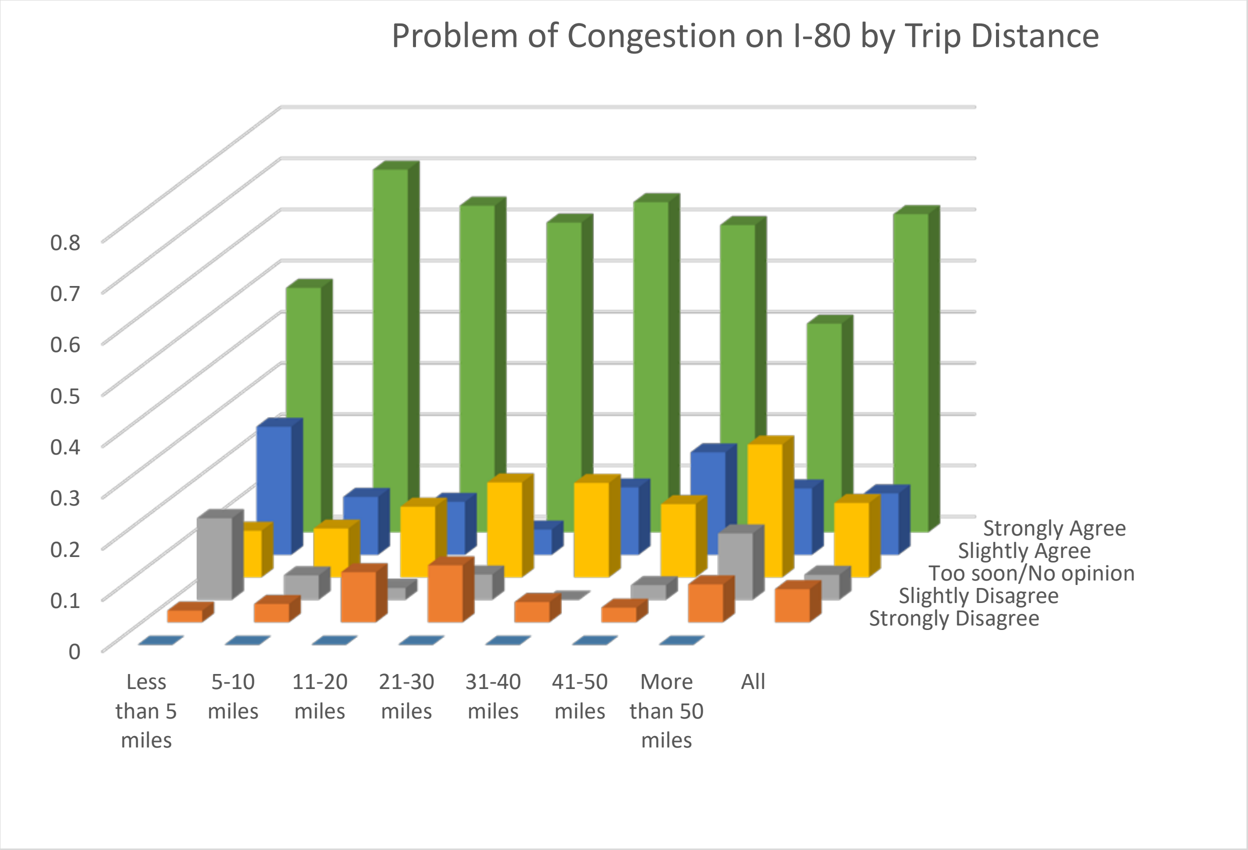
User Sentiments of Survey Respondents

Overall, survey respondents were so far less than enthusiastic in their agreement with many of the positive expectations from the adaptive ramp metering project.

Problem of congestion on I-80

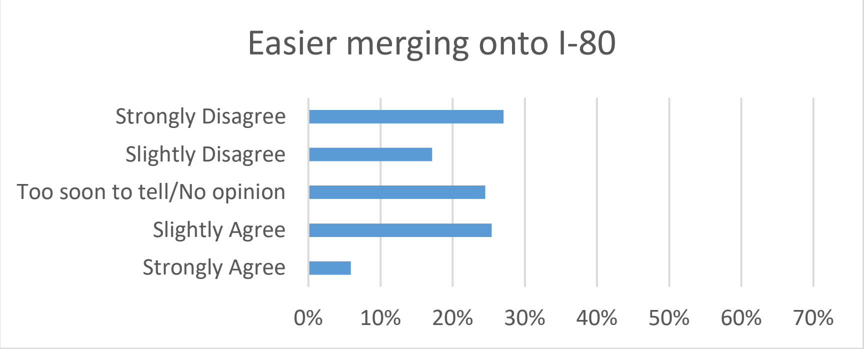
Respondents overwhelmingly (74%) held the strong opinion that congestion remained a problem in the I-80 corridor. Differences by trip distance were not statistically significant.





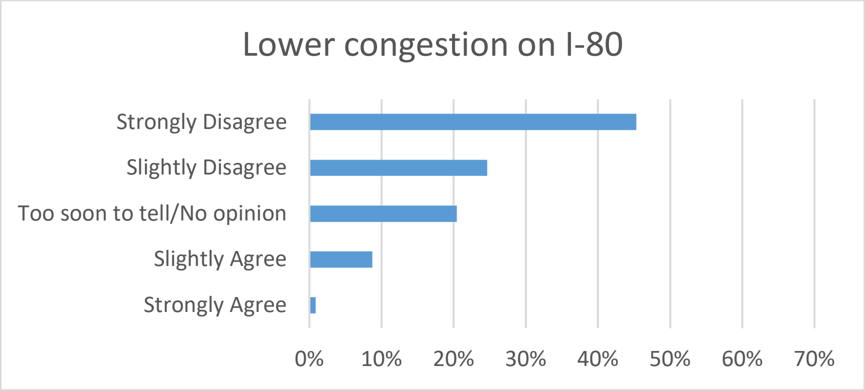
Easier merging onto I-80

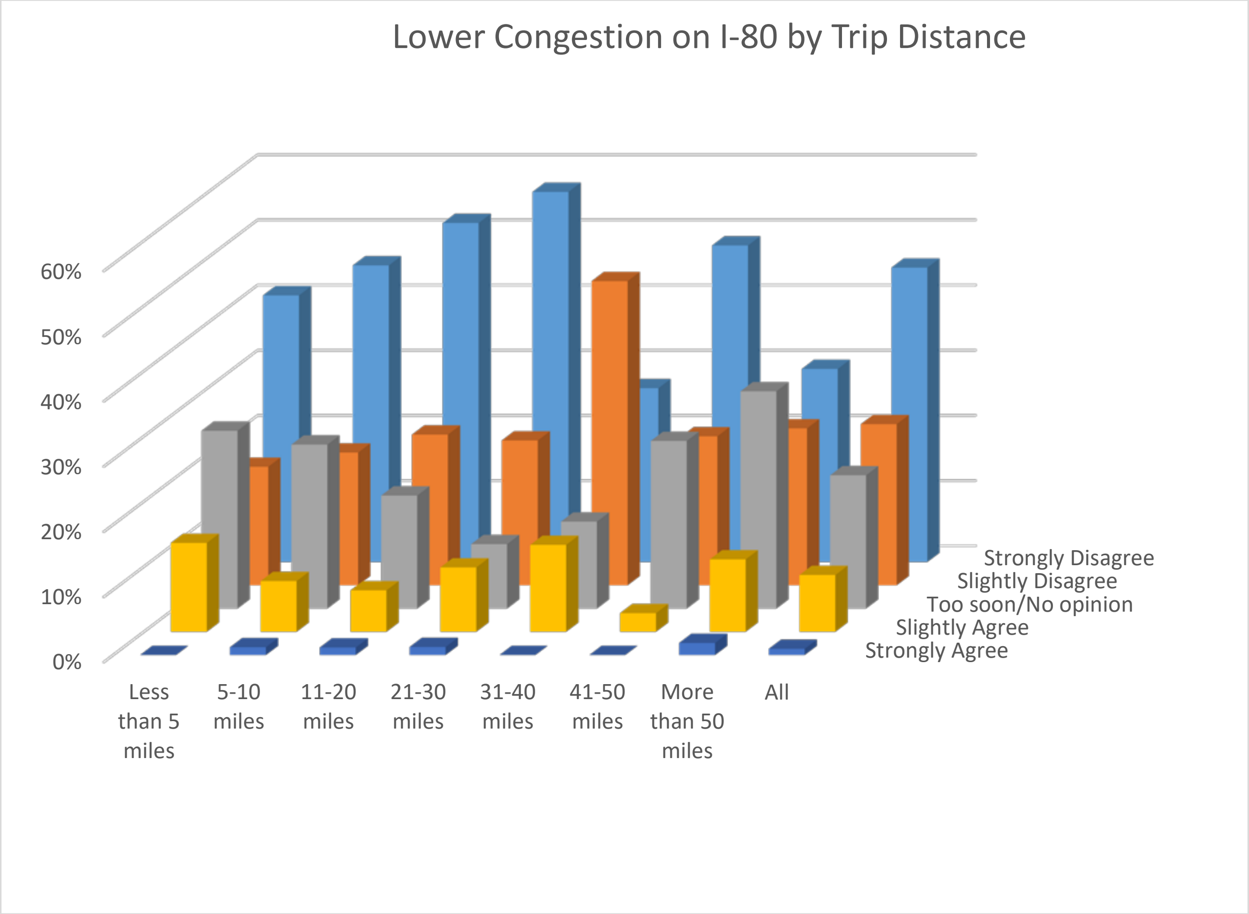
Respondents were divided on the statement of easier merge onto I-80 with 31% agreeing, 25% no opinion, and 44% disagreeing.



