# EARLY EMPIRICAL EVIDENCE FOR THE EFFECTS OF ADAPTIVE RAMP METERING ON MEASURES OF TRAVEL TIME RELIABILITY

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Master of Science in Civil and Environmental Engineering

by

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ABSTRACT

Early Empirical Evidence for the Effects of Adaptive Ramp Metering on Measures of Travel Time Reliability

Travis Charles Low

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 a state department of transportation. Early evidence of improvements following these projects can be valuable to 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 thesis explores travel time reliability measures for the eastbound (EB) Interstate 80 (I-80) corridor in the San Francisco Bay Area before and after implementation of ARM using INRIX data. These measures include buffer index, planning time, and measures from the literature that account for both skew and width of the travel time distribution. 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. A new metric for measuring unreliability that may be derived from readily available INRIX data is also proposed in the thesis using data from the study corridor. While the ARM system is relatively new, the results indicate positive trends in measures of reliability even as the number of incidents on the corridor has increased in line with the national crash trends. The spatio-temporal trend evaluation framework used here may be used in the future to obtain more robust conclusions. However, since multiple smart corridor components were installed simultaneously, it may not be possible to fully isolate the effects of the ARM, or any of the other systems, individually.

Keywords: Adaptive Ramp Metering, ITS, Travel time reliability, Smart Corridors, INRIX data

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# 1. INTRODUCTION

Smart corridors that implement various ITS technologies are a 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 the San Francisco Bay Area in northern California, the freeway serves as a heavily-traveled corridor connecting to Sacramento. 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 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, 2016a).

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 (TTI & Cambridge, 2006). 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).

#### 1.1.1 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.

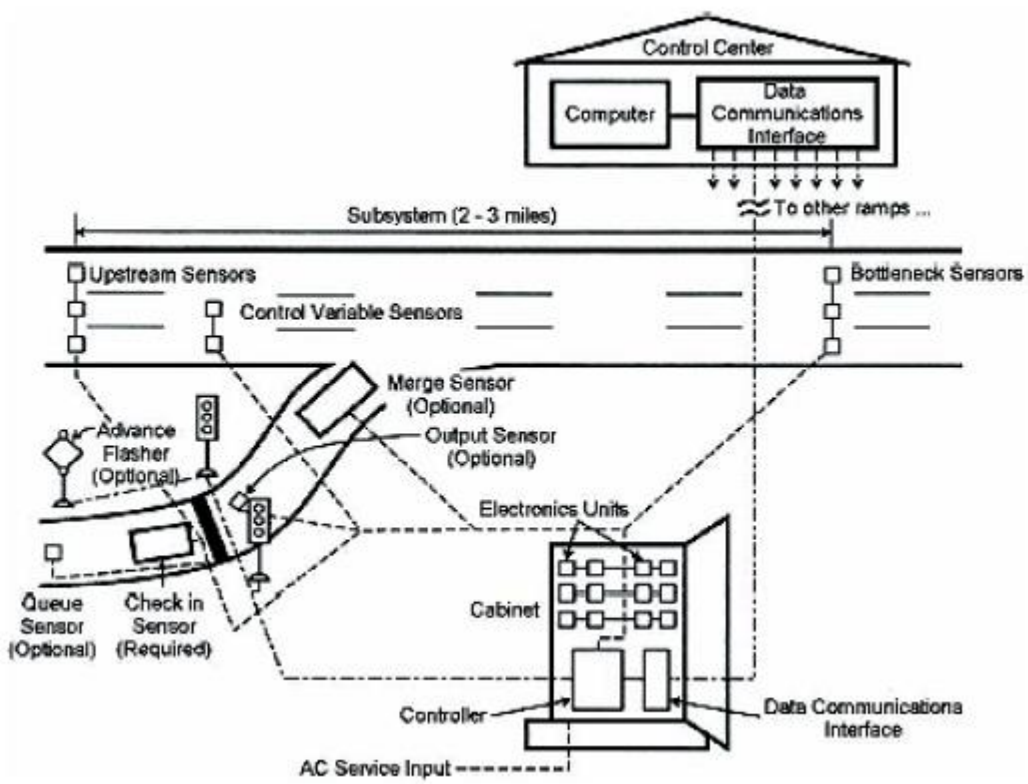



*Figure 1: Typical Detector Requirements for Adaptive Ramp Metering (DKS Associates, 2010)*

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.

### 1.1.2 Ramp Metering in California

The California Department of Transportation (Caltrans) states in their Ramp Metering Design Manual (Caltrans, 2016b) and in their Ramp Metering Development

Plan (Caltrans, 2016c) 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.

## 1.2 MOTIVATION

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, 2016a). 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. An image of a typical installation is shown in Figure 2.


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

The ramp meters were first activated in August 2016, with Local Traffic Responsive ramp metering. The ARM system of operation began in April 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.

One perception of installing ramp metering along the project corridor is that long-distance commuters who traverse the entire length of the corridor on their way to and from other destinations will experience the project's benefits at the expense of users who make shorter trips within the corridor. However, this is not expected to be the case on the project corridor since ramp metering has provided benefits in safety and mobility to all users in studies throughout the United States (DKS Associates, 2010).

## 1.3 ORGANIZATION OF THE THESIS

Following this Introduction is a chapter which provides a review of Adaptive Ramp Metering and Travel Time Reliability. Chapter 3 details the source of the data, the scope of the study area, and the methodologies used for estimating metrics of Travel Time Reliability. The following chapter presents a performance analysis of the corridor before and after implementation of Adaptive Ramp Metering and also includes exploration of a new measure of Travel Time Reliability. Chapter 5 draws conclusions on the early effectiveness of the Adaptive Ramp Metering system as well as on the future usefulness of the new Travel Time Reliability measure presented. The final chapter also presents ideas on future expansion of this research.

# 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.

## 2.1 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 & Papageorgiou, 1995) (Kang & 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 & 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.

## 2.2 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 noncoordinated metering (Yuan et al., 2009). Another coordinated ramp metering algorithm was implemented in Germany and showed promising results (Bogenberger et al., 2002).

## 2.3 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.

### 2.3.1 Assessments of Traditional Measures

In some of the earliest research into travel time reliability measures for use as practical performance measures, Lomax et al. (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).

### 2.3.2 New Measure Based on Width and Skew of Travel Times

Van Lint et al. (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.

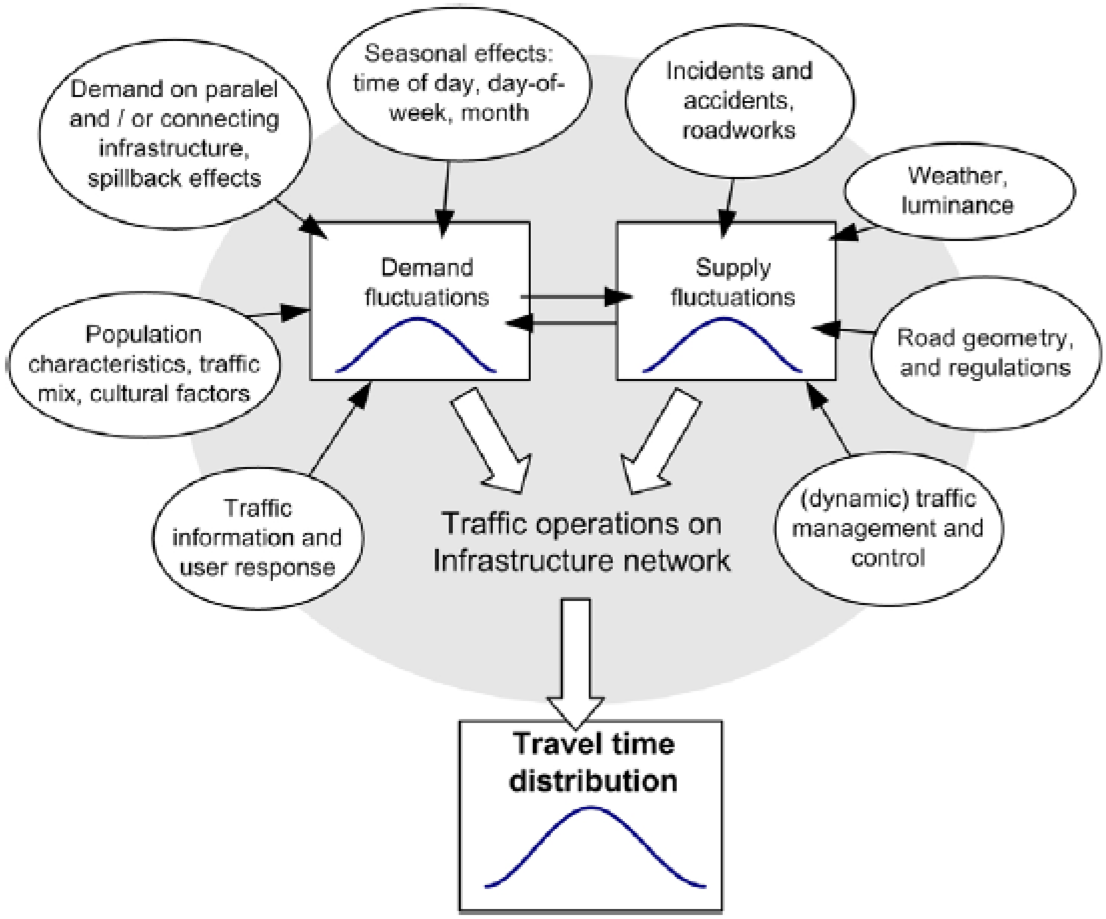



*Figure 3: Factors Influencing the Distribution of Travel Times (Van Lint et al., 2008)*

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.

### 2.3.3 Assessment of New Measure

Bhouri et al. (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.

### 2.3.4 Effects of Ramp Metering Strategy

Bhouri et al. (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.

## 2.4 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 on Travel Time Reliability of Adaptive Ramp Metering as part of a Smart Corridor implementation 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.

# 3. DATA AND METHODOLOGY

## 3.1 DATA SOURCE

Data for this research has been obtained from INRIX Insights (see Figure 4) 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.

