SAN FRANCISCO CASE STUDY:

PEDESTRIAN SAFETY AND BUS EFFICIENCY TRADEOFFS

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BY AGNES LO

FACULTY ADVISOR: ALISON ANASTASIO

PRECEPTOR: ILANA VENTURA

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1. Introduction

Globally, multi-modal transportation agencies constantly struggle to balance both efficiency and safety between various forms of pedestrian, vehicular, and transit traffic. City traffic systems must rely on street design and precise signal engineering to influence millions of human and mechanical movements daily. Considering the myriad traffic variables influencing these systems' performance, it is difficult or impossible for transit agencies to satisfy all transportation users simultaneously. San Francisco's traffic signal retiming project demonstrates firsthand how protecting pedestrian safety can come at a cost to transit efficiency.

Like many other major US cities, San Francisco has long faced a problem with pedestrian injuries and fatalities. Pedestrian deaths have varied over the past decade, as shown by Figure 1 below. According to this graphic from SFMTA, pedestrian fatalities have remained fairly constant at about 15 or more per year ("Vision Zero SF Traffic Fatalities" 2019).

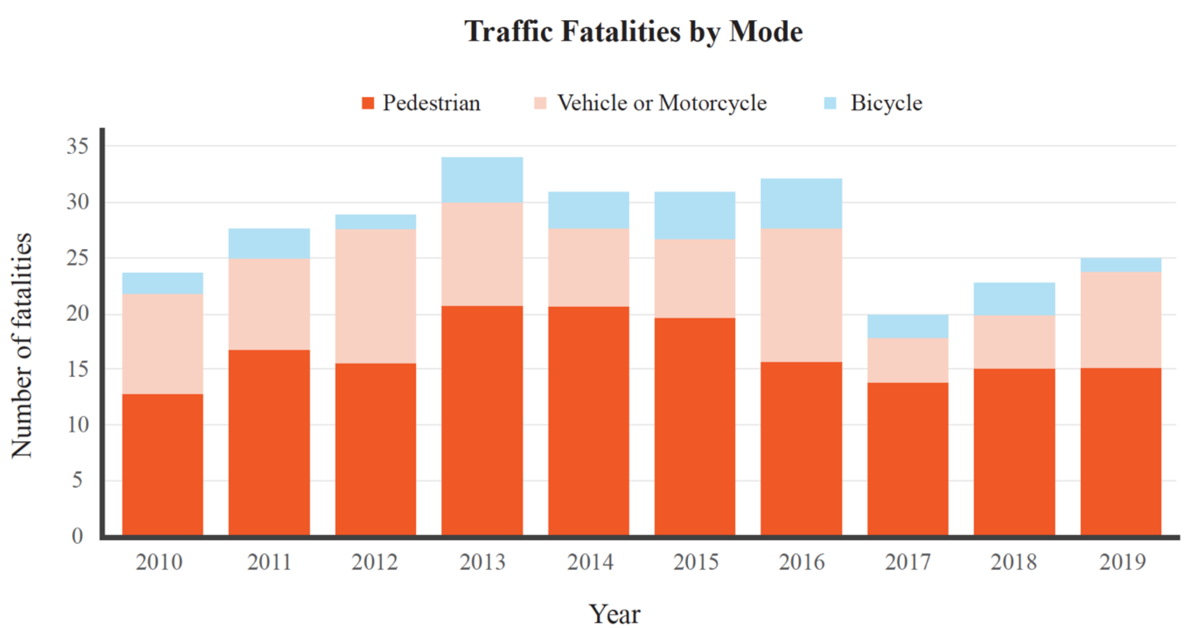


Figure 1: *San Francisco traffic fatalities by transportation mode over the past ten years.*

In the past few years, San Francisco has announced citywide initiatives to alleviate this situation. The Mayor's 2013 Pedestrian Strategy listed engineering strategies to protect pedestrian safety, emphasizing the benefits of walking for health, equity, and economic welfare ("SF Pedestrian Strategy" 2013). A year later, the City established its Vision Zero initiative, aiming to end San Francisco traffic fatalities by the year 2024. The new 2019 Action Strategy, the third one since Vision Zero's establishment in 2014, is the first to go beyond standard engineering, enforcement, and education to encompass more peripheral policies and goals included in the Vision Zero plan ("Vision Zero Action Strategy" 2019).