Lower congestion on I-80

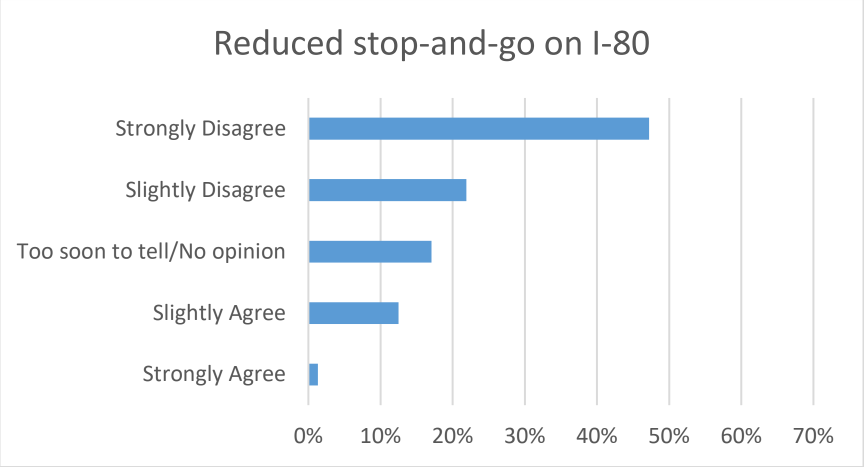
Respondents predominantly disagreed (70%) with the statement of lower congestion on I-80. A tiny minority (10%) agreed while the rest had no opinion on the statement.

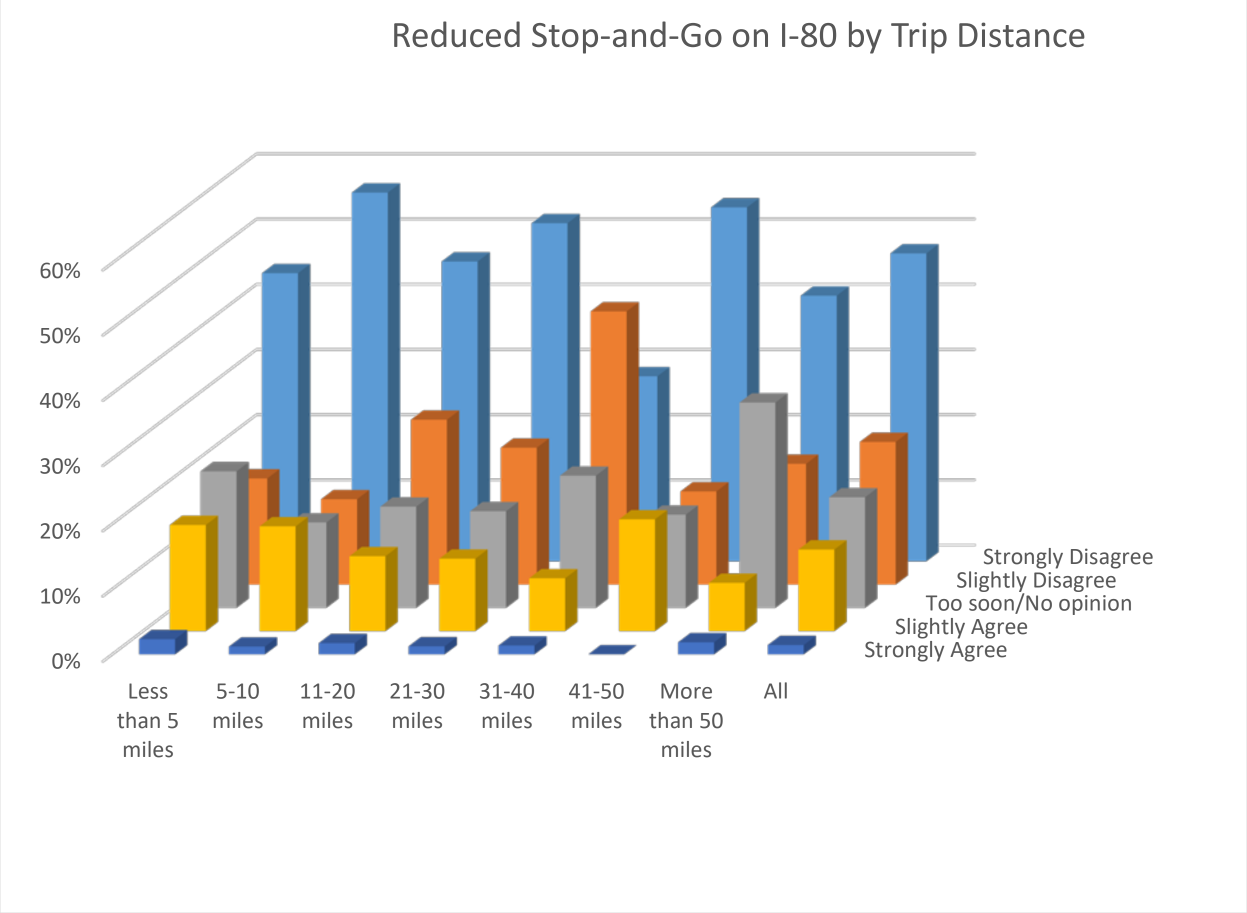




Reduced stop-and-go on I-80

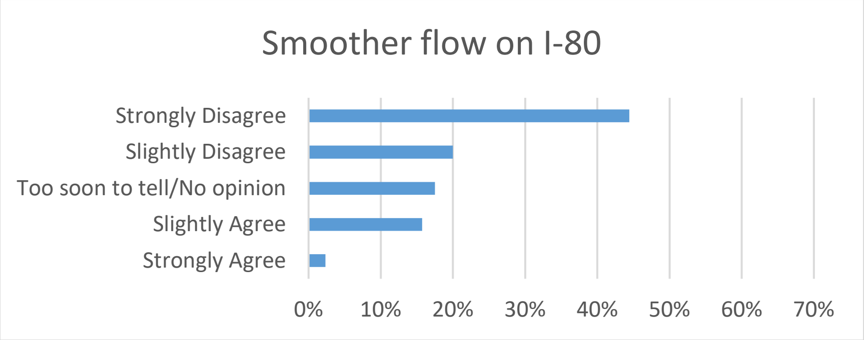
A majority of 7 out of 10 respondents (69%) disagreed with the statement of lower stop-and-go conditions while 17% had no opinion and the 14% who agreed, mainly did so slightly. Nearly half of the respondents (47%) disagreed strongly.

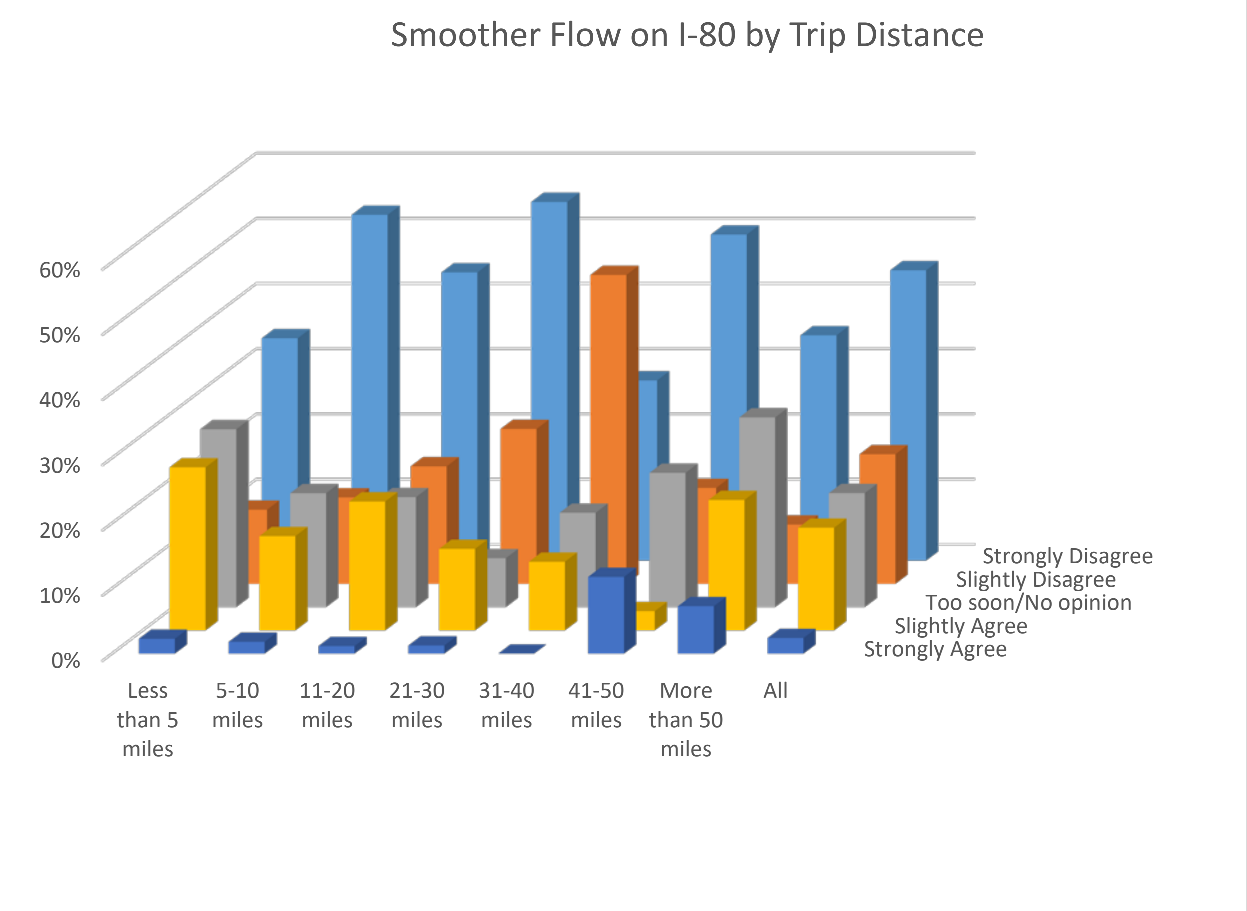




Smoother flow on I-80

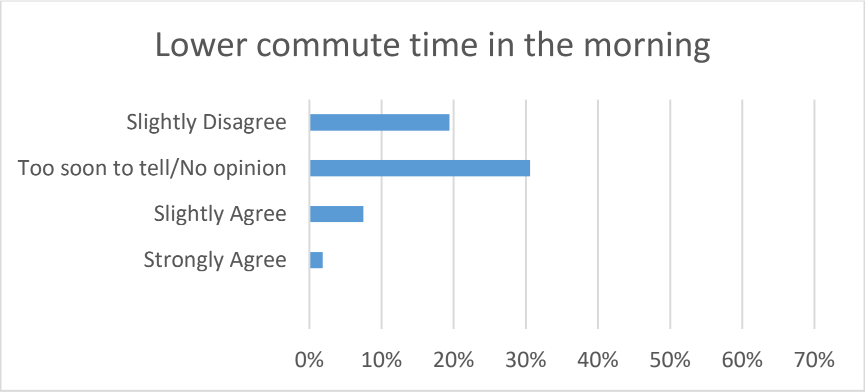
Although two-thirds of respondents (64%) disagreed with the statement of smother flow conditions on I-80 and 18% had no opinion, a noticeable 18% agreed, but only slightly. The responses to this statement are very consistent with the statement on stop-n-go.