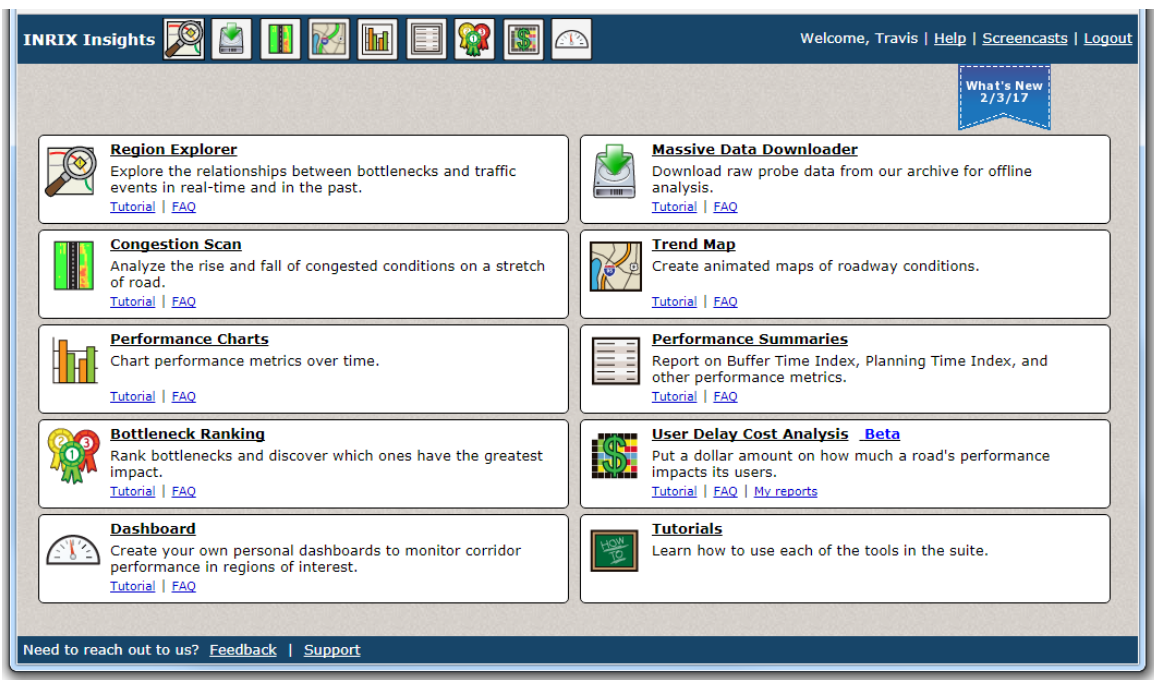



*Figure 4: Screenshot of INRIX Insights*

## 3.2 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.

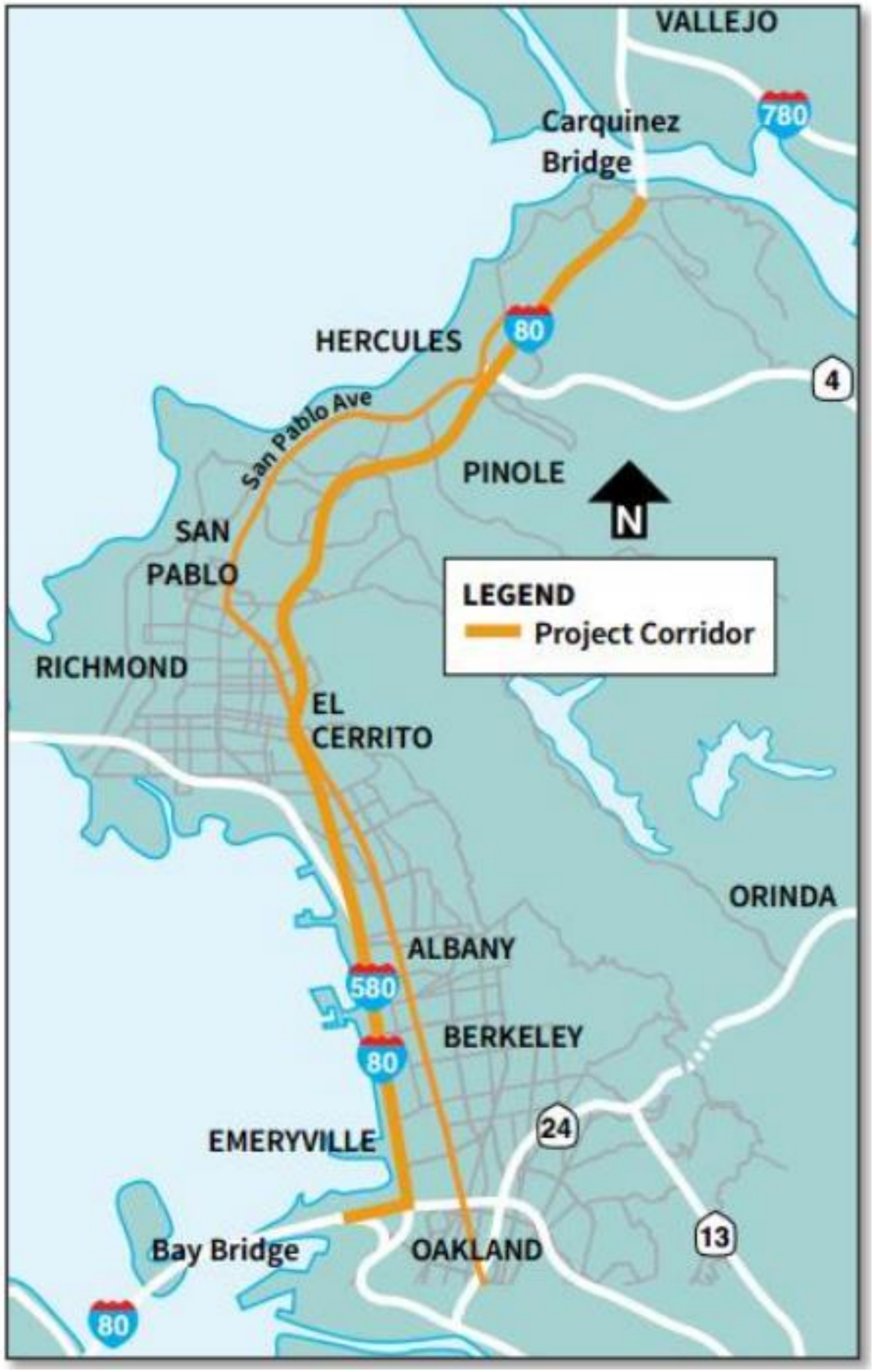



*Figure 5: 19-mile Smart Corridor project map (Caltrans, 2016a)*

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.

## 3.3 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.

### 3.3.1 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:

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

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 ($T_{ff}$):

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

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 (INRIX, 2017).

### 3.3.2 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, $\lambda_{skew}$, 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:

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

In general, as $\lambda_{skew}$ 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. (2008) also proposed a measure for width, $\lambda_{var}$, defined as the distance between the 90th and 10th percentile travel times relative to the median:

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

Large values of $\lambda_{var}$ indicate the travel time distribution has a large width, relative to its median. Van Lint et al. (2008) combined $\lambda_{var}$ and $\lambda_{skew}$ 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.

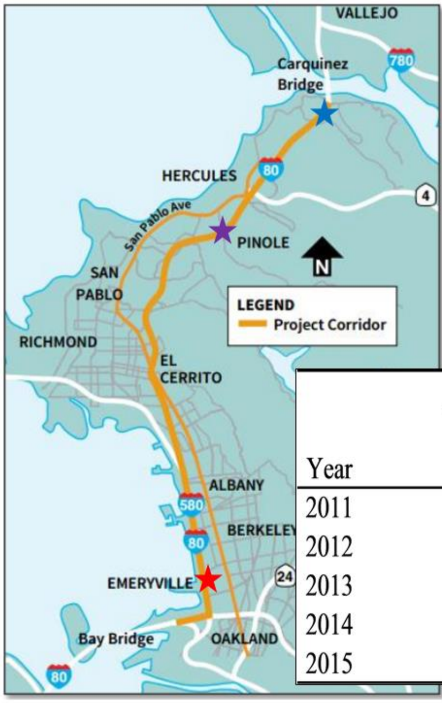
# 4. ANALYSIS AND RESULTS

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

## 4.1 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 (Caltrans, 2016a & 2017)*




| | AADT | | |
|---|---|---|---|
| Year | West of Ashby ★ Milepost 9.89 | West of Pinole Valley ★ Milepost 21.86 | West of Pomona ★ Milepost 26.84 |
| 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 |

## 4.2 ANALYSIS OF 19-MILE I-80 SMART CORRIDOR

This first set of analyses considers the full length of the eastbound project corridor, a distance of 19 miles, during May midweekdays (i.e., Tuesdays, Wednesdays, and Thursdays) for each year "Before" (2011–2016) and "After" (2017).

### 4.2.1 Speed and Travel Time

The average speed along the corridor was generated using INRIX Insights, averaged by hour, and is shown below as a bar chart in Figure 6. A heat map of speeds along the corridor, comparing only 2016 to 2017, is shown below in Figure 7.

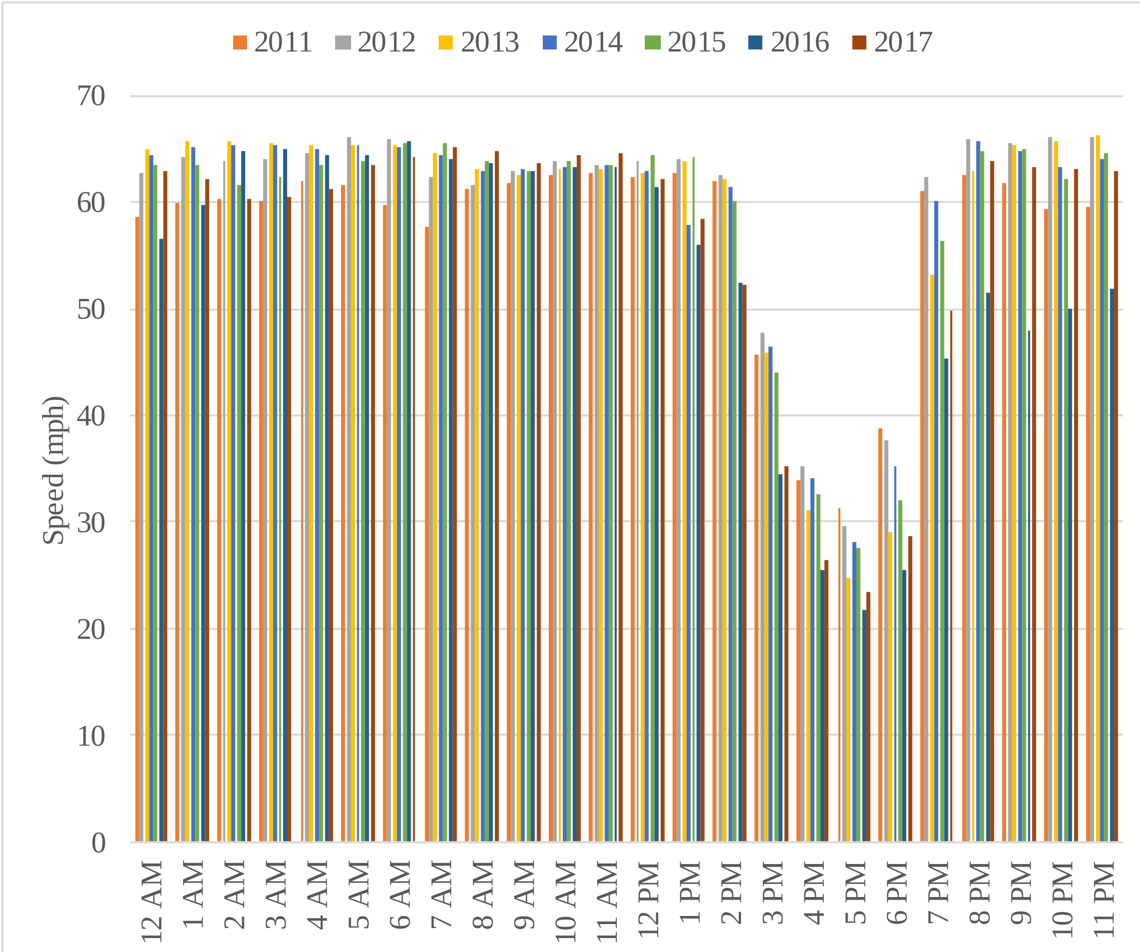



*Figure 6: Bar chart of hourly midweekday speed for 19-mile eastbound I-80 SMART Corridor 2011–2017*

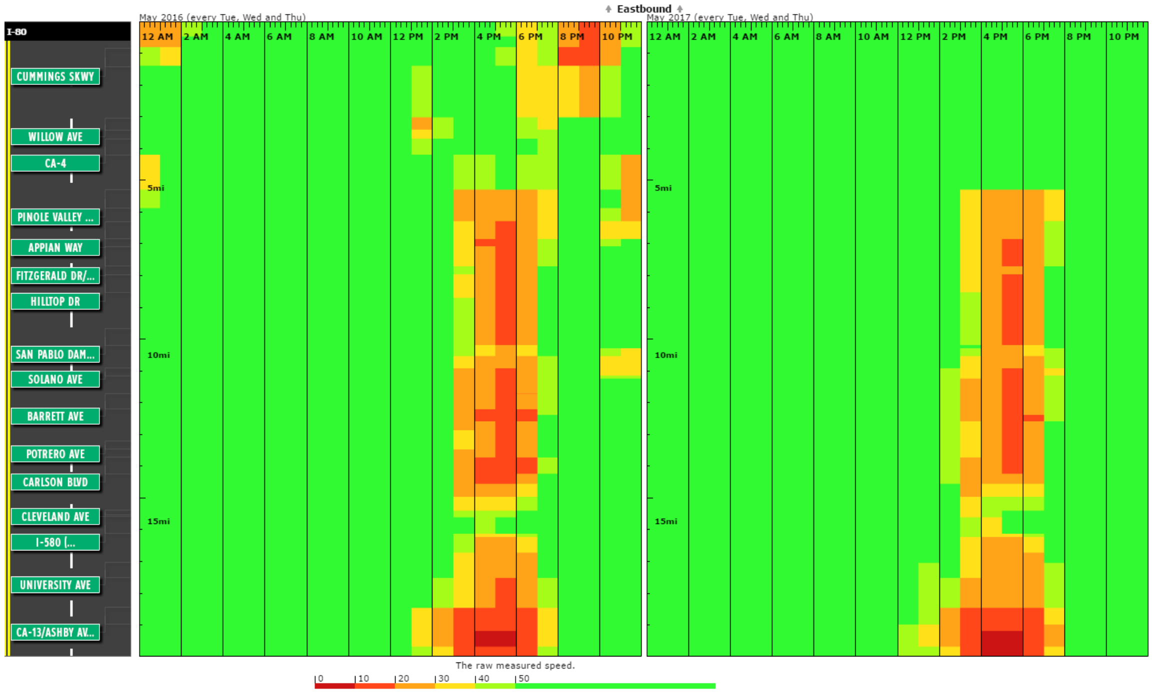



*Figure 7: Heat map of hourly midweekday speed along 19-mile eastbound I-80 SMART Corridor 2016–2017*

The figures above indicate that traffic generally moves close to free-flow speed outside of the PM peak hours, which is when the eastbound direction carries commuters returning home from San Francisco and Oakland. However, the decrease in speed associated with these PM peak hours can begin as early as the 12 PM hour on the westernmost portion of the corridor and can last into the 7 PM hour. This potentially early onset of congestion and late amelioration of congestion causes issues related to travel time reliability. During the congestion, speeds dropped to well below half of their free-flow value during the worst hours (typically 4, 5, and 6 PM).

Comparing only 2016 to 2017, it appears the ARM system is associated with small increases in speed that contribute to a slight lessening of the congested period. However, looking at the historical trends, speeds varied from year to year and effects are harder to discern.

The travel time for the corridor, averaged by hour, is shown below in Figure 8.