One component of pedestrian safety is street-crossing interval lengths. The US Federal Highway Administration recommends using a crossing speed of 4 feet/second when deciding signal timing. Unfortunately, this does not allow enough time for some children, elderly, and mobility impaired pedestrians to cross safely (Fitzpatrick, Brewer, and Turner 2006). In recent years, the San Francisco Municipal Transportation Agency (SFMTA, also known as Muni) has received many citizen complaints about having to dodge cars in intersections, having insufficient time to cross the street safely (Cabanatuan 2018). Notably, the death of 77-year-old Galina Alterman in a May 2019 traffic accident (Rubenstein 2019) was just one of several recent fatalities that increased political pressure on the city to accelerate pedestrian safety upgrades (Rodriguez 2019).

To address this issue, SFMTA has been incrementally retiming over 1,200 traffic signals in 360 intersections around the downtown, North of Market (NoMa), and South of Market (SoMa) areas. To give pedestrians more time to cross the street, most of these intersections have been retimed with an assumption of a 3 feet/second crossing speed, down from the previous 3.5 feet/second. At smaller intersections, the crossing time has been extended by only a couple of seconds, while at larger intersections, the extensions could be closer to 5 seconds. This seems like a minor increase, but it means the difference between a safe and a dangerous crossing for individuals who need extra protection (Cabanatuan 2018).

According to the Transit First Policy ("San Francisco Charter, Article VIIIA: The Municipal Transportation Agency" 2013), the City of San Francisco recognizes that walking and public transit play a vital role in managing travel demand, providing equitable mobility, encouraging compact development, saving energy, reducing emissions (Satiennam, Fukuda, and Oshima 2006), relieving congestion (Eichler and Daganzo 2006), and promoting economic growth for cities ("Transit's Role in Environmental Sustainability" 2015). To achieve these benefits, San Francisco's Transit First Policy prioritizes modes of transit that are not private vehicles ("San Francisco Charter, Article VIIIA: The Municipal Transportation Agency" 2013). Thanks to its Transit First efforts, San Francisco has experienced increases in bus ridership in recent years ("SFMTA Ridership" 2019), whereas other US cities have been struggling with declining ridership (Chakrabarti 2015).

However, the path to universally effective transit is by no means a smooth one. Cities all over the world constantly battle roadblocks to efficient transit, including construction projects and rideshare services that further worsen already-increasing street congestion ("There's a Reason Transit Ridership Is Rising in These 7 Cities" 2019). In contrast to cities like Los Angeles, New York, and Chicago, which make up 40% of all US bus ridership decline since 2008, San Francisco's focus on improving bus service makes it unique. SFMTA invests in bus efficiency strategies, thereby improving ridership – including dedicated bus lanes, all-door boarding, modern fare technology, and transit signal priority (Accuardi 2018). However, SFMTA also manages all other modes of transportation in the city, including non-vehicular modes such as biking and walking. SFMTA's new pedestrian safety measures have recently created a new focus point for the agency, as the measures undoubtedly affected transit service performance in some manner.

Numerous studies outline ways to protect pedestrians crossing the street (Fitzpatrick, Brewer, and Turner 2006; Leden, Gårder, and Johansson 2006; Guo et al. 2012; Y.-C. Liu and Tung 2014; Amosun et al. 2007; Li 2013; Arango and Montufar 2008), proving SFTMA's signal timing project is necessary for those who cannot walk as quickly as others. Many empirical investigations have also established a causal relationship between bus reliability and ridership, implying that if these pedestrian signals negatively impacted transit reliability, they would have decreased ridership in the process (Nakanishi 1997; Tyrinopoulos and Antoniou 2008; Cantwell, Caulfield, and O'Mahony 2009; Kittelson 2013; Benezech and Coulombel 2013; W. Chen and Chen 2009; Chakrabarti 2015; Rietveld, Bruinsma, and van Vuuren 2001).

However, there is a lack of studies that examine both issues under the same comprehensive lens. On a larger scale, previous studies have looked at enhancing bus-line-wide and city-wide traffic signal timing to benefit transit efficiency (Kong et al. 2011; Duerr 2000; Yang and Ding 2016; Gettman et al. 2007; Ye et al. 2014). Unfortunately, this research does not account for optimizing signals for pedestrian safety simultaneously. Consequently, the feasibility of extending pedestrian crossing time without negatively impacting bus scheduling is currently unknown.