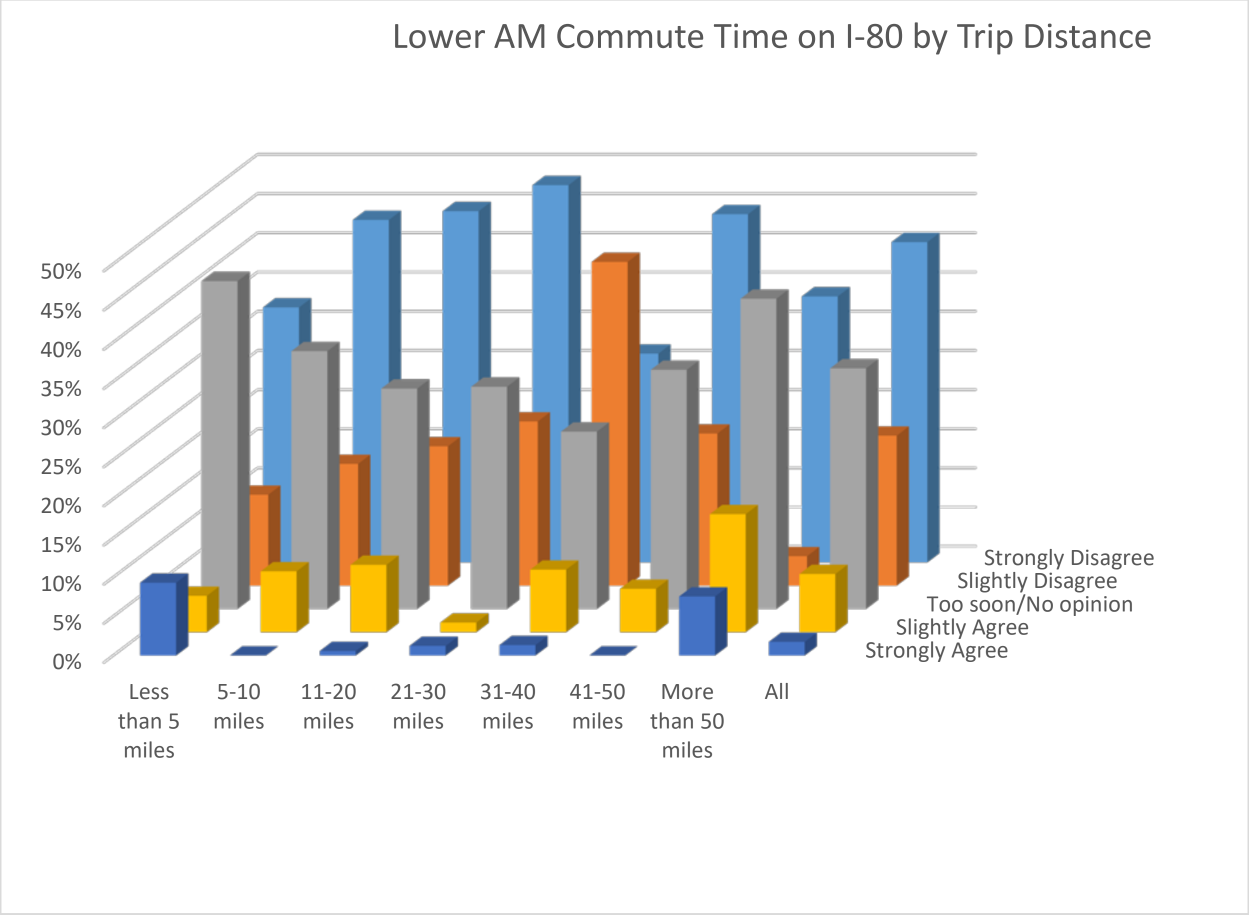




Lower commute time in the morning

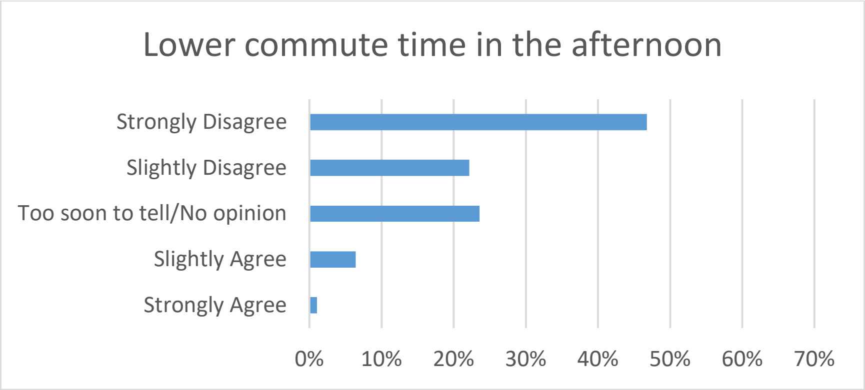
There was general disagreement (60%) or caution (31%) about the statement on lower commute time in the morning as a result of the ramp meters. Less than 10% agreed, but only slightly

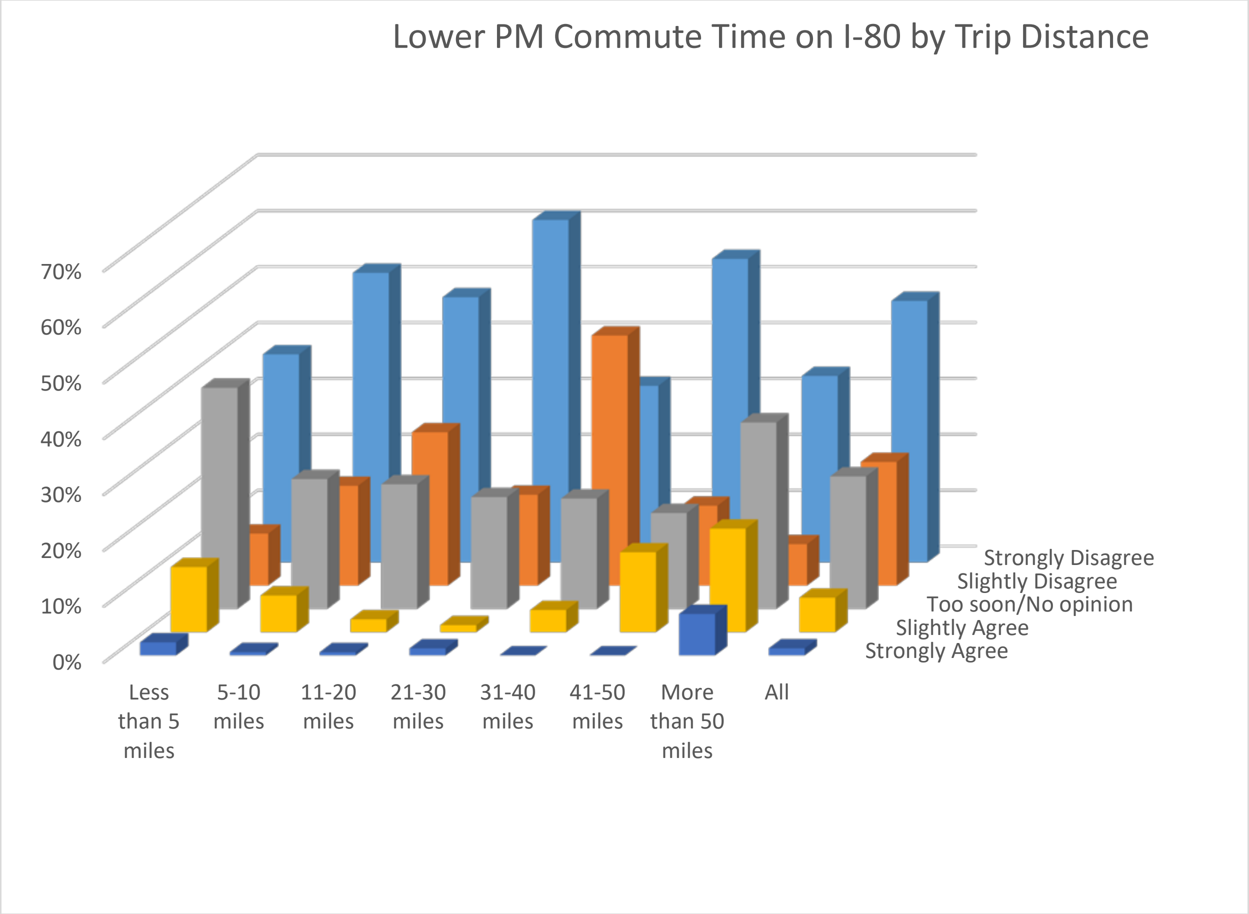




Lower commute time in the afternoon

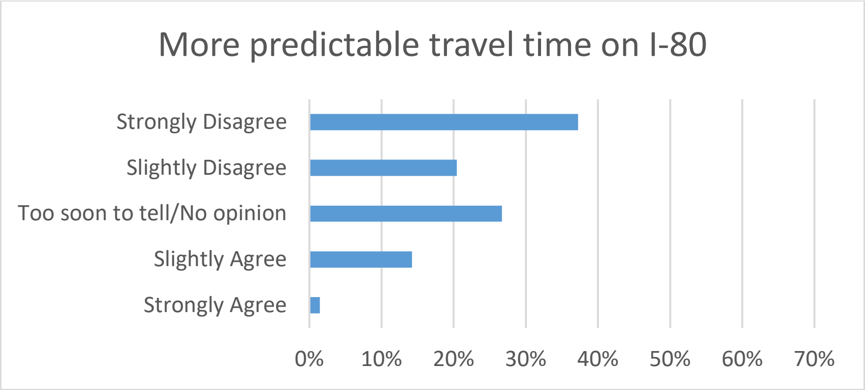
Similarly, there was major disagreement (69%) or caution (24%) about the statement on lower commute time in the afternoon as a result of the ramp meters. Just 7% agreed.