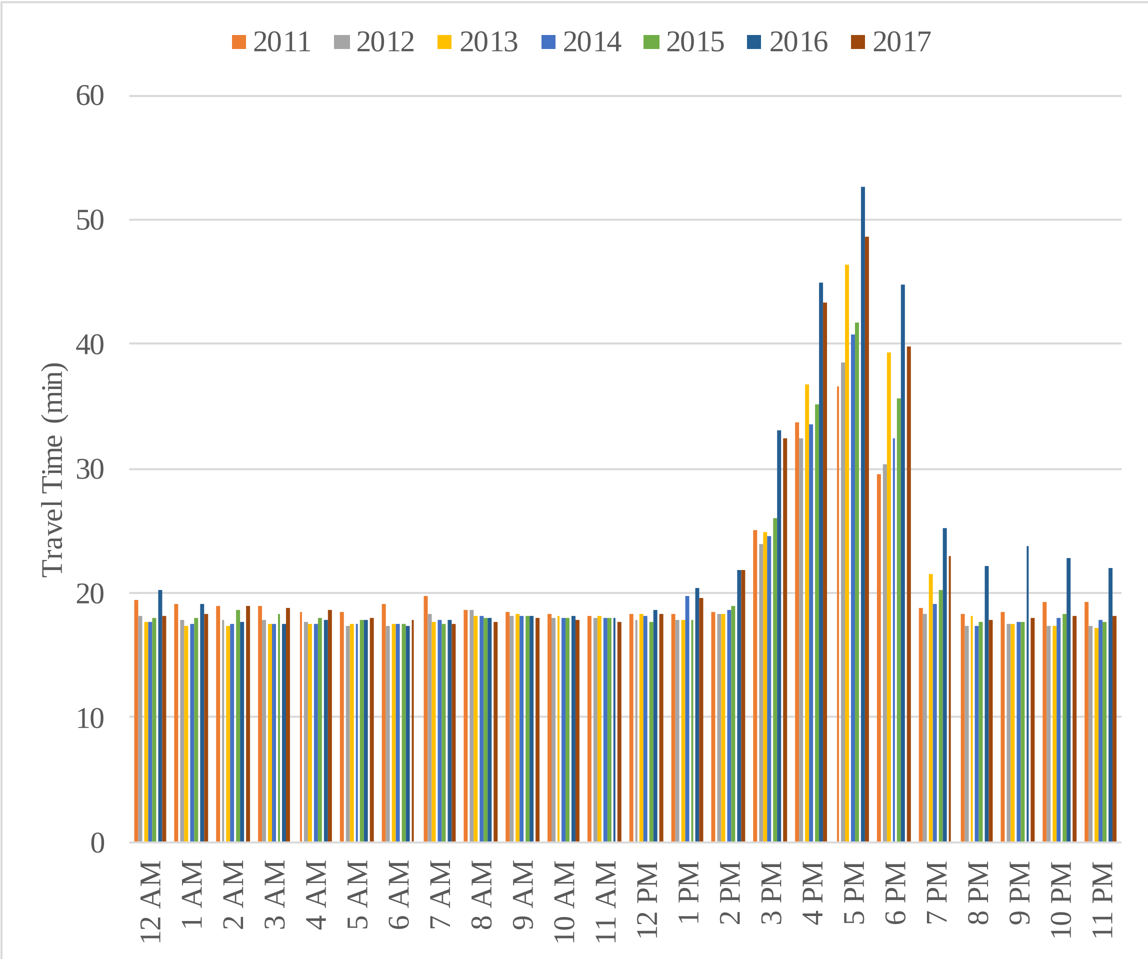



*Figure 8: Hourly midweekday travel time for 19-mile eastbound I-80 SMART Corridor 2011–2017*

The free-flow travel time for the corridor is approximately 17.5 minutes. Generally, travel times are close to this except during the PM peak hours when they can rise well above 35 minutes. The historical travel times have been variable during the PM peak hours, though it appears they may be on a slight increasing trend since 2011.

### 4.2.2 Travel Time Reliability Measures

Hourly Buffer Indices (Figure 9), Planning Time Indices (Figure 10), and Travel Time Indices (Figure 11) were computer for the 19-mile corridor.

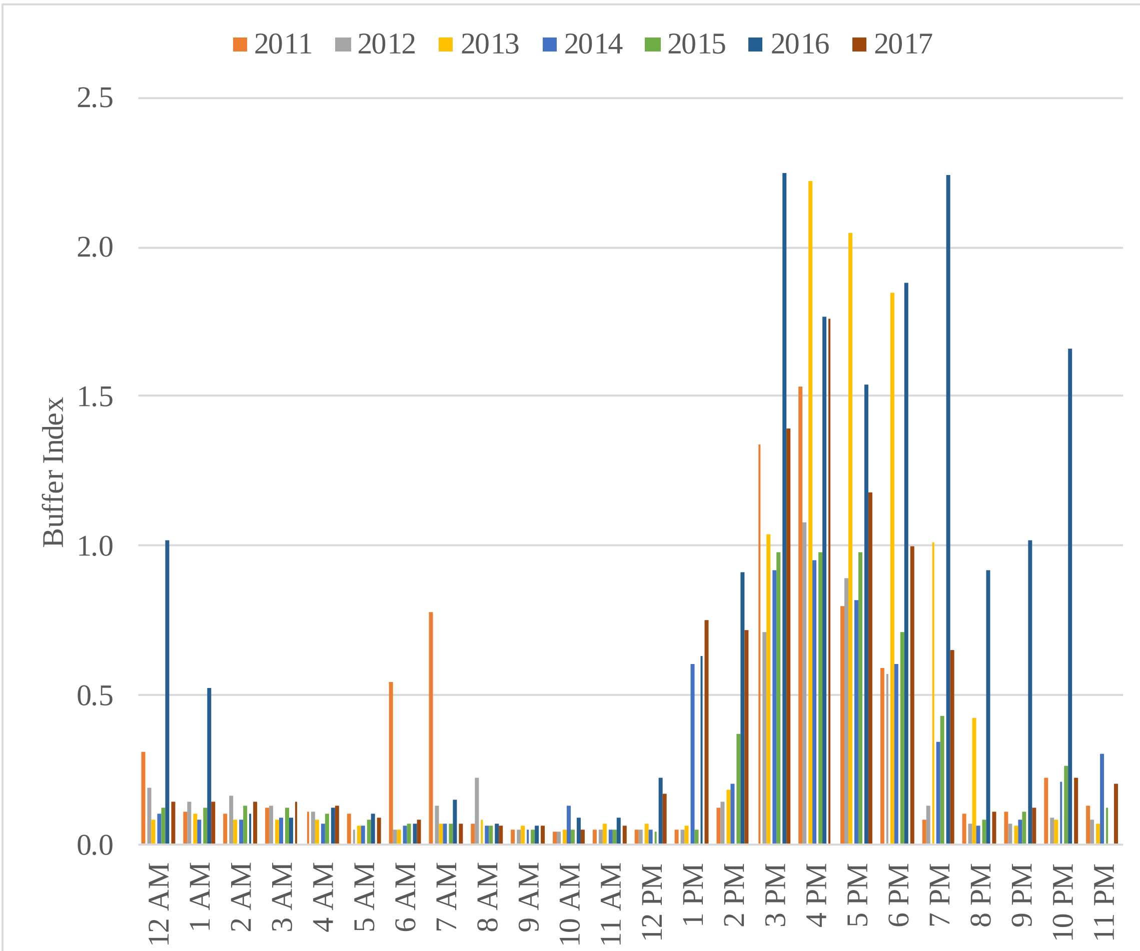



*Figure 9: Hourly midweekday buffer index for 19-mile eastbound I-80 SMART Corridor 2011–2017*

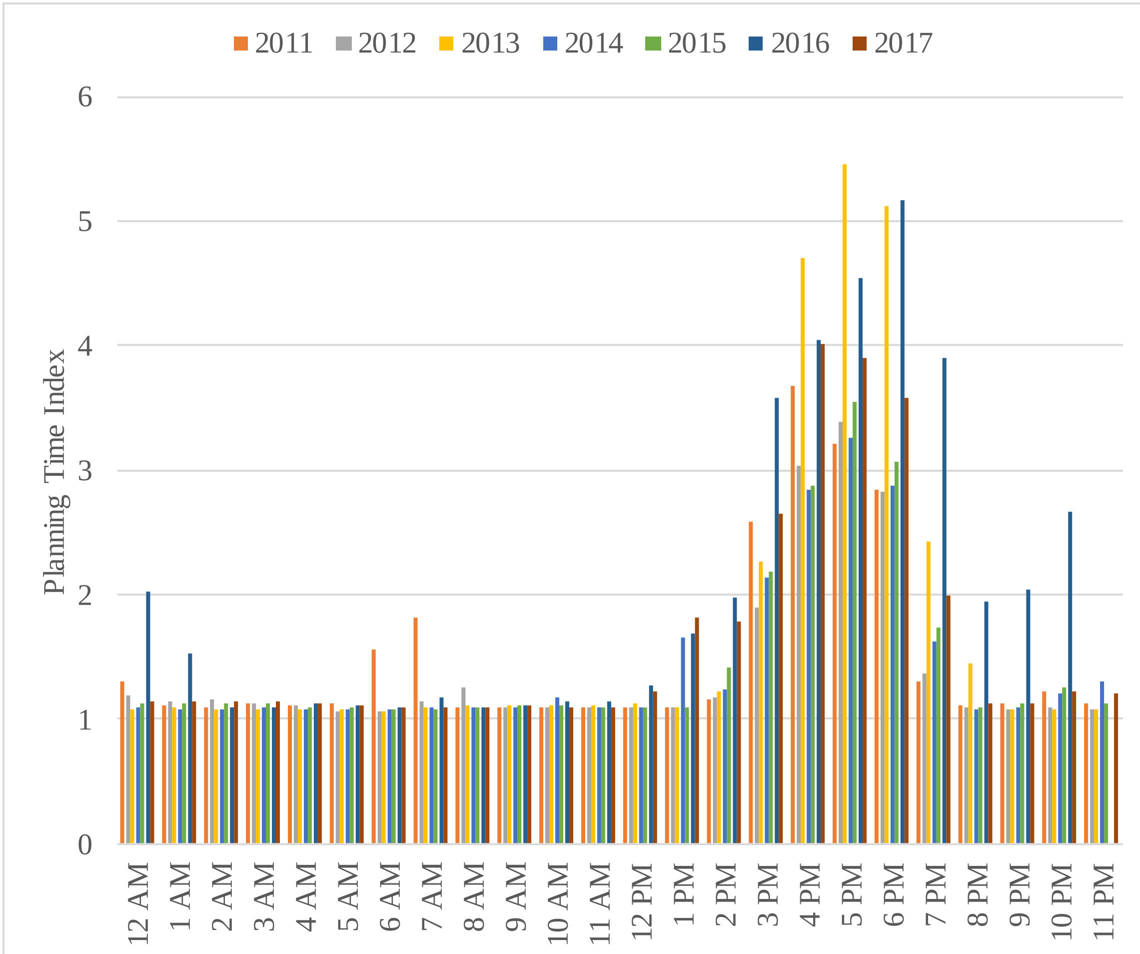



*Figure 10: Hourly midweekday planning time index for 19-mile eastbound I-80 SMART Corridor 2011–2017*

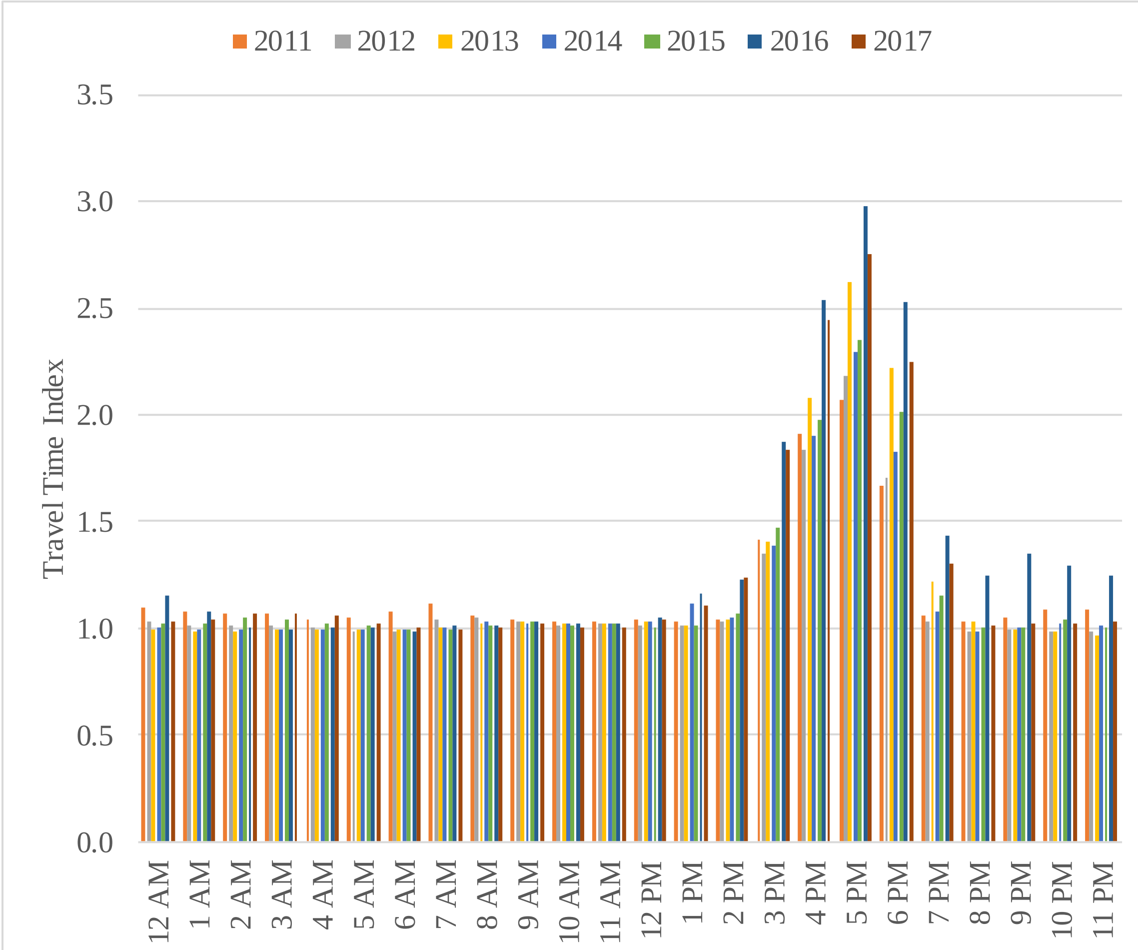



*Figure 11: Hourly midweekday travel time index for 19-mile eastbound I-80 SMART Corridor 2011–2017*

As seen in the figures above, for the entire 19-mile eastbound corridor the indices all varied widely since 2011 during the congested PM peak hours. In general, during the off-peak periods from midnight to noon, the indices remained low (with a few exceptions). Regardless of the oscillating year over year trends, it can be seen that during the worst of the congestion users often need to allow well over 3 times the free-flow travel time to ensure 95% on-time arrivals.