Within the complex world of multimodal transportation management, it is difficult to strike the delicate balance between what benefits bus riders, and what benefits pedestrians. My research analyzes the effects of the adjusted traffic signal timing on bus travel times in the NoMa region. Ultimately, I aim to evaluate SFMTA's level of success in balancing pedestrian safety with reliable bus service. In other words, how effectively did SFMTA optimize bus service performance within the constraint of pedestrian safety considerations?

In this paper, I use mean travel time and standard deviation (SD) as indicators of change in service before and after the signal timing adjustments. Focusing on two large areas of retimed traffic signals in San Francisco, I analyze data on bus travel times from 22 directional bus lines and 87 total stop-to-stop travel segments. After identifying the most problematic sections in terms of increased mean travel time, I use detailed traffic observations to further understand bus movements in relation to signal timing.

Through this two-part process, I identify weak areas in the transit network and analyze the signal coordination problems within a few specific intersections more thoroughly. Overall, I conclude that the signal changes had a negative impact on mean bus travel times and standard deviation for more than half of travel segments in this study. My field observations also provide more insight into adjusted signals' negative effects at certain intersections. My findings will inform preliminary SFTMA efforts to retime certain intersections, allowing for more efficient and reliable bus travel without decreasing crossing time for pedestrians.

2. Research Context

2.1 Pedestrian safety

Solving the complex pedestrian safety challenge involves various actors, including street planners, engineers, and car manufacturers in addition to pedestrians themselves. Road widths and speed limits fundamentally influence pedestrian safety, since wider roads and high vehicular speeds lead to more frequent and severe pedestrian collisions (Gårder 2004). Therefore, pedestrians would benefit from restructuring streets to restrict fast-flowing vehicular traffic.

Leden et al.'s study explains that certain street redesigns, such as pulling back vehicle stop lines, and removing crosswalk-adjacent parking spots to improve visibility (Leden, Gårder, and Johansson 2006), can protect pedestrians from potentially dangerous vehicular traffic. Aside from street improvements, car manufacturers have also contributed by enhancing active safety systems such as automatic braking and evasive steering (Keller et al. 2011). Such engineering improvements in streets and vehicles dramatically reduce chances of pedestrian injuries and deaths. However, this issue is complicated by the fact that pedestrian risk-taking behavior, while generally predicable in theory, cannot be fully prevented in practice.

Research has long proven that some pedestrians will choose to cross a street even in unsafe conditions, sometimes causing fatal traffic accidents (Papadimitriou, Lassarre, and Yannis 2016). One North Carolina study identified pedestrians were at fault in 59% of studied pedestrian-motor vehicle crashes (Ulfarsson, Kim, and Booth 2010). The likelihood of a pedestrian crossing unsafely depends on myriad factors, including age, gender, personality, number of surrounding people waiting to cross, the amount of time spent waiting, traffic conditions, distance to cross the street and number of traffic lanes, and past involvement in accidents (Guo et al. 2012; Hamed 2001; Granié 2009; Lam 2005). More specifically, risk-taking behaviors are heightened by internal factors such as masculine conformity (Hamed 2001) or cultural perceptions of traffic hazards, which cannot necessarily be influenced by external factors like street adjustments (Lam 2005). The longer pedestrians wait, the more likely they are to run across the street and incite a crossing violation (Guo et al. 2012). This concerning trend is most dangerous for vulnerable pedestrians, who cannot always accurately judge how much time they need to cross the road. A Taiwan study found elderly pedestrians would decide to cross even when they would not realistically have enough time, due to inaccurate assumptions of their own walking speed (Y.-C. Liu and Tung 2014).

In light of these dangers, traffic engineers cannot directly control whether or not individuals decide to cross the street in an illegal manner. It is impossible for anyone to fully prevent illegal and unsafe behavior, but planners and engineers can keep these tendencies in mind when designing for traffic signal timing, as well as provide a time buffer for extra safety. Amosun et al.'s research in South Africa found that insufficient crossing times made elderly pedestrians afraid to cross the street (Amosun et al. 2007). Another study further explained this risky dynamic, showing that pedestrians' willingness to wait depends on the no-crossing phase's duration. This study concluded that shortened vehicular phases would reduce pedestrians' impatience, thereby decreasing their impulse to cross the street out of turn. Additionally, increasing the crossing duration would further minimize risk of pedestrian injury or death (Li 2013). In support of such concerns, studies have strongly suggested using a walking speed of 3 feet/second in timing signals for mobility-impaired pedestrians (Arango and Montufar 2008; Fitzpatrick, Brewer, and Turner 2006). SFMTA weighed these considerations when reducing their walking speed assumptions from 3.5 to 3 feet/second, thereby protecting pedestrians who need extra walking time.