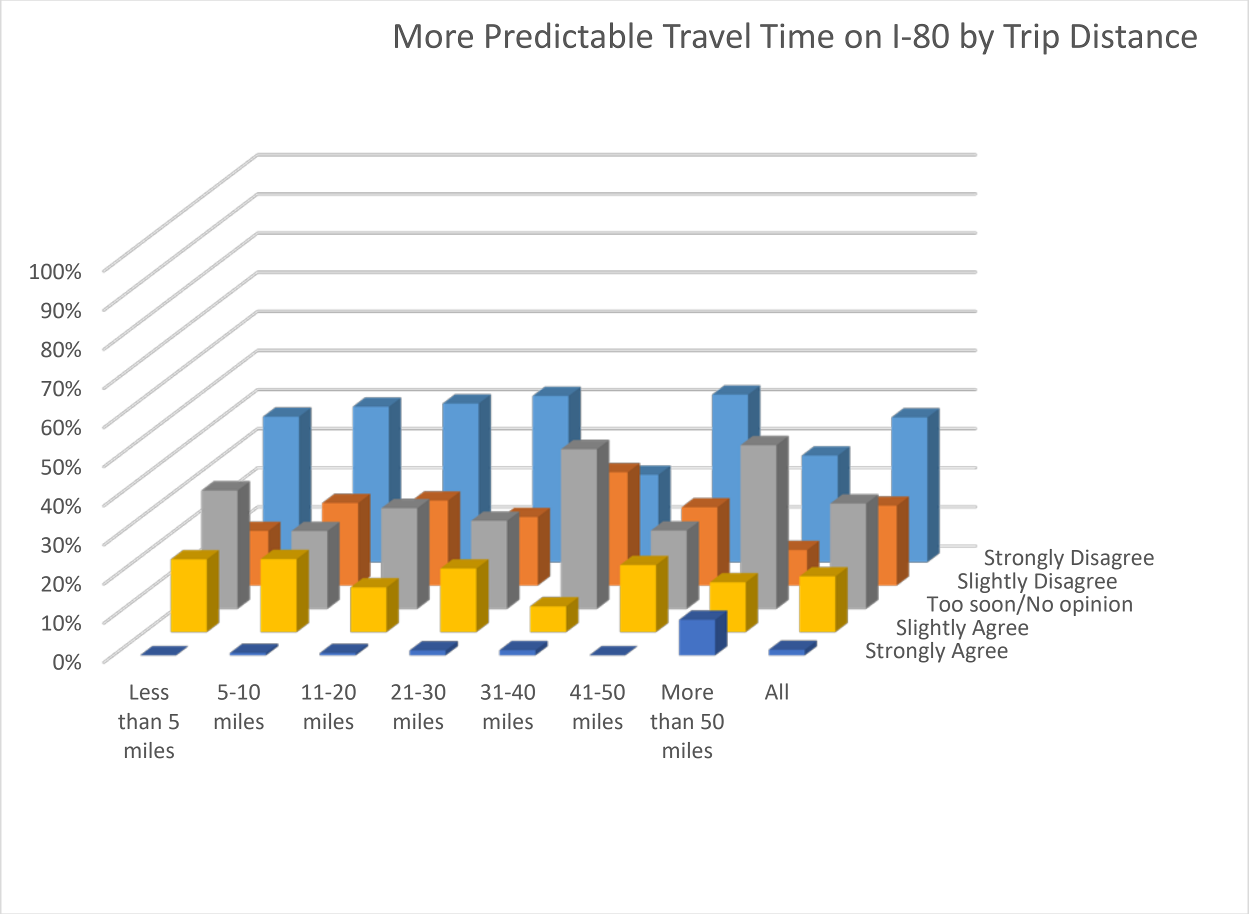




More predictable travel time on I-80

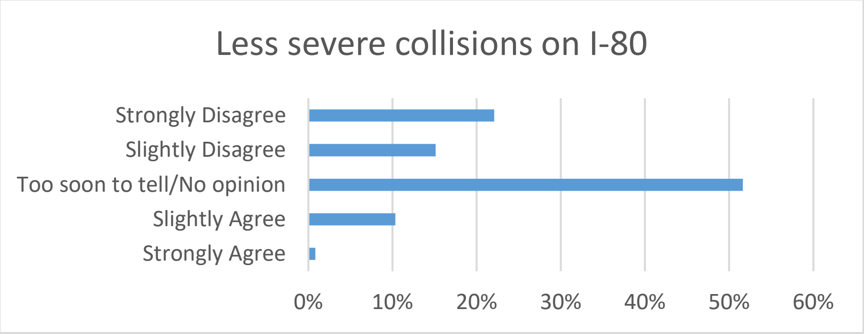
There was major disagreement (58%) or caution (27%) with the statement about improved predictability of travel time. The responses to this statement are very consistent with the previous two sentiments on commute travel time. Although nearly two times as many people agreed (15%) with predictability of commute time compared to lengths of commute times, they again mostly agreed slightly.





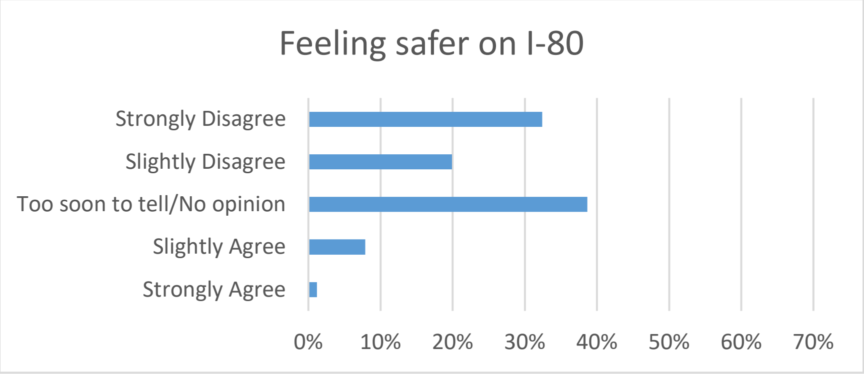
Less severe collisions on I-80

Most respondents (52%) would rather exercise caution on the statement about less severe collisions while 37% disagreed outright and mostly disagreed strongly with the statement.



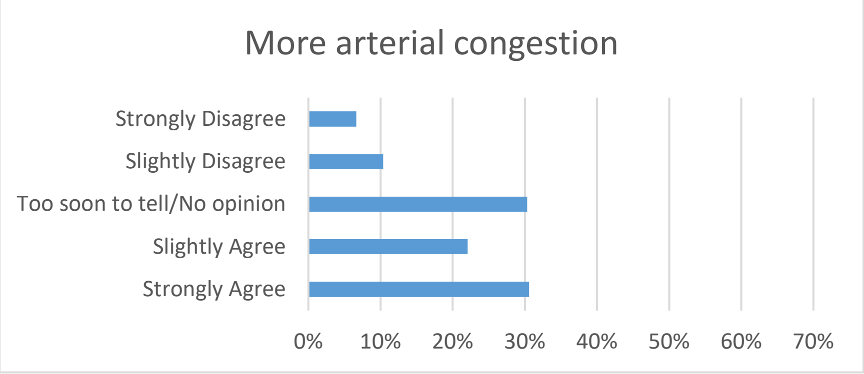
Feeling safer on I-80

Half of the respondents (52%) did not perceive that they were safer traveling in the corridor as a result of the ramp meters while two out of five (39%) would consider it too soon to tell. Less than 10% agreed.



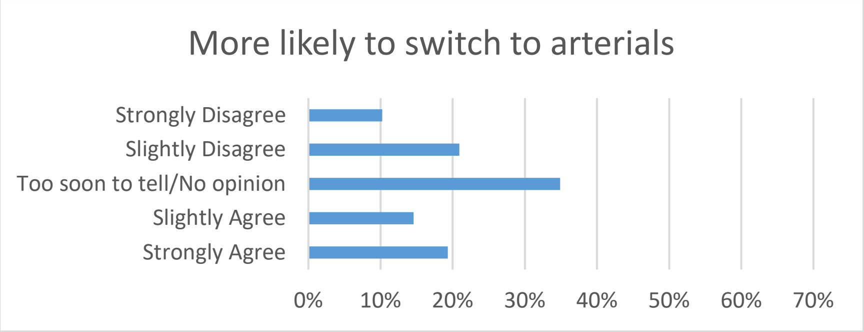
Increased congestion on arterials in I-80 corridor

Half of the respondents (53%) agreed with the assertion that the ramp meters increased arterial street congestion in the I-80 corridor, but nearly a third (30%) had no opinion on the statement while 17% disagreed.



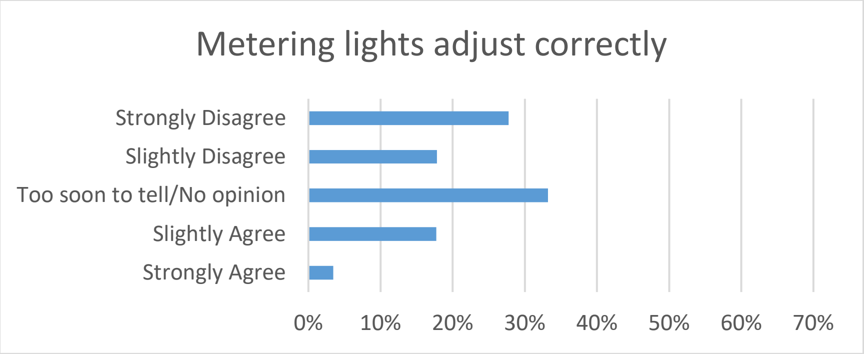
More likely to use arterial streets instead of I-80

Respondents were evenly divided in agreement (34%) and disagreement (35%) with the suggestion that they were more likely to switch to arterial streets from I-80 because of the ramp meters. The remaining 31% reserved their opinion on the subject.