## 4.3 ESTIMATION OF UNRELIABILITY INDICATOR

To calculate the Unreliability Indicator $UI_r$ defined by Van Lint et al. (2008) $90^{th}$, $50^{th}$, and $10^{th}$ percentile values of travel time need to be estimated. INRIX data directly only provides $95^{th}$, Average, and $5^{th}$ percentile values. To estimate the former set of values, i.e., $90^{th}$, $50^{th}$, and $10^{th}$ percentiles, travel time data for all study days was downloaded at the 1-minute granularity and analyzed at 5-minute intervals. Therefore, there were 60 to 75 travel time observations for any given 5-minute period on a study day (e.g., 1:00 PM to 1:05 PM) depending on the number of study days (i.e., midweek days) in each month. Using these observations, needed travel time percentiles can be estimated for the Unreliability Indicator equation.

As an alternative to calculating the Unreliability Indicator using this process, a new measure was created using percentiles that are readily available through INRIX Insights. For this method, called the Modified Unreliability Indicator (MUI), the 5th and 95th percentile travel times (directly available from INRIX) were substituted for the 10th and 90th percentile, respectively. Additionally, the average travel time (also directly available from INRIX) was substituted for the 50th percentile. Modified equations for $\lambda_{skew}$ and $\lambda_{var}$ values are shown below as Equations 6 and 7. The results are then used to calculate the MUI based on the previously established Equation 5, shown again below.

$$\lambda_{skew} = \frac{T_{95} - T_{avg}}{T_{avg} - T_5} \ldots Eq. 6$$

$$\lambda_{var} = \frac{T_{95} - T_5}{T_{avg}} \ldots Eq. 7$$

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

The MUI was compared to the Unreliability Indicator (UI) for the entire eastbound I-80 corridor, shown in Figure 12 below.

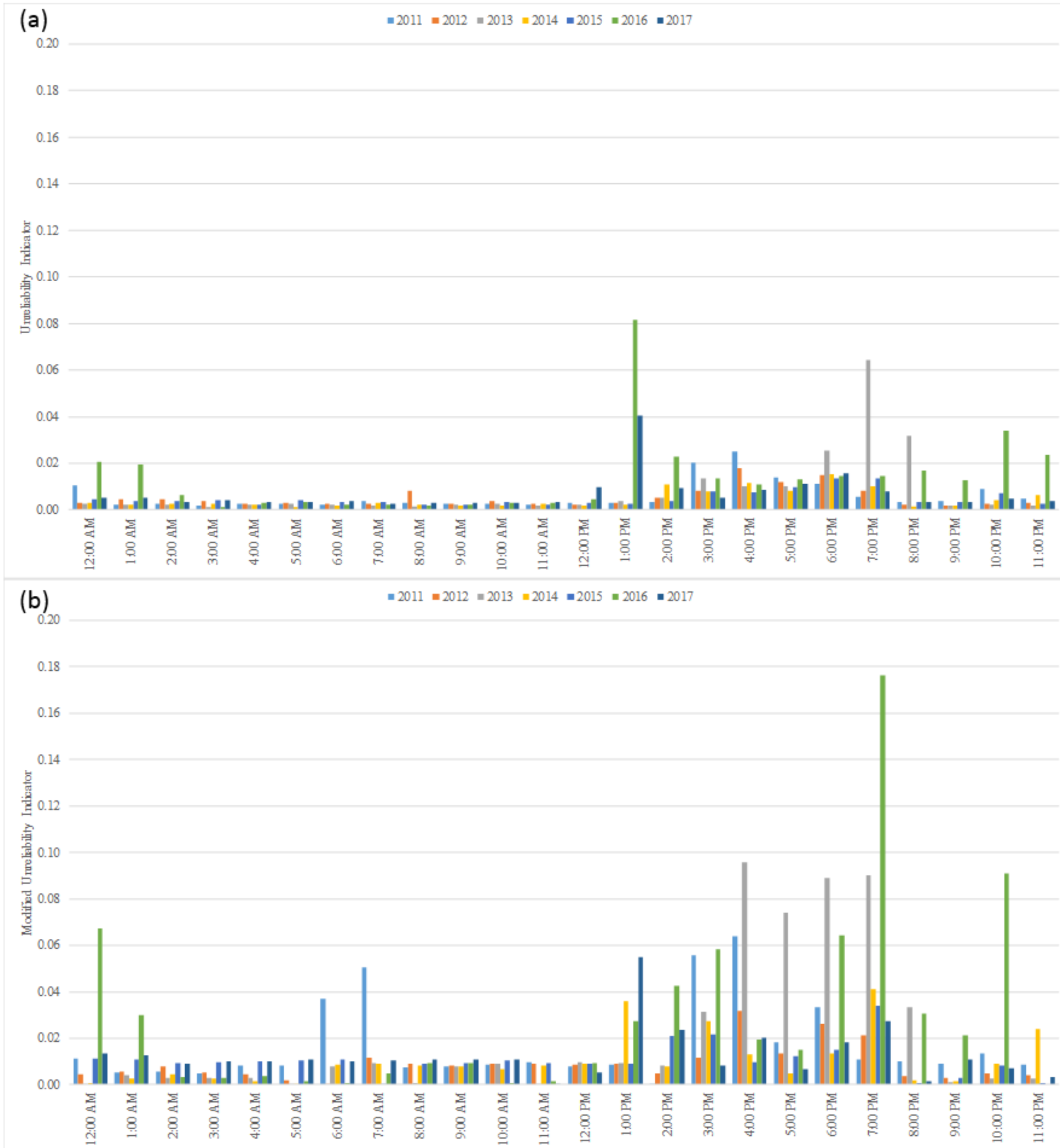



*Figure 12: Comparison of Unreliability Indicators*

Both unreliability indicators show that the shoulders of the PM peak period, typically the 1 PM and 7 PM hours, are the least reliable. However, the MUI shows more unreliability throughout the day than the UI. Despite their similarities and the greater practicality of estimating the MUI, they are not necessarily interchangeable. The relationship between these two indicators is explored in section 4.7.

## 4.4 SPATIAL ANALYSIS USING SUB-SEGMENTS

In addition to analyzing the entire study corridor of 19 miles, smaller segments were analyzed by dividing the corridor into three sequential sub-segments. The first chosen boundary point was the I-80/I-580 interchange near Richmond where capacity reduces from 5 to 4 lanes. The second chosen boundary point was the Pinole Valley Road interchange. The Bottleneck Ranking tool on INRIX Insights confirmed anecdotal reports that a bottleneck routinely forms on eastbound I-80 at Pinole Valley Road. The segment lengths, sequentially, were 4, 10, and 5 miles. Buffer indices for each sub-segment are shown below sequentially in Figure 13, Figure 14, and Figure 15.

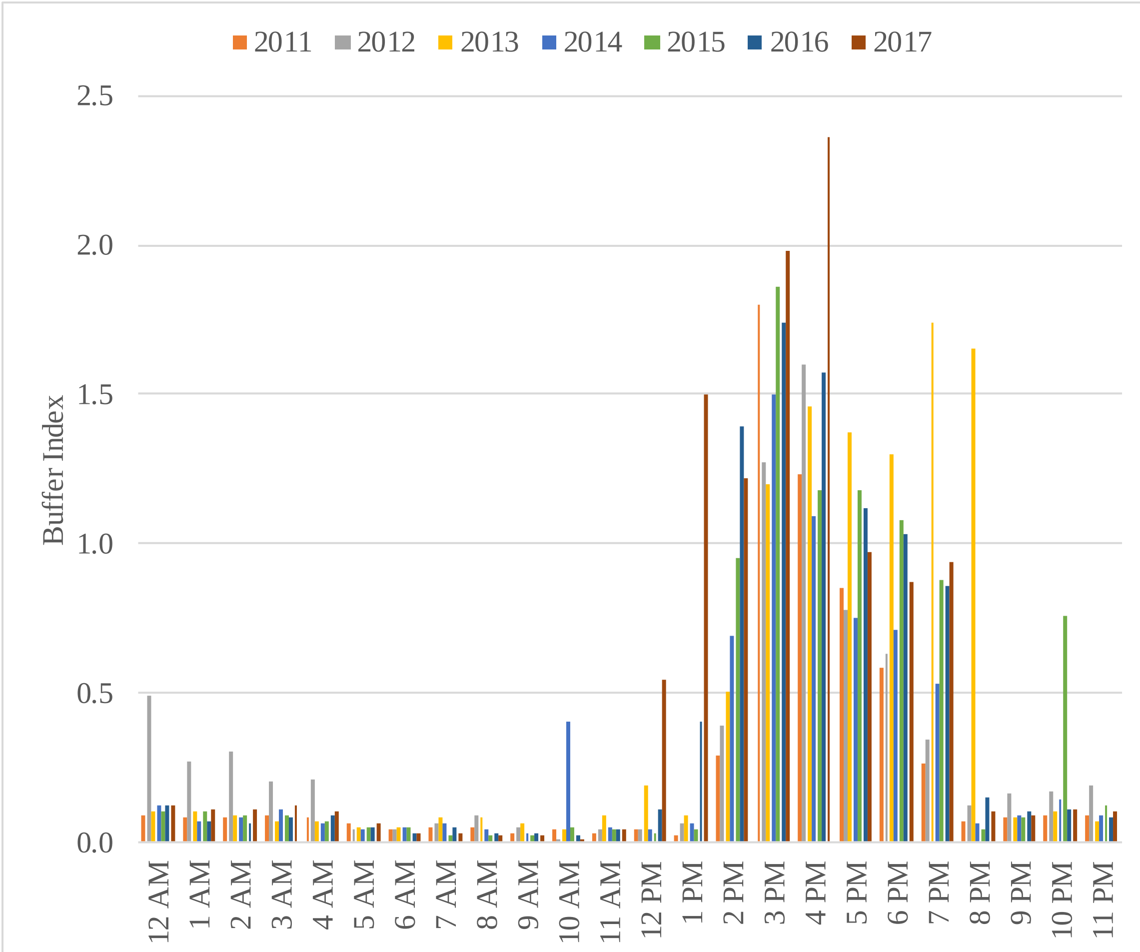



*Figure 13: Hourly midweekday buffer index for eastbound I-80 between Powell St. and I-580 (Richmond) 2011–2017*

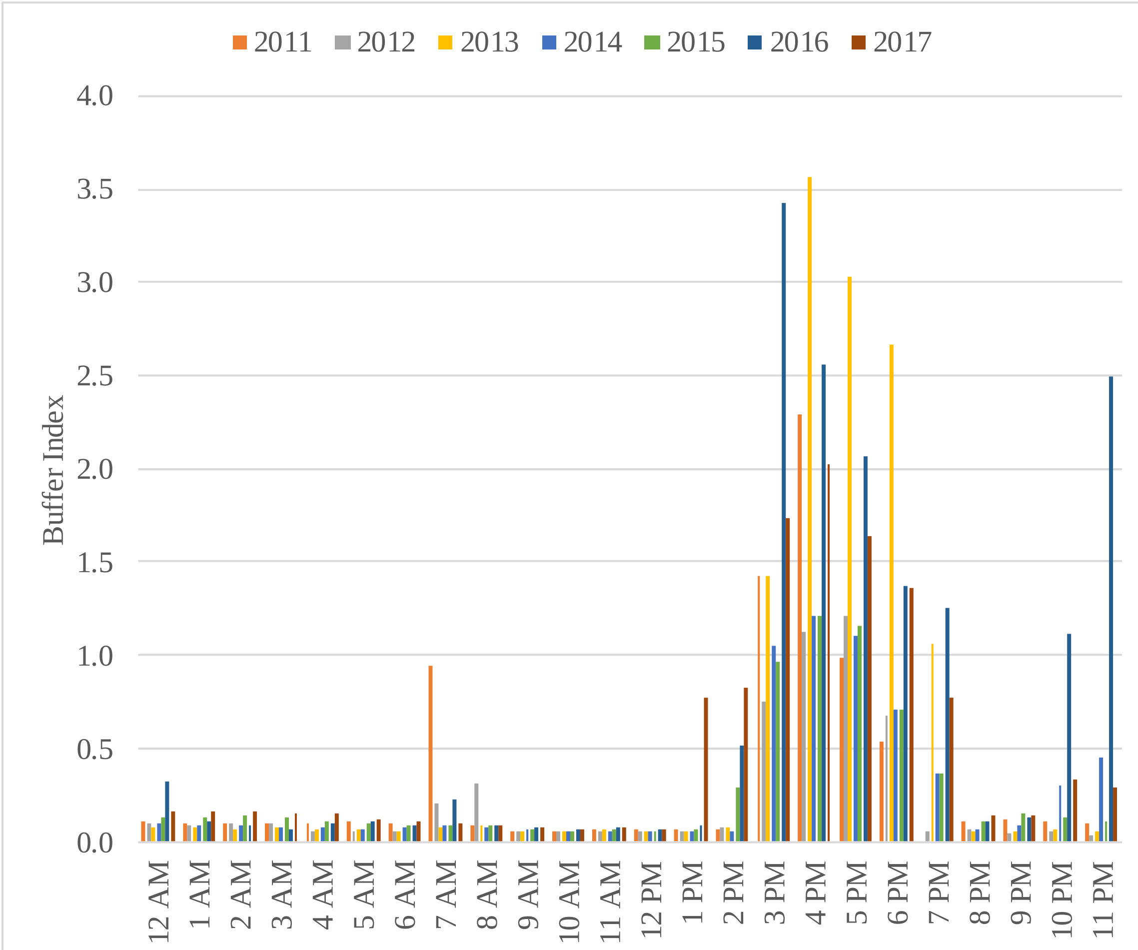



*Figure 14: Hourly midweekday buffer index for eastbound I-80 between I-580 (Richmond) and Pinole Valley Rd. 2011–2017*