2.2 Bus reliability

SFMTA strives to increase bus ridership because public transit provides an environmentally sustainable transportation option for customers of all backgrounds ("Muni Service Equity Strategy" 2018). The agency has shown its dedication to sustainability by using of the country's lowest-emission bus fleets, commonly called Muni ("San Francisco

Transportation Sector Climate Action Strategy" 2017). Muni's trolley buses run on 100% renewable hydroelectricity, and many of its non-trolley buses are hybrids that run on battery and diesel. SFMTA has committed to only purchasing all-electric buses starting in 2025, and will have an entirely electric bus fleet by 2035 (Banchero 2018). The agency hopes that as transit becomes more ubiquitous and reliable, people will choose transit over private vehicles, thereby reducing citywide congestion and vehicular greenhouse gas emissions. In turn, reduced congestion would further bolster public transit efficiency (Beimborn, Greenwald, and Jin 2003). In summary, high transit ridership is instrumental to SFMTA's sustainability goals.

Numerous studies have shown passengers highly value bus reliability, defined as a bus's likelihood to arrive when passengers expect it to. Riders consider unreliability one of the most significant drawbacks of public transit (Nakanishi 1997; Tyrinopoulos and Antoniou 2008; Cantwell, Caulfield, and O'Mahony 2009; Kittelson 2013) because it impairs a passenger's ability to schedule trips and increases their wait times and travel costs (Benezech and Coulombel 2013; W. Chen and Chen 2009). Bus reliability is positively correlated with ridership, and riders make decisions on what routes to take based on service reliability (Chakrabarti and Giuliano 2015). Especially for riders who generally make one or more transfers in their bus trips, unpredictable and longer-than-expected wait times can discourage public transit use (Rietveld, Bruinsma, and van Vuuren 2001). Since reliability is so important to riders, it is a consistent priority for transit authorities.

In attempts to quantify the causes and effects of this issue, researchers have devised various methods of measuring transit reliability and its dependent factors. A comprehensive report by Saberi et al. captures extreme cases of unreliability and contrasts drawbacks of being early versus being late (Saberi et al. 2013). Research has strongly connected reliability with factors such as travel segment length, exclusive bus lanes, and headways – the amount of time between bus arrivals at a stop (X. Chen et al. 2009). Another study added factors including staff shortages, traffic congestion, and poor operational control to this list (Buchanan and Walker 2002). Still other studies have made recommendations on ways to improve reliability. Based on promising results from traffic simulations, researchers have proposed a combination of advanced system operations, traffic management, and real-time information sharing (Turnquist 1982; Safdarian et al. 2014). The latter was implemented in New York City and proved to increase ridership (Brakewood, Macfarlane, and Watkins 2015).

Improving reliability in practice is extremely complicated because it involves rigorous inter-agency coordination and both internal and external incentives (Chakrabarti 2015). Additionally, making independent bus lines more reliable does not definitively increase ridership. Chakrabarti aptly explains that reliability improvements in one certain line or segment could detract riders from another line, thus negating the net benefits and not improving ridership overall. Measuring reliability and ridership on a stop-by-stop, line-by-line basis is not necessarily precise because riders will often take more than one line to arrive at their destination (Bordagaray et al. 2011). Lastly, reliability at one part of someone's trip can influence that rider's decisions about their entire journey. On a grander scale, this can affect rider volumes at other boarding points on that line or on other lines (Chakrabarti 2015).

2.3 Traffic signal timing challenges

On the traffic engineering side, transit signal priority (TSP) presents a relatively inexpensive solution to transit efficiency, as it does not require major infrastructure changes. Most active TSP systems use wireless communications between buses and signalized intersections to facilitate small shifts in green-yellow-red signal cycles. This type of TSP works by extending traffic signals' green phases, allowing buses to pass through an intersection without delay. Alternatively, engineers can time a large region of streets strategically, allowing for buses to automatically flow through intersections more smoothly. This passive TSP method is used more frequently because of its cost-effectiveness; its implementation does not require new expensive signaling hardware (Lee 2001). The SFMTA signal retiming project in question used passive TSP in an effort to maintain or improve transit performance. This study aims to determine whether or not SFMTA achieved this goal.