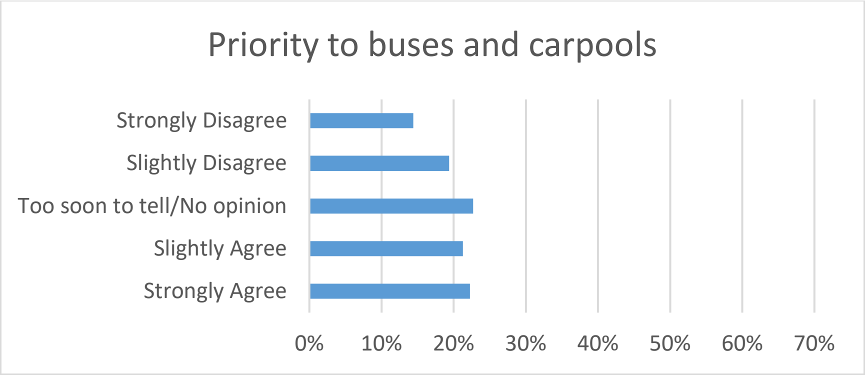
Metering lights adjust correctly for conditions

Nearly half (46%) of the respondents did not perceive that the ramp meters adjusted correctly for prevailing conditions while one out of five (21%) agreed and 33% had no opinion on the topic.



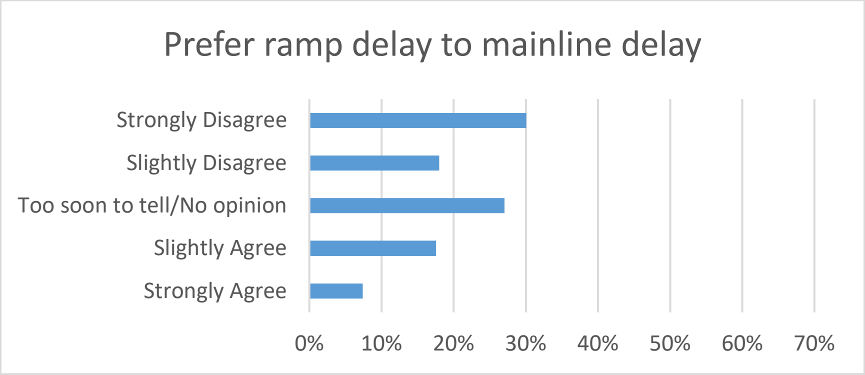
Buses and carpools should receive priority when possible

Just under half of the respondents (43%) agreed with the suggestion to give priority to buses and carpools when possible while 34% disagreed and 23% had no opinion on the subject.



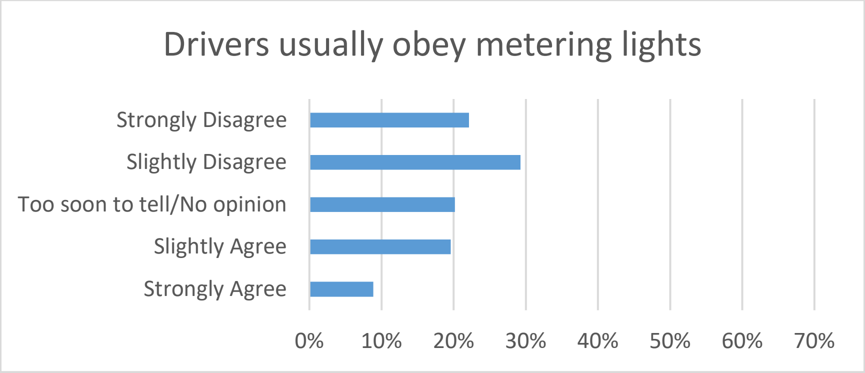
Prefer delay at ramp meter to delay on the freeway

Nearly half (48%) of the respondents disagreed with the suggestion that they would prefer delay at the ramp meters to delay on the mainline freeway. A quarter (25%) agreed while 27% had no opinion on the subject.



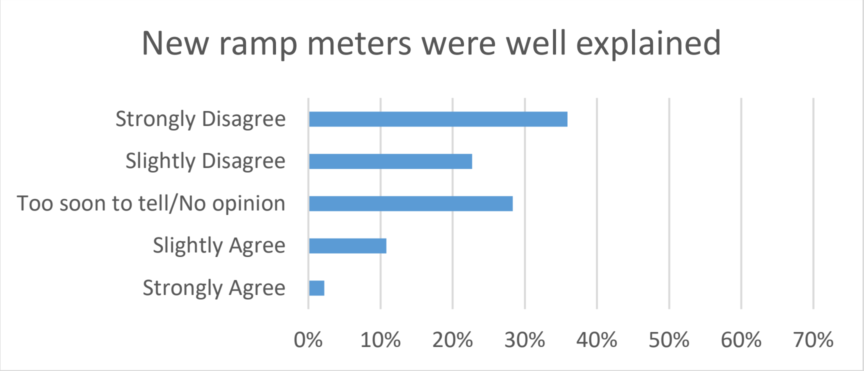
Drivers usually obey metering lights

Half of the respondents (51%) did not agree that drivers obey the metering lights while 28% agreed and 20% had no opinion on the issue.



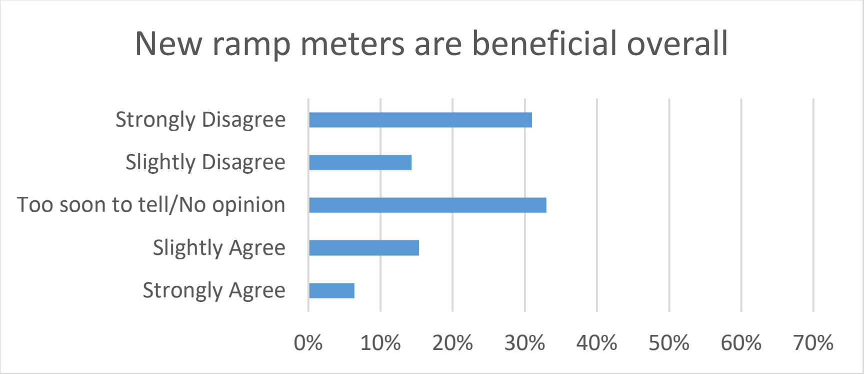
New ramp meters were well explained to the public

The majority (59%) of the respondents did not agree that the new ramp meters were explained well to the public. Relatively few respondents (13%) agreed while a quarter (28%) had no opinion on the issue.



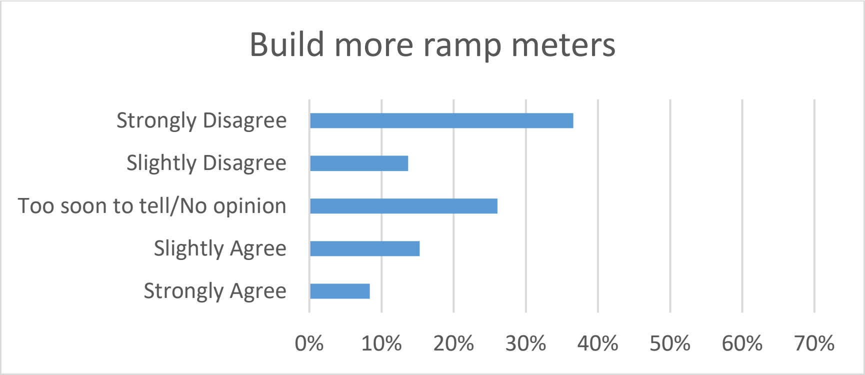
New ramp meters are beneficial overall

Just 22% of the respondents agreed with the suggestion that the new ramp meters were beneficial overall, while 45% disagreed outright, mostly strongly, and a third considered it too soon to tell.



Build more ramp meters in San Francisco Bay Area

Consistent with user sentiment on the benefits of ramp meters, a little under a quarter (24%) of the respondents agreed with the suggestion to build more ramp meters in the San Francisco Bay Area while 50% disagreed outright, mostly strongly, and the rest had no opinion on the suggestion.


Build more ramp meters
Strongly Disagree
Slightly Disagree
Too soon to tell/No opinion
Slightly Agree
Strongly Agree
0%
10%
20%
30%
40%
50%
60%
70%

Discussion

Descriptive Summary

Table 1 summarizes the results of the survey on user experiences and sentiments. There was a preponderance of disagreement from the traveling public about operating conditions and about improvements to travel time via the study section of I-80. It is conceivable that conditions that prompted the installation of the adaptive ramp meters were so bad that most travelers could not notice the improvements especially during commute periods. However, survey results indicate almost as equally heavy use of the freeway during the off-peak and on weekends as during commute periods. Other areas of majority disagreement were sufficiency of publicity about the new ramp meters, feeling of improved safety on I-80, and users obeying ramp metering lights. These results indicate little public perception of the expected benefits of the adaptive ramp meters.