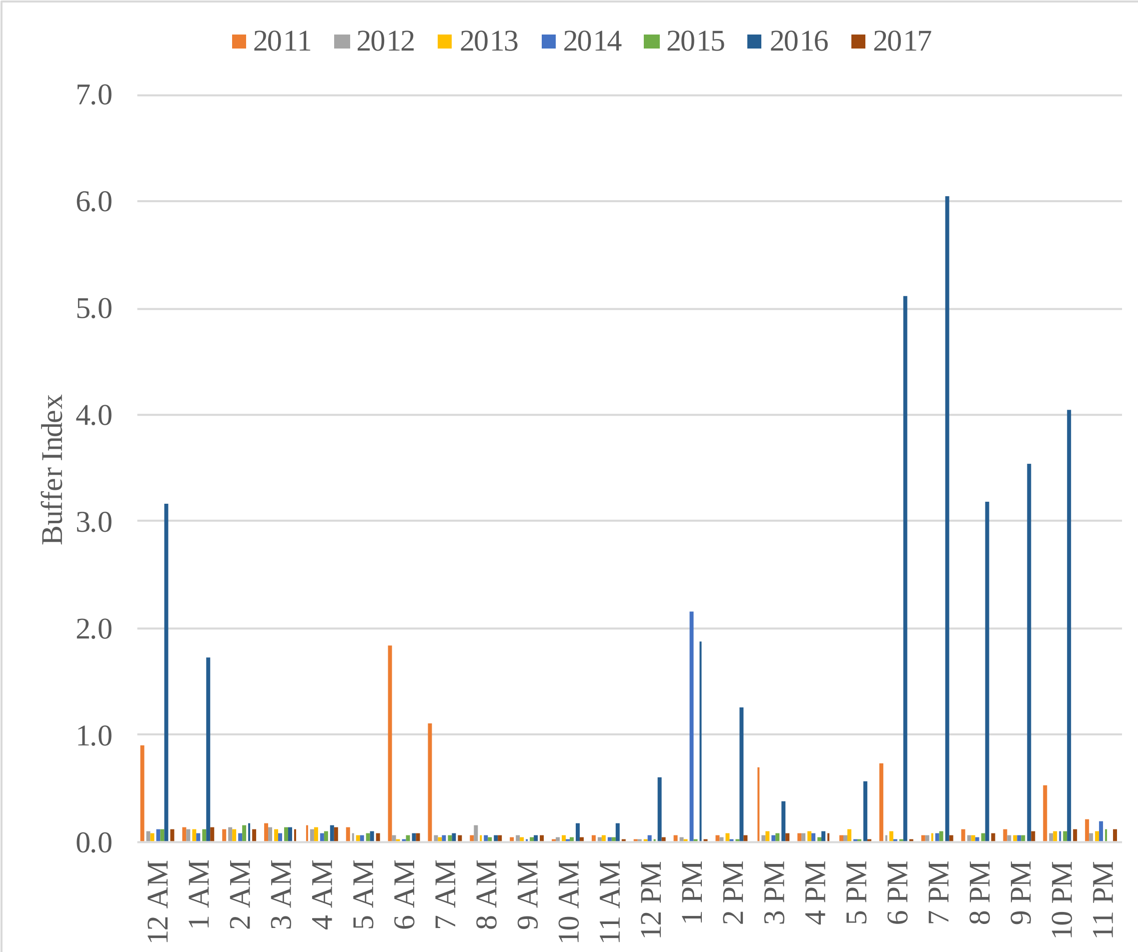



*Figure 15: Hourly midweekday buffer index for eastbound I-80 between Pinole Valley Rd. and Pomona St. 2011–2017*

The sub-segment analysis shows that, aside from unusual conditions in 2016, the final 5 miles of the corridor, after the bottleneck location, tend to be very reliable throughout the day. The first 4 miles of the corridor appear to be slightly less reliable than the middle segment during the PM peak hours.

## 4.5 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 16 shows a schematic diagram depicting three such segments as an illustration.

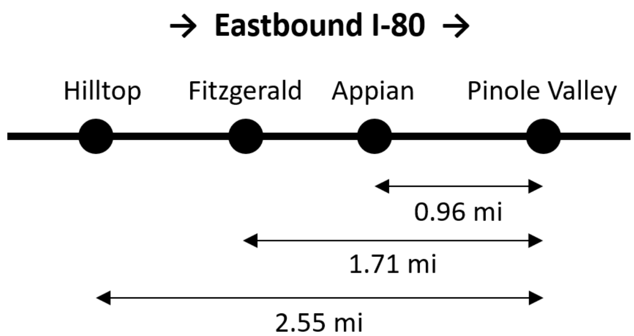



*Figure 16: Three upstream segments closest to Pinole Valley Road bottleneck*

MUI for the month of May for years 2011-2017 was estimated for 9 segments identified using the process depicted in Figure 16. For each segment from 2011–2017 the MUI was estimated for the 5 PM hour and is shown in Figure 17.

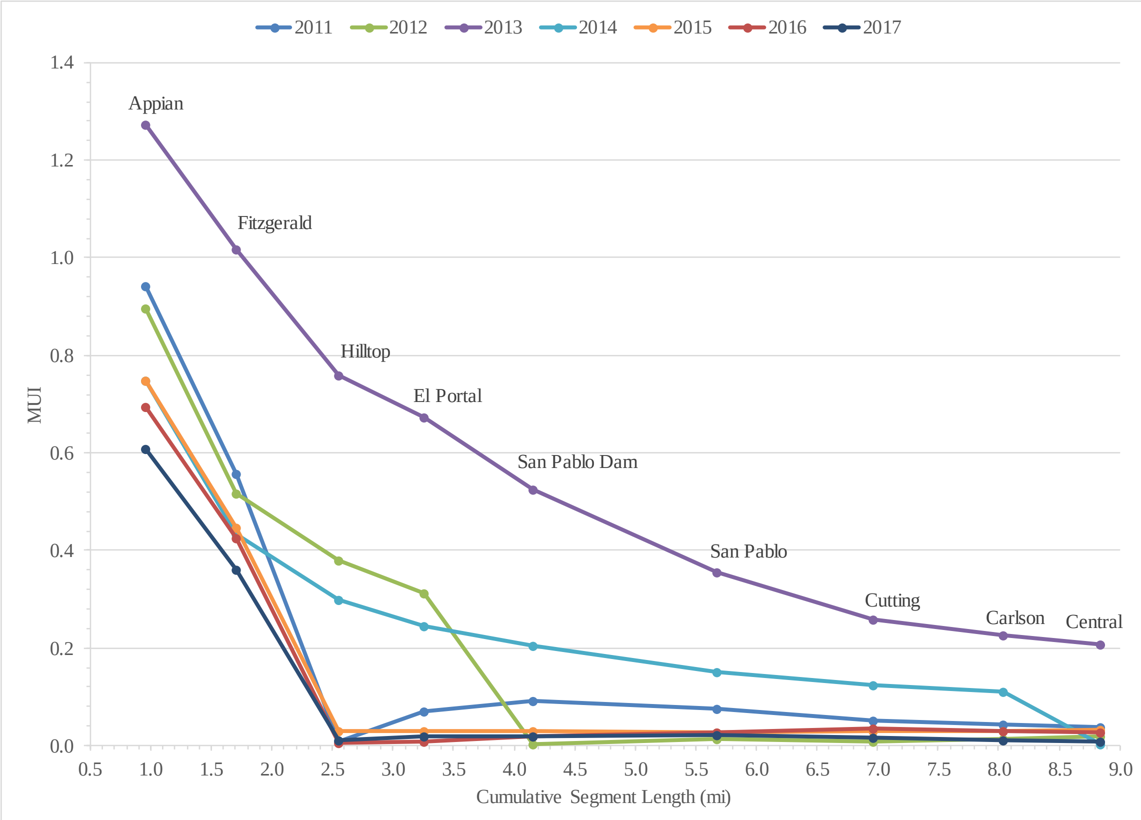



*Figure 17: Midweekday Modified Unreliability Indicator for cumulative segment lengths upstream of Pinole Valley interchange on eastbound I-80 2011–2017*

It is worth noting that the month of May 2017, after activation of the ARM system, was generally estimated to have the lowest MUI for each segment. This may reflect the effectiveness of the new ARM system. It was also observed that MUI typically reduces to a low value about 2.5 miles upstream of the bottleneck location. Hence, in the following section, the annual trends in MUI for three corridor segments up to 2.5 miles upstream of the Pinole Valley interchange are analyzed.

## 4.6 ANNUAL TRENDS IN UNRELIABILITY INDICATORS WITH INCREASING TRAVEL DISTANCE ALONG THE CORRIDOR

Further analysis was conducted for the three segments that included the closest interchanges upstream of the bottleneck location: Appian, Fitzgerald, and Hilltop (see

Figure 16). In addition to an examination of annual trends in MUI, trends in travel time, traffic incidents, and Buffer Index were also examined. Travel time distributions for the three study segments during the 5 PM hour are shown in Figure 18.

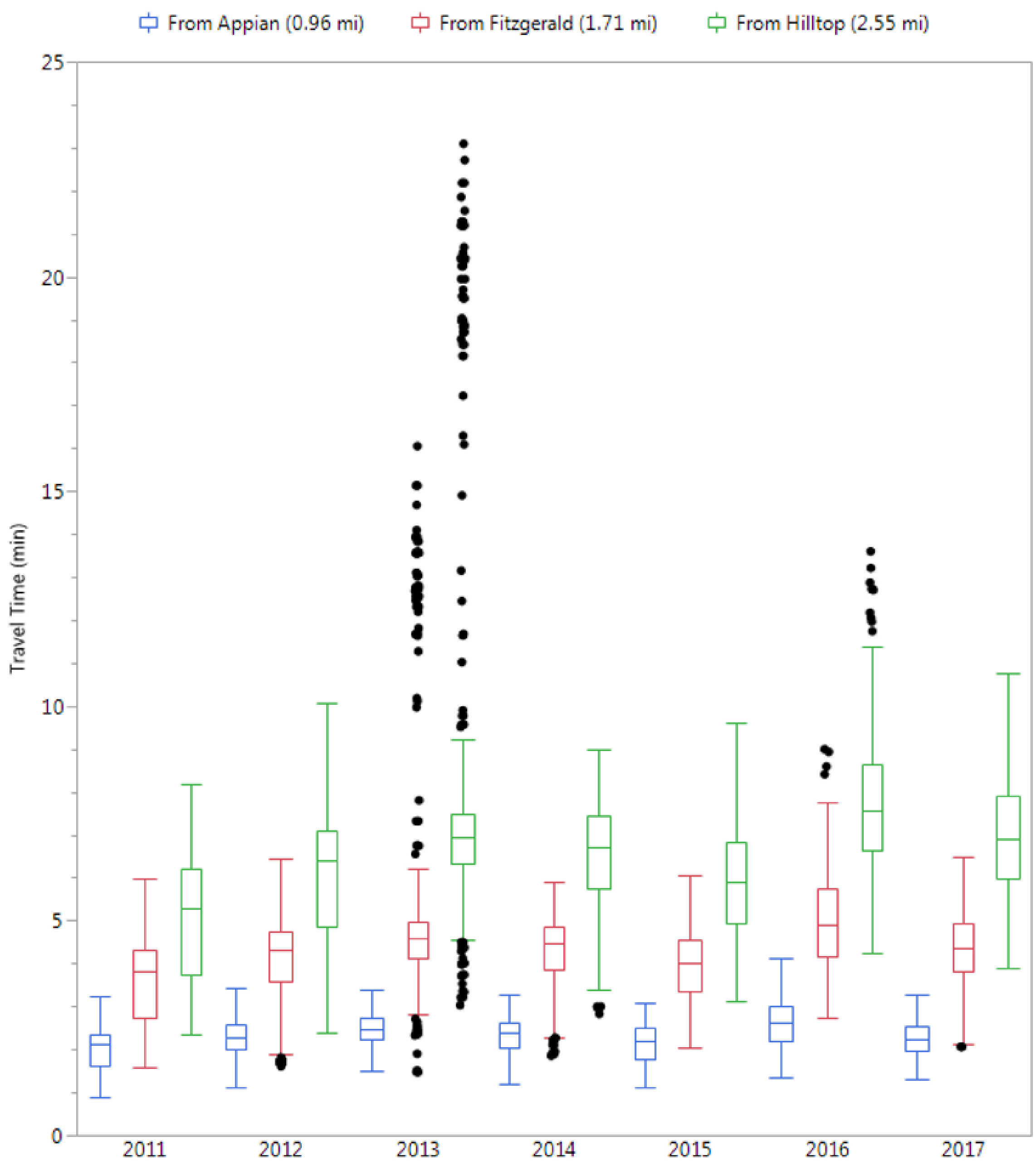



*Figure 18: Midweekday Travel Time Distribution during 5 PM hour for three segments on eastbound I-80 (2011–2017)*

While the months of May during 2013 and 2016 had numerous outliers with high travel time, all of the other years, including 2017, did not have any.

Traffic incidents and events for the month of May were available on INRIX Insights for the study segments beginning with 2013. For traffic incidents and events, those occurring downstream of the bottleneck location up to the next interchange were included as well, adding an additional 1.5 miles. Buffer index, MUI, and UI were estimated for the 5 PM hour beginning May 2011. These trends are shown below in Figure 19. The circular blue data points represent historical values (from 2011– 2016) of each measure (i.e., Incident Count, Buffer Index, MUI, and UI) and are used to estimate the trends shown in Figure 19(d) through Figure 19(l). The square red data points in each chart represent the measures post-implementation (from May 2017).

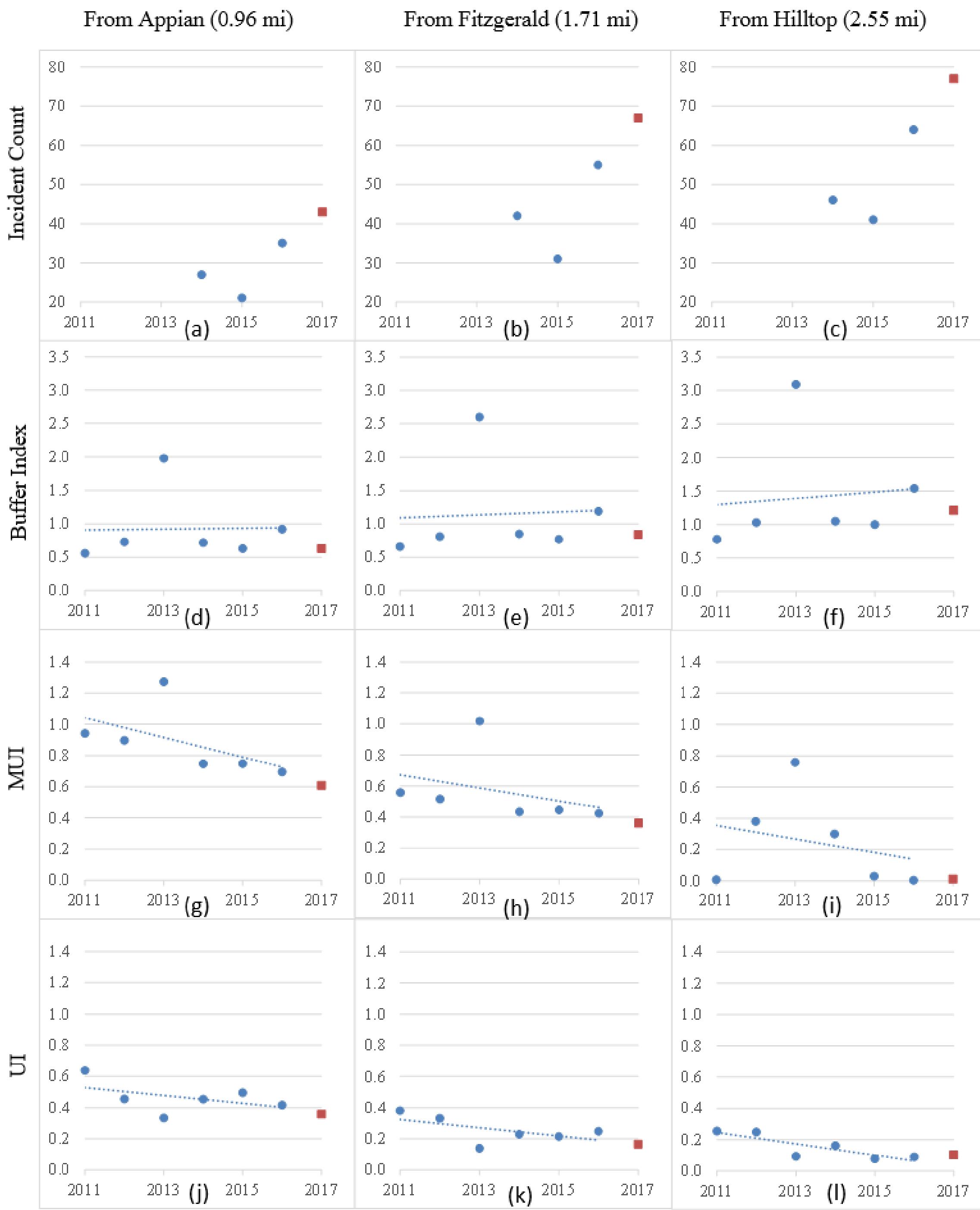



*Figure 19: Midweekday Incident Count, Buffer Index and Modified Unreliability Indicator for three segments on eastbound I-80 (2011–2017)*

Figure 19(a) through Figure 19(c) indicate that the incident counts in these segments were increasing during the years before ARM. Buffer Index had a slight increasing trend during the years 2011 through 2016. MUI and UI show a decreasing trend for the years 2011 through 2016. Looking at 2017 values, the incident count was the highest of recent years. Despite this, the study segments all experienced a Buffer Index improved from the historical trend and MUI on track with the historical decreasing trend. However, for UI, the 2017 value is slightly above the historical trend for the longest of the three segments.

## 4.7 CORRELATION BETWEEN UI AND MUI

MUI is an alternate measure used in this study which allows for the calculation of unreliability using the travel time metrics readily available from the INRIX Insights data. In order to better understand the relationship between UI and MUI, correlation coefficients were estimated to compare the corresponding travel times used in the equations in addition to the measures themselves.

The correlation coefficients for the full length of the corridor were calculated to compare the UI and MUI. Additionally, the corresponding travel times used in the equations were compared (i.e. the tenth percentile travel time used in the UI equation was compared to the fifth percentile travel time used in the MUI equation). Each correlation coefficient is calculated from 24 comparisons. The results are shown in Figure 20.

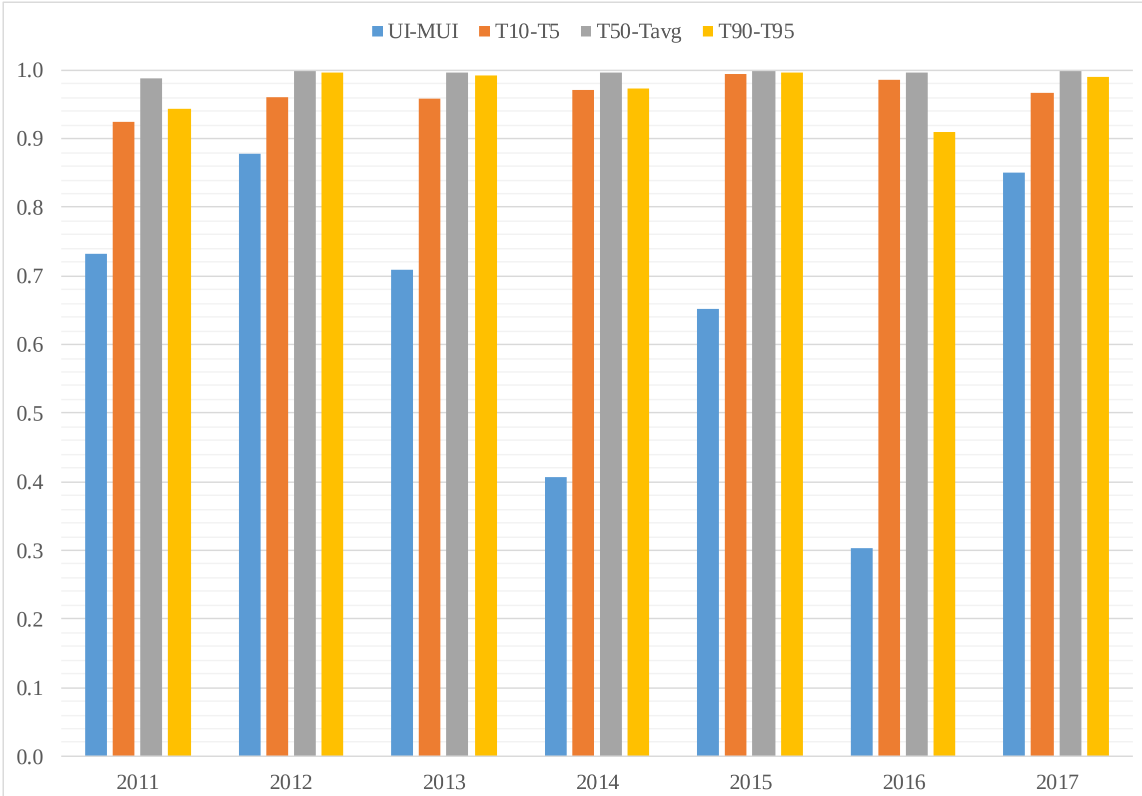



*Figure 20: Correlation Coefficients for 19-mile Corridor*

The correlation between UI and MUI varied from year to year, with some years above 0.8 and other years below 0.5. However, average and median travel time were strongly correlated for all years. UI and MUI had their lowest correlation of about 0.3 in 2016, the same year that $T_{90}$ and $T_{95}$ had their lowest correlation of about 0.91.

To give more context to the correlation coefficients between UI and MUI, and between $T_{50}$ and $T_{avg}$, the average value of each metric for each year was calculated for comparison, shown in Figure 21 below.

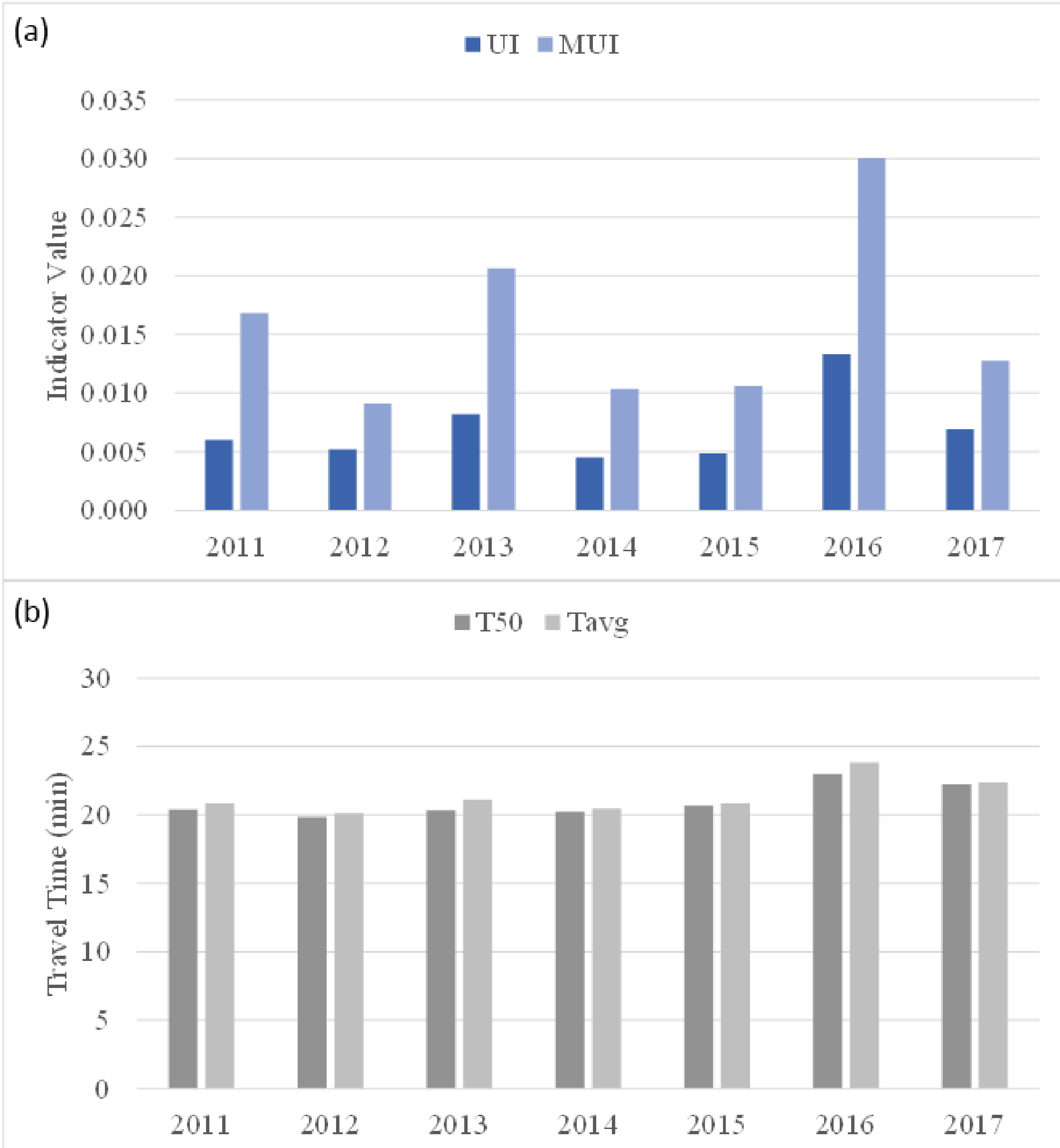



*Figure 21: Averages of Hourly Values Used in Correlation Calculation*

It can be seen that $T_{50}$ and $T_{avg}$ have similar average values each year, with $T_{avg}$ expectedly being slightly larger due to extreme values always being high and influencing the average more than the median. However, average MUI was always higher than average UI, often more than double, indicating that the two are likely not directly interchangeable. The segment level correlation analysis may be found in Appendix A.