Table 1: Summary of I-80 User Experiences and Sentiments

Theme	User Experiences and Sentiments of Survey Respondents	Agree	No opinion	Disagree	All
Conditions on I-80					
	Problem of congestion on I-80	74%	14%	11%	100%
	Easier merging onto I-80	31%	25%	44%	100%
	Lower congestion on I-80	10%	20%	70%	100%
	Reduced stop-and-go on I-80	14%	17%	69%	100%
	Smoother flow on I-80	18%	18%	64%	100%
Travel time effects					
	Lower commute time in the morning	9%	31%	60%	100%
	Lower commute time in the afternoon	7%	24%	69%	100%
	More predictable travel time on I-80	16%	27%	58%	100%
Safety					
	Less severe collisions on I-80	11%	52%	37%	100%
	Feeling safer on I-80	9%	39%	52%	100%
Arterials in corridor					
	Increased congestion on arterials in I-80 corridor	53%	30%	17%	100%
	More likely to use arterial streets instead of I-80	34%	35%	31%	100%
Attitudes toward ramp meters					
	Metering lights adjust correctly for conditions	21%	33%	46%	100%
	Buses and carpools should receive priority when possible	44%	23%	34%	100%
	Prefer delay at ramp meter to delay on the freeway	25%	27%	48%	100%
	Drivers usually obey metering lights	28%	20%	51%	100%
	New ramp meters were well explained to the public	13%	28%	59%	100%
	New ramp meters are beneficial overall	22%	33%	45%	100%

	Build more ramp meters in San Francisco Bay Area	24%	26%	50%	100%
	Majority of respondents agree	🟩			
	Majority of respondents have no opinion		🟨		
	Majority of respondents disagree			🟧	

The operational phenomenon with the most promising observation was merging onto I-80, which had almost a third of respondents (31%) in agreement and less than a majority (44%) in disagreement. Indeed, the one item of overwhelming agreement (74%) is strong insistence from users that congestion remained a major problem on I-80. Closely aligned with this notion was the agreement by a simple majority of respondents (53%) that there was increased congestion on arterials as well.

From the user perspective, the one area of desirable feedback was that 44% of respondents agreed to give priority to buses and carpools. This would support queue-jump treatments rather in addition to standard or adaptive ramp metering.

It is conceivable additional, informational outreach could change user attitudes in favor of ramp meters if the public has a much better understanding of its benefits to the community. A majority of respondents (59%) disagreed with the statement about the ramp meters being well-explained to the public.

One of the least observable, expected benefits of the ramp metering treatment relates to safety. Since users would be hard pressed to discern the severity of collisions even if they were on the freeway at the time of incidents, 52% of respondents would rather exercise caution about assertions on reduction in severity of collisions. Closely mirroring this sentiment, 52% of respondents disagreed with the statement of feeling safer on I-80.

Chi-Square Tests of User Sentiments and Preferences by Trip Distance

Table 2 shows a summary of Chi-Square analyses of user sentiments versus total trip distances. A Chi-Square test of independence tests the null hypothesis that there is no relationship between two categorical variables. In this application, the test is to discern if sentiments vary with the total trip distances of I-80 users. Large Chi-Square statistics and small significance levels ($p < 0.05$) indicate that it is very unlikely that these variables are independent of each other. The chi-square tests on the survey data indicate that user sentiments are likely dependent on trip distances of respondents although patterns are not entirely clear. The graphs of the crosstabs of sentiments versus total trip distances generally indicate stronger disagreement as trip distances increased till about 20-mile to 30-mile long trips after which it declines slightly and fluctuates thereafter.

Table 2: Summary & Chi-Square Tests of User Experiences and Sentiments by Total Trip Distance

Theme	User Sentiments by Trip Distance	N of Valid Cases	Pearson Chi-Square	Likelihood Ratio	p-value
Conditions on I-80					
	Delay getting onto I-80	633	74.129a	58.2	0.0000001
	Delay traveling on I-80	633	90.926a	82.7	0.0000183
	Lower congestion on I-80	631	62.931a	68.7	0.0025933
	Reduced stop-and-go on I-80	631	69.933a	70.5	0.0004090
	Smoother flow on I-80	629	114.112a	104.4	0.0000000
Travel time effects					
	Lower commute time in the morning	631	95.755a	87.6	0.0000001
	Lower commute time in the afternoon	633	119.871a	111.2	0.0000000
	More predictable travel time on I-80	632	81.870a	70.8	0.0000127

0.0 ~ p-value lower than 0.05 – reject the null; variables are NOT independent, that is, user sentiments do depend on trip distance.

Gamma Tests of User Sentiments and Preferences by Trip Distance

Gamma is used to measure the strength and direction of two ordinal-level variables that have are arrayed in bivariate tables. Total trip distances of I-80 users, which were categorized into distance bins, and user sentiments, which were arrayed from most favorable to least favorable, were cross-tabulated and subjected to Gamma tests to yield further indications on the direction and strength of relationships between user sentiments and traveler distances. Table 3 shows the summary of results. Delay getting onto I-80 and smoother flow on I-80 indicated negative directions meaning as traveler distance increased users agreed less with expectations from the ramp metering project. Longer distance travelers reported lower delay getting onto I-80 but less smoother flow on I-80. Other variables indicated positive direction meaning as traveler distance increased users agreed more with expectations. In general, longer distance travelers reported higher delay in traveling on I-80; they also agreed more with expectations of easier merging lower congestion, and reduced stop-and-go as well as lower commute time and more predictable travel time on I-80. However, the test statistics indicate that apparent relationships between travel distance and user sentiments (previously indicated by Chi-Square tests) are extremely weak and statistically insignificant except for delay in getting onto I-80. The latter finding supports an argument that ramp meters tend to favor longer distance travelers.

Table 3: Summary & Gamma Tests of User Experiences and Sentiments by Total Trip Distance

Theme	User Sentiments by Trip Distance	Gamma Value	Approximate T	Approximate Significance	Direction of Relationship	Strength of Relationship
Conditions on I-80						
	Delay getting onto I-80	-0.15546	-2.946	**0.003**	negative	weak
	Delay traveling on I-80	0.05180	1.045	0.296	positive	weak
	Easier merging onto I-80	0.02674	0.657	0.511	positive	weak
	Lower congestion on I-80	0.03221	0.709	0.479	positive	weak
	Reduced stop-and-go on I-80	0.00007	0.002	0.999	positive	weak
	Smoother flow on I-80	-0.00678	-0.151	0.880	negative	weak
Travel time effects						
	Lower commute time in the morning	0.01546	0.341	0.733	positive	weak
	Lower commute time in the afternoon	0.00033	0.007	0.995	positive	weak
	More predictable travel time on I-80	0.01479	0.339	0.735	positive	weak

Strength	**Range of Gamma Value**
Weak	~ Between 0.0 and 0.30
Moderate	~ Between 0.30 and 0.60
Strong	~ Greater than 0.60

Recommendations

The following recommended actions to the Metropolitan Transportation Commission derive from analysis of the survey results:

1. First, increase outreach efforts via multiple media to educate the public about the expected benefits of ramp meters in general and adaptive ramp meters in particular.
2. Next, publicize the results of a parallel analysis to this survey effort to shed light on the operational gains of installing the adaptive ramp meters especially in comparison to prior conditions as discerned from traffic monitoring data.
3. Finally, continue periodic assessment of field conditions and user sentiments as part of the agency's continuous monitoring efforts. This could help in decision-making whether to improve controls, expand the program, or discontinue it, all for the public good.

Conclusions

This research attempts to examine the effect of ARM on traffic operations immediately following the implementation of the system. Early evidence is useful for agencies as they report to elected officials and plan for future implementations. The focus of this research is on measures of travel time reliability since system users are expected to be less tolerant of the unexpected delays even as they plan for expected delays.

Specific measures of reliability used in this study include Buffer Index and Buffer time. In addition, based on a review of relevant literature, robust measures based on different percentiles of travel times were also identified and estimated for the before (May 2016) and after (May 2017) period. The Modified Unreliability Indicator (MUI) was determined to be a more practical metric as it could be estimated using readily available data from INRIX Insights. The comparison between the before and after period was set up to minimize confounding variables.

Travel Time Reliability

Preliminary investigations with the entire 19-mile I-80 EB corridor revealed that the shoulders of the PM peak hours tend to be the least reliable times of the day due to the uncertainty of how early congestion will form and how long it will persist. Following the preliminary investigations focus of the analysis was shifted onto the corridor segments with the worst travel time reliability. These segments were located upstream of the bottleneck on eastbound I-80 at the Pinole Valley Road interchange. Three segments of the corridor were examined for further analysis: i) from Appian Interchange to Pinole Valley interchange (0.96 miles), ii) from Fitzgerald Interchange to Pinole Valley interchange (1.71 miles), and iii) from Hilltop Interchange to Pinole Valley interchange (2.55 miles). The addition of ARM along I-80 east of San Francisco in 2017 has generally appeared to show improvements in available travel time reliability metrics as compared to those measured in 2016. However, looking at the historical trends since 2011, the improvements become less pronounced given the variability from year to year. It is noteworthy that even in light of an increasing number of incidents, the unreliability as measured by Buffer Index and the MUI seem to be below and on the temporal trend line, respectively.

Correlations

UI and MUI had varying correlation coefficients each year and their average values for the full 19-mile corridor showed that MUI was often double the UI value. This makes it difficult to directly compare MUI values with UI values.

Future Research

This research has presented a promising approach for the use of granular data for a before and after active traffic management performance evaluation. The framework to examine spatio-temporal trends needs to be implemented over a longer horizon for more robust conclusions. With the availability of data, further analysis could also be conducted, including other days (Mondays, Fridays, and weekends), additional months to account for possible seasonal effects, and for additional segments (including portions of westbound I-80). Through the Caltrans Performance Measurement System (PeMS) and through INRIX Insights, a wide array of potential dashboard-style analyses can be conducted with relative ease. Putting the data in the hands of analysts and decision-makers can improve not only day-to-day operations, but also more long-term operational strategies.

Future research should also investigate whether time of day has an effect on how UI and MUI are correlated. Another important area for future research is investigating user perceptions and satisfaction related to the ARM system and comparing those results to the operations data. To that end, a User Satisfaction Survey instrument was designed for the I-80 ARM system and is included in Appendix A.

In Conclusion it should also be noted that since ramp metering may impact ramp queues and arterial performance, further analysis of travel times on ramps and on nearby arterials, specifically San Pablo Avenue, also needs to be performed to understand the true impact of the project. Another caveat to consider is that as part of the I-80 SMART Corridor project, several other traffic management components in addition to ramp metering were added to the I-80 corridor nearly simultaneously. Thus, it may not be entirely possible to isolate the effects of the ARM or any of the other systems individually with 100% confidence.

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Appendices

Appendix 1 – Weighting

Appendix 1: Distributions and Weighting of Survey Data

The "Party" table of the Statewide Integrated Traffic Records System (SWITRS) crash database, which is accessible through the portal of the Transportation Injury Mapping System (TIMS), includes such factors as the age and gender of the drivers involved in each crash. We extracted driver information for 5,143 crashes that occurred in the study corridor over a decade (from 2006 through 2017) and found that 7,886 drivers involved in the crashes were not at fault. The pool of 7,886 not-at-fault drivers produced 7,669 records of drivers who provided either age or gender or both. By the induced exposure method, this population is assumed to be representative of the driving population in the I-80 corridor. We categorized the ages of the drivers into the same ranges as in the survey questionnaire.

Weighing procedure began with a reasonableness check of the not-at-fault distributions of drivers with the distribution of similar age ranges for residents of Alameda and Contra Costa counties which the I-80 traverses. Results were determined to be consistent between the two data sets. Then we redistributed cases where one variable was known while the other was not known in the survey data proportionally to cases for which both variables were known. Table A1-1 shows the resulting percentage distributions by age and gender from the adjusted number of cases. The division of the not-at-fault proportions by the survey proportions produced the initial weights applied in the SPSS procedures that generated initial frequencies. Table A1-2 1 shows the weights to correct for bias in age and gender distribution.

Table A1-1: Distributions of I-80 Motorists: Not-at-Fault Motorists vs. ARM Survey Respondents

Age	I-80 Not-at-Fault Drivers, 2006-2017				I-80 ARM Survey, 2018			
	All Sexes	Male	Female	Sex Unknown	All Sexes	Male	Female	Sex Unknown
Number of Cases								
18-24	965	527	438	0	61	38	19	4
25-34	1,812	1,016	793	3	151	92	55	4
35-44	1,702	1,022	676	4	143	64	75	4
45-54	1,624	985	639	0	126	68	57	1
55-64	1,101	714	385	2	82	42	39	1
65 or above	465	315	150	0	45	21	24	0
Total	7,669	4,579	3,081	9	608	325	269	14
Age Unknown					6	3	3	12
All cases	7,669	4,579	3,081	9	626	328	272	26
Column Percentages (by Age)								

Age	I-80 Not-at-Fault Drivers, 2006-2017				I-80 ARM Survey, 2018			
	All Sexes	Male	Female	Sex Unknown	All Sexes	Male	Female	Sex Unknown
18-24	13%	12%	14%	0%	10%	12%	7%	29%
25-34	24%	22%	26%	33%	25%	28%	21%	29%
35-44	22%	22%	22%	44%	24%	20%	28%	29%
45-54	21%	22%	21%	0%	21%	21%	21%	7%
55-64	14%	16%	12%	22%	13%	13%	14%	7%
65 or above	6%	7%	5%	0%	7%	6%	9%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table A1-2: Two-Variable Combined Weighting

Weights to correct for bias in age and gender distributions			
Age	**Male**	**Female**	**Gender Unknown**
18-24	0.944	1.925	0.004
25-34	0.782	1.253	1.167
35-44	1.129	0.782	1.556
45-54	1.045	0.992	0.016
55-64	1.221	0.870	3.111
65 or above	1.090	0.557	0.001
Total	1.000	1.000	1.000
Age Unknown	1.035	1.063	0.976

Further scrutiny revealed that respondents with college degrees were five and a half times the 13% in the 2016 ACS of the US Census for the East Bay (Alameda, Contra Costa and Solano Counties) and nearly double that of the San Francisco Metropolitan Area (at 42%). This implies a more-than-averagely educated group of respondents. Table A1-3 shows comparative distributions. Table A1-4 shows weights for education and gender distributions. Table A1-5 shows composite weights for age, gender, and education distributions.

Table A1-3: Distributions by Education and Gender for 2016 ACS vs. ARM Survey Respondents

Educational Attainment (Age 18+)	2016 ACS – Alameda, Contra Costa, Solano Counties			2018 ARM Survey		
	Male	Female	**Tri-County Total**	Male	Female	Survey Total
Less than high school	145,008	145,631	290,639	9	9	17
High school graduate (includes equivalency)	243,021	243,349	486,370	15	6	21
Some college or associate's degree	368,259	407,777	776,036	77	55	132
Bachelor's degree or higher	465,627	498,418	964,045	241	215	456
Other	0	0	-			
Total (Age 18+)	1,221,915	1,295,175	2,517,090	342	284	626

Table A1-4: Education by Gender Weights

Weights to correct for bias in education and gender distributions

Education	**Male**	**Female**	**Gender Unknown**
Less than high school or other	4.768	3.763	4.266
High school graduate (includes equivalency)	4.528	8.908	6.718
Some college or associate's degree	1.334	1.633	1.484
Bachelor's degree or higher	0.540	0.509	0.525
Total	1.000	1.000	1.000
Education Unknown	4.768	3.763	4.266

Table A1-5: Weights for Age by Gender by Education

Age & Education	Male	Female	**Gender Unknown**
18-24			
Less than high school or other	4.500	7.243	0.018
High school graduate (includes equivalency)	4.274	17.145	0.028
Some college or associate's degree	1.259	3.144	0.006
Bachelor's degree or higher	0.510	0.979	0.002
Prefer not to answer	4.500	7.243	0.018
25-34			
Less than high school or other	3.729	4.714	4.977
High school graduate (includes equivalency)	3.542	11.159	7.838
Some college or associate's degree	1.043	2.046	1.731

Age & Education	Male	Female	**Gender Unknown**
Bachelor's degree or higher	0.423	0.637	0.612
Prefer not to answer	3.729	4.714	4.977
35-44			
Less than high school or other	5.384	2.942	6.635
High school graduate (includes equivalency)	5.113	6.965	10.451
Some college or associate's degree	1.506	1.277	2.308
Bachelor's degree or higher	0.610	0.398	0.816
Prefer not to answer	5.384	2.942	6.635
45-54			
Less than high school or other	4.982	3.733	0.070
High school graduate (includes equivalency)	4.731	8.837	0.110
Some college or associate's degree	1.394	1.620	0.024
Bachelor's degree or higher	0.565	0.505	0.009
Prefer not to answer	4.982	3.733	0.070
55-64			
Less than high school or other	5.823	3.273	13.271
High school graduate (includes equivalency)	5.530	7.749	20.901
Some college or associate's degree	1.629	1.421	4.616
Bachelor's degree or higher	0.660	0.443	1.632
Prefer not to answer	5.823	3.273	13.271
65 or above			
Less than high school or other	5.199	2.097	0.005
High school graduate (includes equivalency)	4.938	4.965	0.008
Some college or associate's degree	1.454	0.910	0.002
Bachelor's degree or higher	0.589	0.284	0.001
Prefer not to answer	5.199	2.097	0.005