# 5. 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.

## 5.1 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.

## 5.2 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.

## 5.3 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 B.

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 A: SEGMENT LEVEL CORRELATION ANALYSIS

In addition to the full length corridor, correlations were similarly calculated for the three overlapping segments immediately upstream of the Pinole Valley Road bottleneck. The results are shown in Figure 22, Figure 23, and Figure 24.

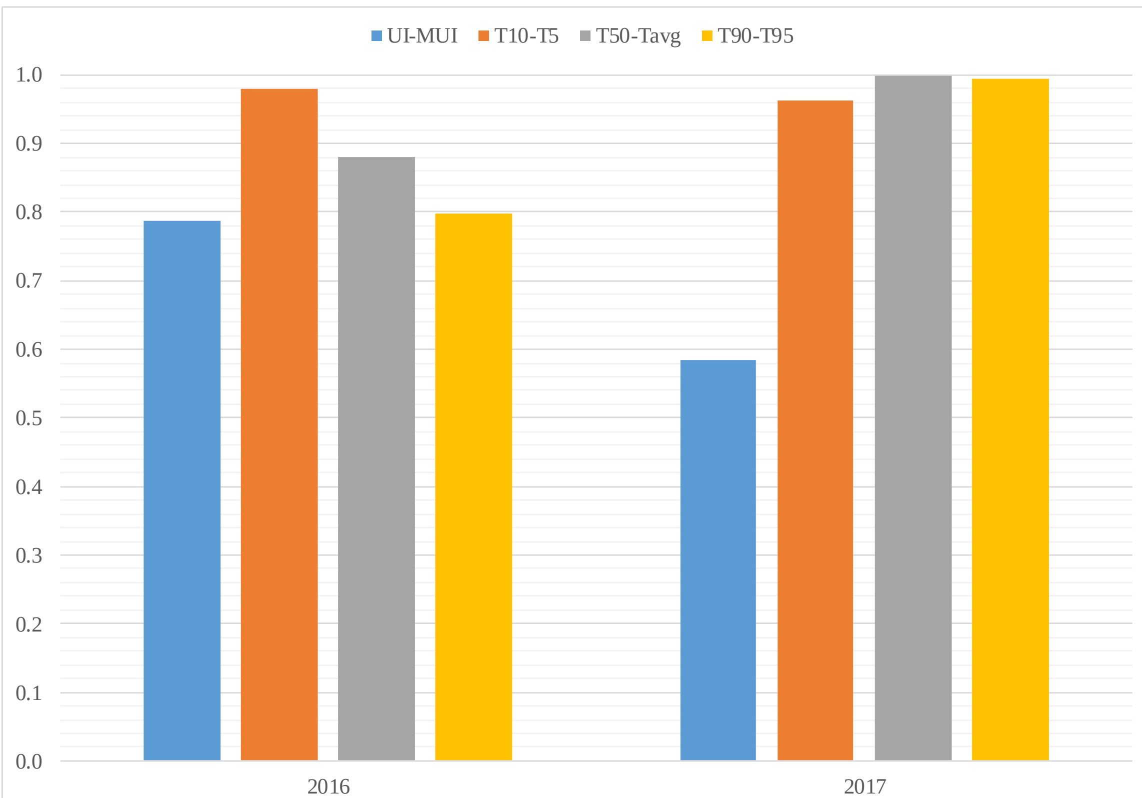



*Figure 22: Correlation Coefficients for 0.96-mile Segment*

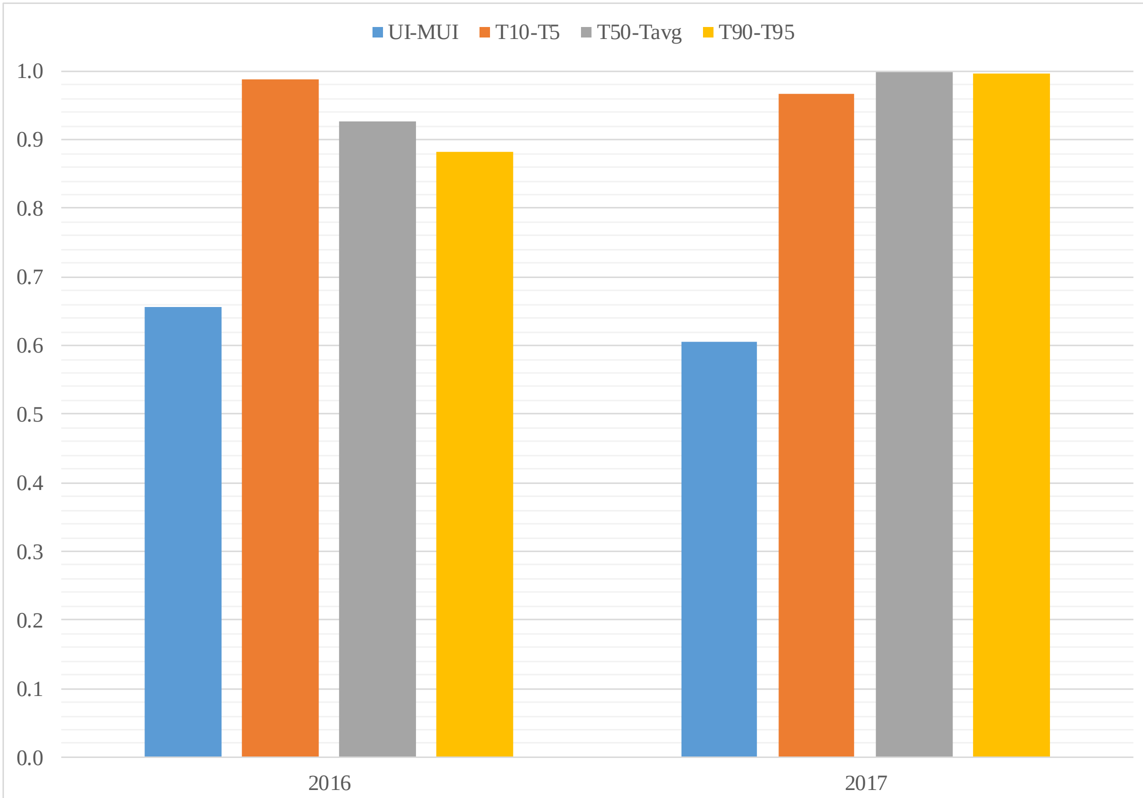



*Figure 23: Correlation Coefficients for 1.71-mile Segment*

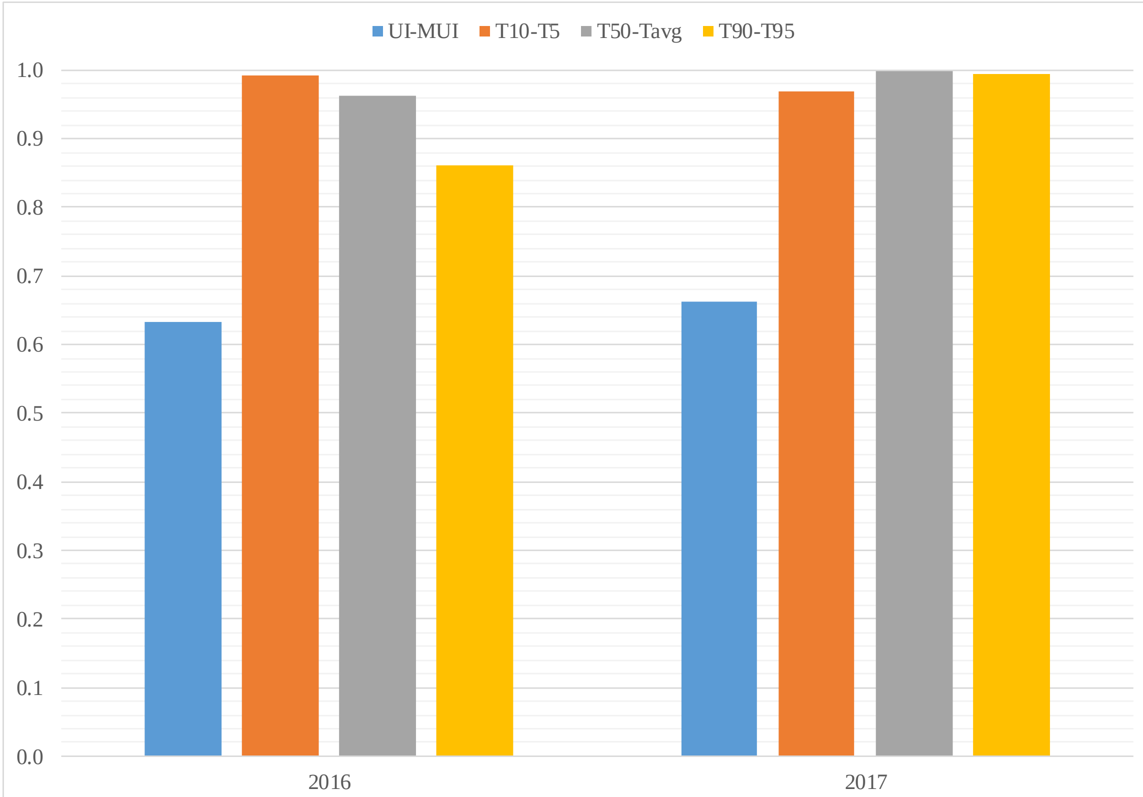



*Figure 24: Correlation Coefficients for 2.55-mile Segment*

The 2016 correlation for UI and MUI was stronger for the segments compared to the full length corridor, while the 2017 correlation was weaker. The travel time percentiles often showed a lower correlation compared to the full length corridor.

# APPENDIX B: USER SATISFACTION SURVEY INSTRUMENT

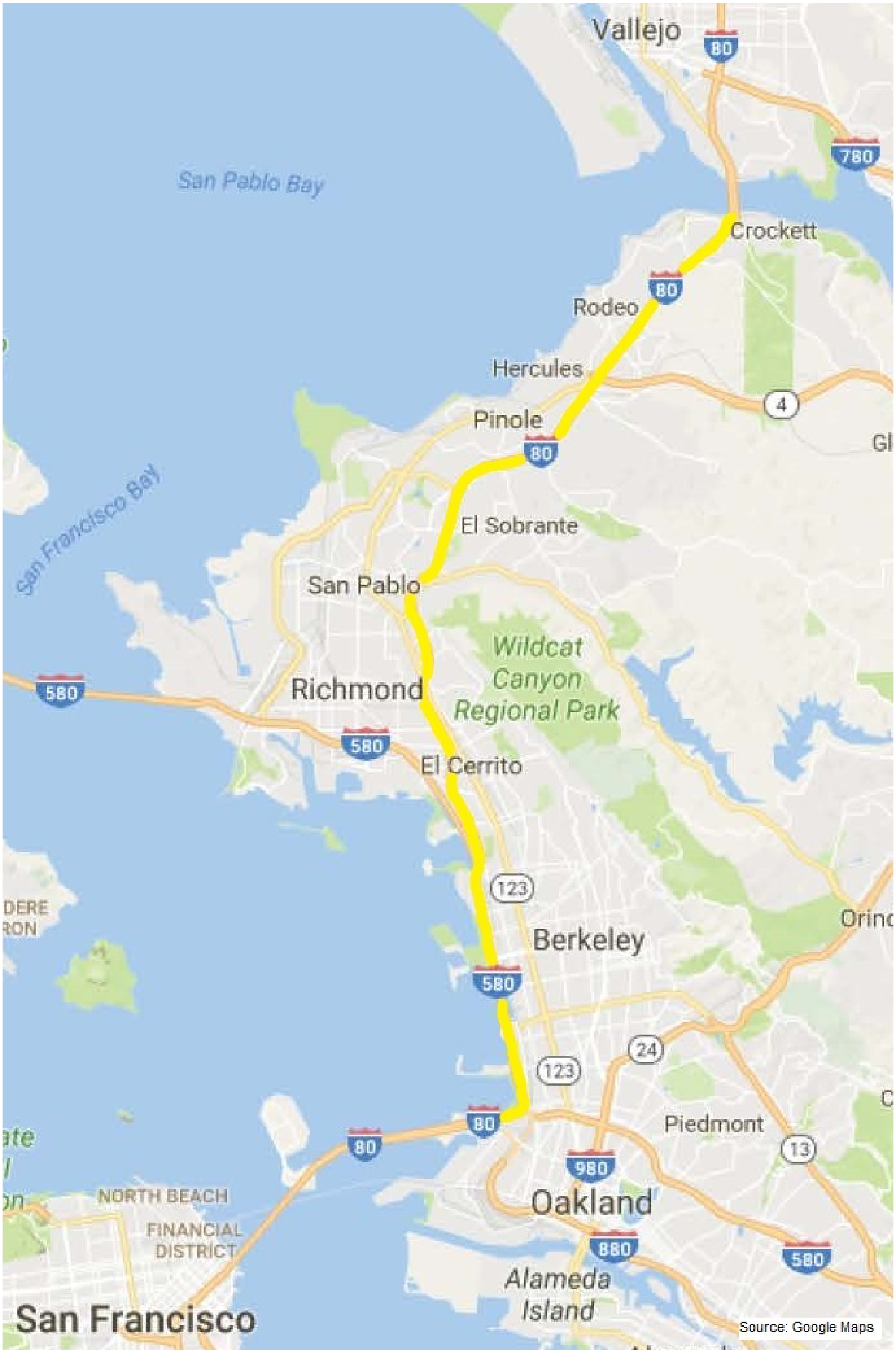
# I-80 Adaptive Ramp Metering User Satisfaction Survey

Cal Poly San Luis Obispo, in partnership with the Bay Area's Metropolitan Transportation Commission, is conducting a User Satisfaction Survey for the new adaptive ramp metering on I-80 in Alameda and Contra Costa Counties (see map and pictures below). Your input on how the ramp metering is working will help us to plan similar operational improvements to manage congestion. Your participation will take approximately 5-10 minutes.