Appendix 2 – Ramp Use

Figure A2-1: Ramp use to get ON I-80 Eastbound

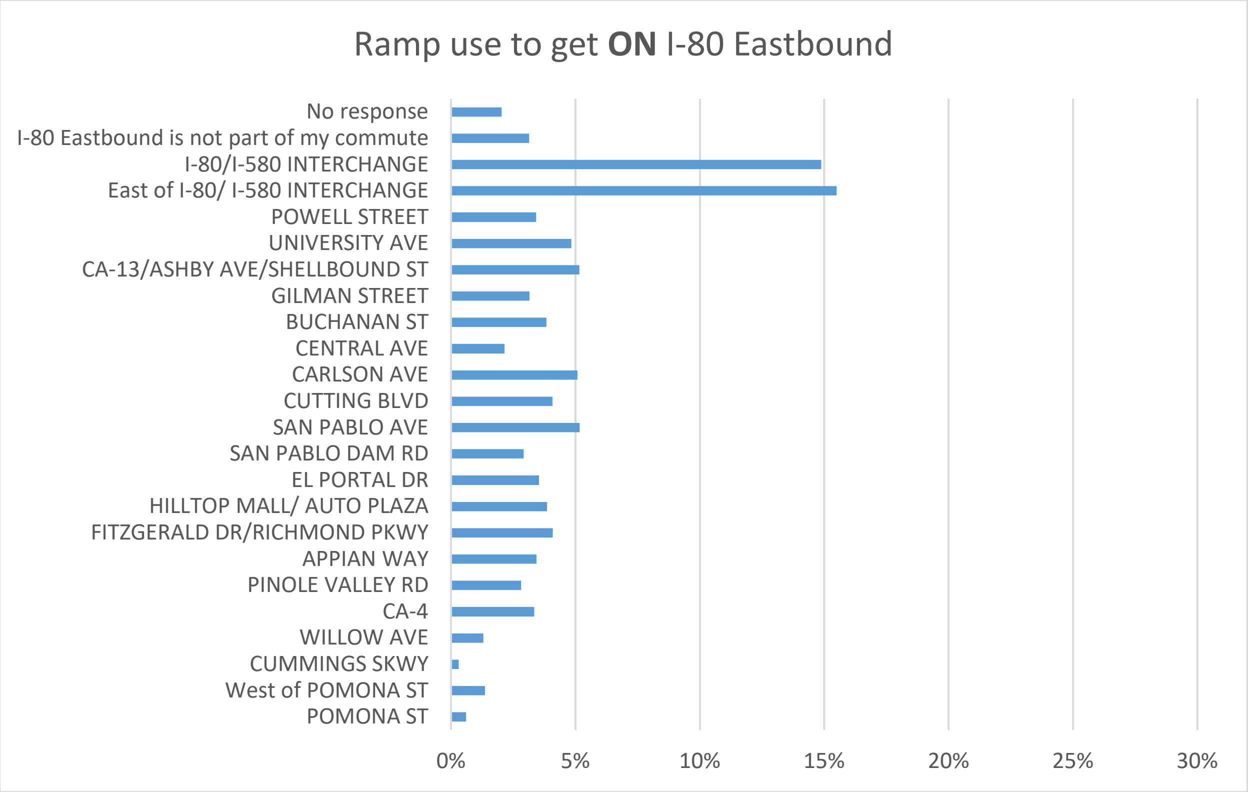


Figure A2-2: Ramp use to get OFF I-80 Eastbound

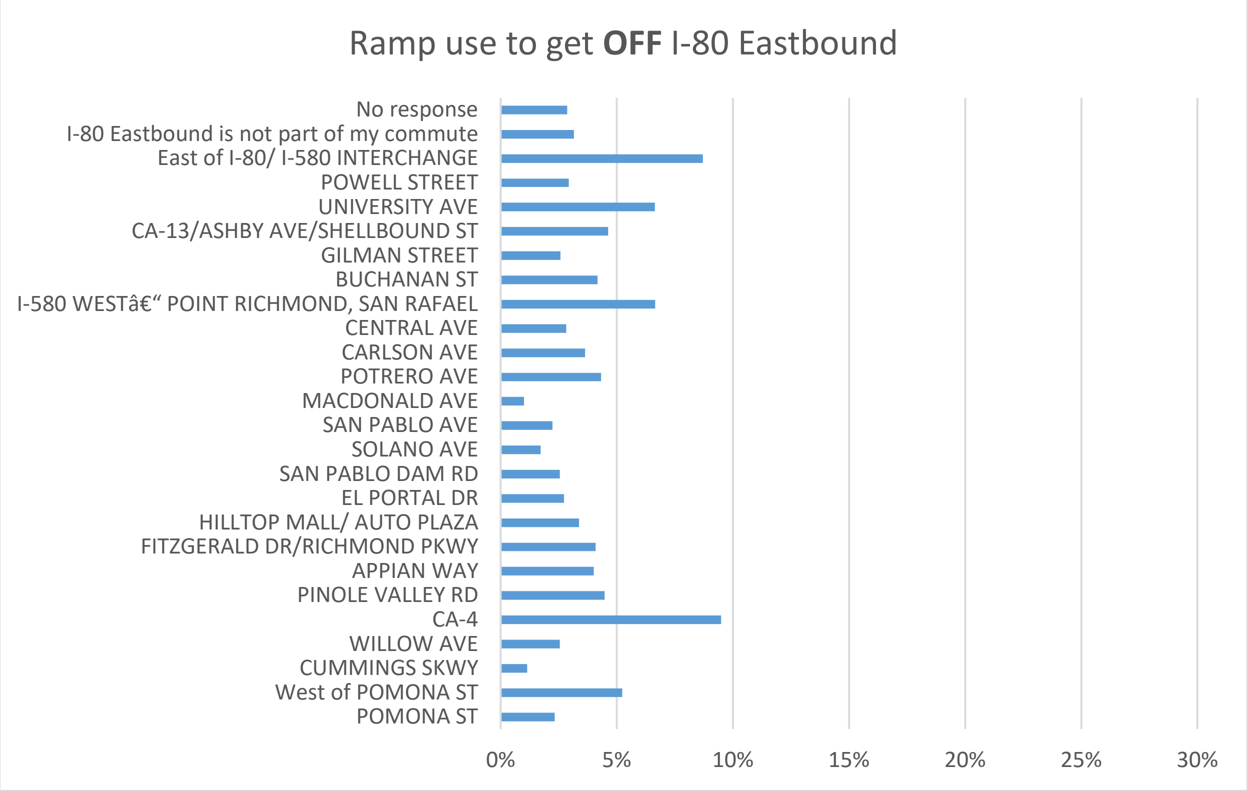


Figure A2-3: Ramp use to get ON I-80 Westbound

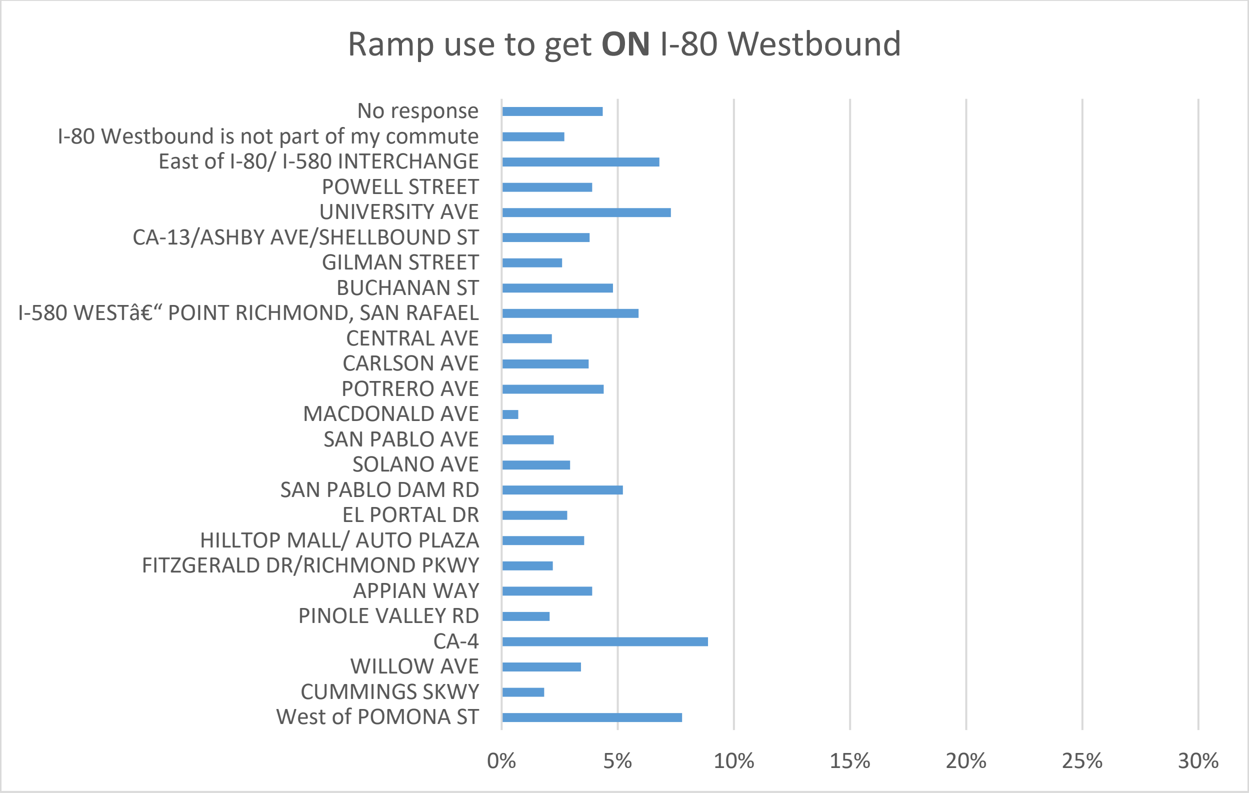
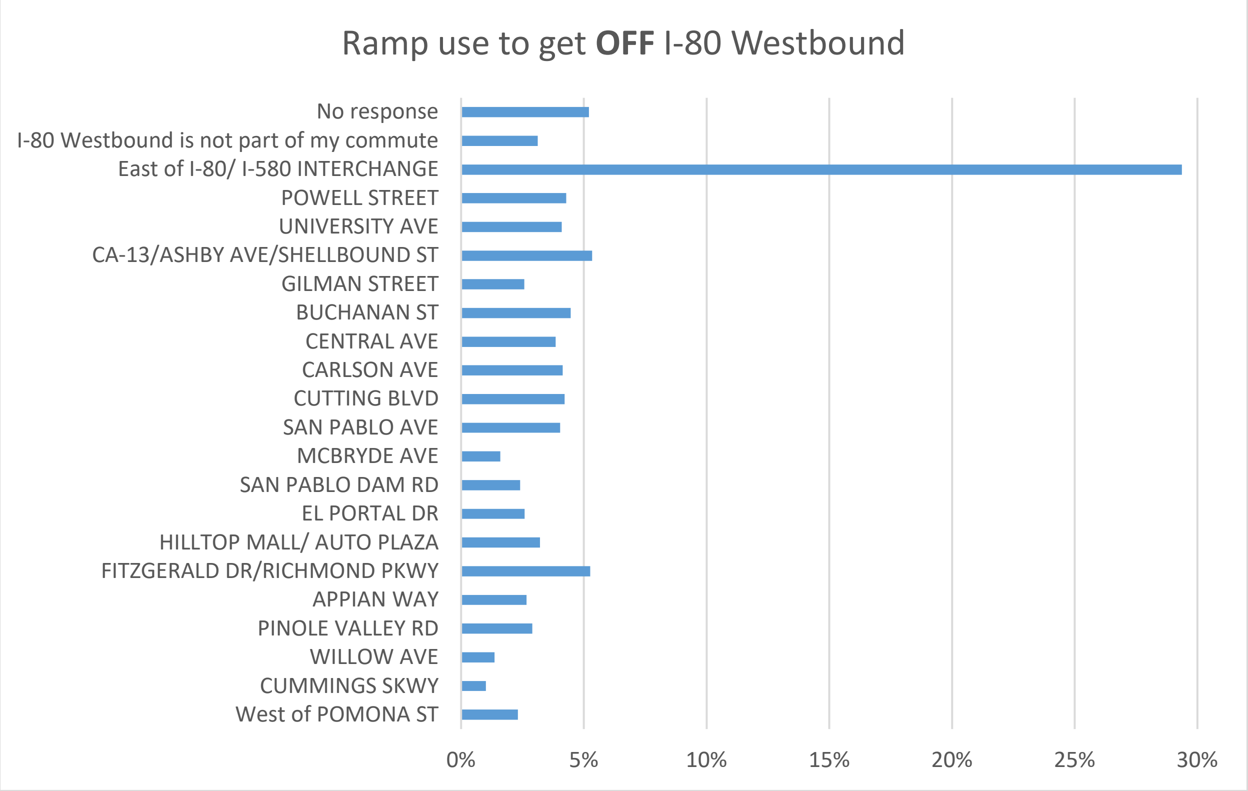


Figure A2-4: Ramp use to get OFF I-80 Westbound



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