Please only complete this survey if you have been using any section of I-80 highlighted below for six months or longer. Note that this survey only covers the new ramp metering on I-80 and not any other new features.

* Required

## Map of I-80 Ramp Metering Corridor




**Example of Ramp Metering**


## Example of Metering Light

1. **You must be 18 or older to participate in this survey.** *

*Mark only one oval.*

- ◯ I am 18 or older. *Skip to question 2.*
- ◯ I am under 18. *Skip to "Thank you for your interest in I-80.."*

*Skip to "Thank you for your interest in I-80.."*

## Thank you for your interest in I-80.

However, you must be 18 or older to participate in this survey.

*Start this form over.*

## Informed Consent Form

INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT, “Evaluation of I-80 Adaptive Ramp Metering: User Satisfaction and Operational Perspective”

A research project on Adaptive Ramp Metering is being conducted by Dr. Anurag Pande in the Department of Civil and Environmental Engineering at Cal Poly, San Luis Obispo. The purpose of the study is to evaluate user perceptions and acceptance of Adaptive Ramp Metering.

You are being asked to take part in this study by completing the following questionnaire. Your participation will take approximately 5-10 minutes. Please be aware that you are not required to participate in this research, you may omit any items that you prefer not to answer, and you may discontinue your participation at any time without penalty.

There are no risks anticipated with participation in this study. Your responses will be provided anonymously to protect your privacy. A $5.00 Starbucks gift card will be offered to each participant. You will have to provide your email address to obtain the card. Potential benefits associated with the study include making Adaptive Ramp Metering more effective and contributing to knowledge in the field of transportation.

If you have questions regarding this study or would like to be informed of the results when the study is completed, please feel free to contact Dr. Anurag Pande at (805) 756-2104, apande@calpoly.edu. If you have concerns regarding the manner in which the study is conducted, you may contact Dr. Michael Black, Chair of the Cal Poly Institutional Review Board, at (805) 756-2894, mblack@calpoly.edu, or Dr. Dean Wendt, Dean of Research, at (805) 756-1508, dwendt@calpoly.edu.

If you agree to voluntarily participate in this research project as described, please indicate your agreement by completing and submitting the following questionnaire. Please print a copy of this consent form now for your reference, and thank you for your participation in this research.

2. **Do you volunteer to participate?** *

*Mark only one oval.*

- ◯ Yes, I volunteer. *Skip to question 3.*
- ◯ No, I do not volunteer. *Skip to "Thank you for your interest in I-80.."*

*Skip to "Thank you for your interest in I-80.."*

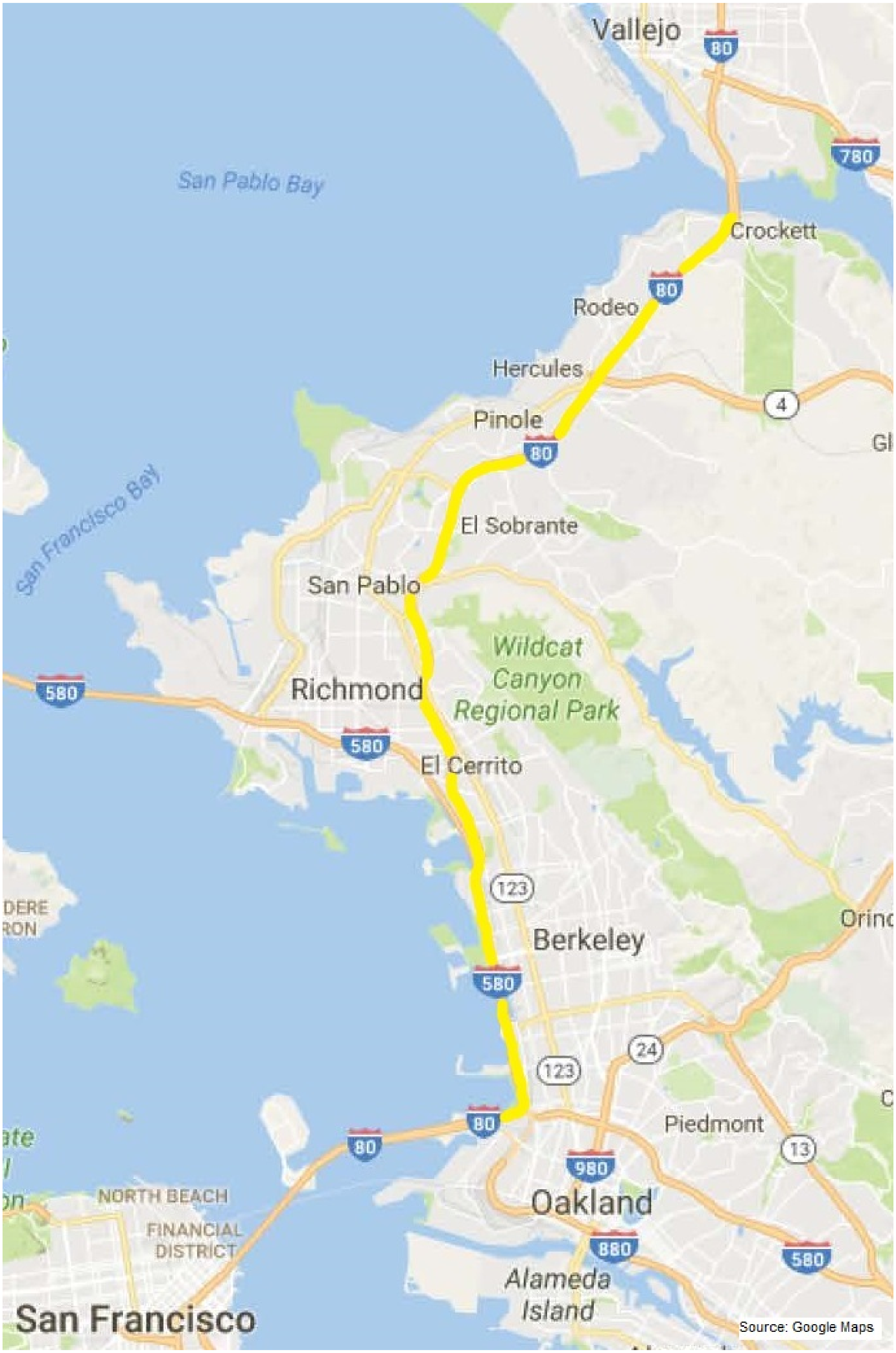
## Thank you for your interest in I-80.

However, in order to participate, you must select "Yes, I volunteer." at the bottom of the Informed Consent Form.

*Skip to question 2.*

## User Satisfaction Survey

## Map of I-80 Ramp Metering Corridor



3. **How long have you been using the highlighted section of I-80?**

*Mark only one oval.*

- Less than 1 year
- 1-5 years
- More than 5 years

4. **How often do you use the highlighted section of I-80?**

*Mark only one oval.*

- At least 4 days per week
- 2 to 3 days per week
- 1 or no days per week

5. **What times of day do you travel Westbound (towards Oakland/San Francisco) on I-80?**

Please select all that apply.
*Check all that apply.*

- [ ] Between 5 AM and 10 AM on weekdays
- [ ] Between 3 PM and 7 PM on weekdays
- [ ] Other times on weekdays
- [ ] Weekends

6. **What times of day do you travel Eastbound (towards Vallejo/Sacramento) on I-80?**

Please select all that apply.
*Check all that apply.*

- [ ] Between 5 AM and 10 AM on weekdays
- [ ] Between 3 PM and 7 PM on weekdays
- [ ] Other times on weekdays
- [ ] Weekends

7. **When you use the highlighted section of I-80, what is the total distance you are normally driving?**

*Mark only one oval.*

- Less than 5 miles
- 5-10 miles
- 11-20 miles
- 21-30 miles
- 31-40 miles
- 41-50 miles
- More than 50 miles

8. **What type of driver do you consider yourself?**

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Extremely Defensive | ◯ | ◯ | ◯ | ◯ | ◯ | Extremely Aggressive |

9. **Recently, what does the metering light look like when you are merging onto the highlighted section of I-80?**

*Mark only one oval.*

- ◯ Normally, the metering light is on
- ◯ Normally, the metering light is off (blank)
- ◯ I usually don't drive through any of the new ramp meters on this section

10. **Do you normally use a ramp meter that is for "HOV 3+"?**

*Mark only one oval.*

- ◯ Yes
- ◯ No
- ◯ I usually don't drive through any of the new ramp meters on this section

11. **Recently, what is your normal wait time to get through the ramp meter?**

*Mark only one oval.*

- ◯ No wait
- ◯ Up to 30 seconds
- ◯ Up to 1 minute
- ◯ Up to 2 minutes
- ◯ Up to 3 minutes
- ◯ Up to 4 minutes
- ◯ Up to 5 minutes or longer
- ◯ I usually don't drive through any of the new ramp meters on this section

12. **Please answer the following questions about the highlighted section of I-80:**

*Mark only one oval per row.*

| | Strongly Disagree | Slightly Disagree | Too soon to tell/No opinion | Slightly Agree | Strongly Agree |
|---|---|---|---|---|---|
| On this section of I-80, congestion is a problem. | ◯ | ◯ | ◯ | ◯ | ◯ |
| On this section of I-80, ramp metering is a good idea. | ◯ | ◯ | ◯ | ◯ | ◯ |

13. **Please answer the following questions about the results of the new ramp metering on I-80:**

*Mark only one oval per row.*

| | Strongly Disagree | Slightly Disagree | Too soon to tell/No opinion | Slightly Agree | Strongly Agree |
|---|---|---|---|---|---|
| It is now easier to merge onto the freeway. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| There is now less congestion on the freeway. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| There is now less stop-and-go traffic on the freeway. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Traffic now flows smoother on the freeway. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| The morning commute now takes less time overall. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| The afternoon commute now takes less time overall. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| My travel time is now more predictable. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Collisions are now less severe. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I now feel safer. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| The surface streets now have more congestion. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I am now more likely to take surface streets instead of I-80. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

14. **Please answer the following questions about the new ramp metering on I-80:**

*Mark only one oval per row.*

| | Strongly Disagree | Slightly Disagree | Too soon to tell/No opinion | Slightly Agree | Strongly Agree |
|---|---|---|---|---|---|
| The speed of the metering lights adjusts correctly for the current conditions. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Buses and carpools should receive priority when possible. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I would prefer to have more delay at the ramp meter so I could have less delay on the freeway. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Other drivers usually obey the metering lights. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| The new ramp meters were well explained to the public. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Overall, the new ramp meters are beneficial. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| More ramp meters should be built in the Bay Area. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

15. **What is your gender?**
*Mark only one oval.*

- Male
- Female
- Other
- Prefer not to answer

16. **What is your age?**
*Mark only one oval.*

- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65 or above
- Prefer not to answer

17. **What is the highest level of education that you have completed?**
*Mark only one oval.*

- Graduate School or higher
- College Degree
- Some college
- High School
- Did not graduate from high school
- Prefer not to answer

18. **What is your yearly personal income?**
*Mark only one oval.*

- $0 to $19,999
- $20,000 to $39,999
- $40,000 to $79,999
- $80,000 to $119,999
- $120,000 to $159,999
- $160,000 or above
- Prefer not to answer

19. **Taking all things into account, how satisfied are you with your life these days? (1 = extremely dissatisfied, 10 = extremely satisfied)**

*Mark only one oval.*

- 1 (extremely dissatisfied)
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10 (extremely satisfied)
- Prefer not to answer

20. **Please write any comments you have about the ramp metering on I-80:**

## Thank You

21. **Thank you for your participation in this survey. To receive a $5.00 Starbucks gift card, please write your email address below.**

Your email address will only be used to send you your gift card. Also, it will not be associated with your survey answers.