TSP efficacy relies heavily on carefully timed signal cycles and progressions between intersections. A "green-wave progression" is a series of signals allowing vehicles to pass through multiple consecutive intersections without stopping. When active TSP systems adjust signal cycles in real-time, they facilitate a more flexible green-wave allowance for buses. Complex signal coordination systems can calculate current traffic conditions, travel speeds, and offsets for both inbound and outbound buses simultaneously. These systems have proven effective in multiple simulations and real-world applications (Kong et al. 2011; Duerr 2000; Yang and Ding 2016; Gettman et al. 2007). However, when programmed efficiently, a green-wave progression can still improve transit efficiency using simple passive TSP (Ye et al. 2014). One major drawback is that sometimes, efficient signal progressions on one side of the street can significantly hinder vehicle flow on the opposite side of the street. This is because logically, signal offsets can rarely benefit both sides of the street concurrently. To counter this issue, transit planners and engineers must factor bus stop placement into the signal offset problem.

The location of bus stops can heavily influence its travel times because of complex interactions with signal timing. Some research claims that a stop's location before a signaled intersection (nearside) can increase delays, unless the street has reserved bus-only travel lanes (Diab and El-Geneidy 2015). Another study refutes this claim, concluding that a farside stop placement (i.e. after the intersection) can cause more delays overall (Wang et al. 2013; Moura et al. 2011; Z. Liu and Jian 2019). However, this argument likely cannot be settled with an answer of which placement is definitively better. The efficiency of these stop locations depends on private vehicle and bus flows and on traffic signal cycle lengths (Moura et al. 2011). A traffic impact analysis by Liu and Jian shows that a farside stop is more efficient when located within 70m (230 ft) of an intersection, but with distances above this threshold, nearside stops are more efficient (Z. Liu and Jian 2019).

Still, other location characteristics, including topography, can factor into bus stop efficacy as well. Furth and SanClemente demonstrated that stops on an uphill slope can cause minor delays because buses have a harder time accelerating uphill after stopping (Furth and SanClemente 2006); this is relevant because San Francisco is a notoriously hilly city. Another study models bus stop placements' efficiency while considering elements like riders' walking speed and acceleration rates on uneven ground (Ceder, Butcher, and Wang 2015).

Connecting signal timing back to the overarching reliability problem, accurately predicting bus arrivals is not a straightforward task. In order to create a high-performing passive TSP system, planners and engineers must design a complex system of signals and offsets, all the while considering hundreds of interconnected streets, bus stop locations, and different street designs. In San Francisco's case, lengthened pedestrian crossing times complicate this problem even further.

2.4 Hypothesis

The main goal of SFMTA's signal retiming project was to extend crossing times to protect more vulnerable pedestrians. At the same time, though, the project would hopefully incorporate passive TSP to improve transit efficiency and reliability (Rhodes 2019). As discussed previously, adding crossing time is one proven, effective way to decrease pedestrian fatalities. This research project's goal is to determine whether the new TSP system decreased buses' travel time, as SFMTA planners and engineers hoped. Longer pedestrian crossing intervals in both cross-street directions means extended red signals and less green time for vehicles, resulting in a lower green-to-red ratio for all directions of traffic. In other words, the signal timing changes would have caused buses to encounter red signals more frequently than they did in the past, thus creating more travel delays. Based on this conjecture, I hypothesize the signal changes negatively impacted overall transit performance, in both travel time and reliability.

3. Research Approach

3.1 Transit data and methodology

In this project, I perform a bus data analysis to determine whether bus travel times changed after SFMTA retimed pedestrian signals. Ultimately, I use these results to quantify SFMTA's success in balancing safer pedestrian signal timing with bus efficiency. To accomplish this goal, I use travel time data collected from SFMTA's Transtat database (for internal agency use only), comparing data from before the signal changes against data from afterwards. In this process, I calculate differences in mean travel time and standard deviation between the two study periods. I focus on two adjacent neighborhoods of San Francisco, named the Western Addition and Bush-Pine (pictured below). I first analyzed this data as an SFMTA employee during August and September 2019, on behalf of the SF Go and Muni Forward project groups.

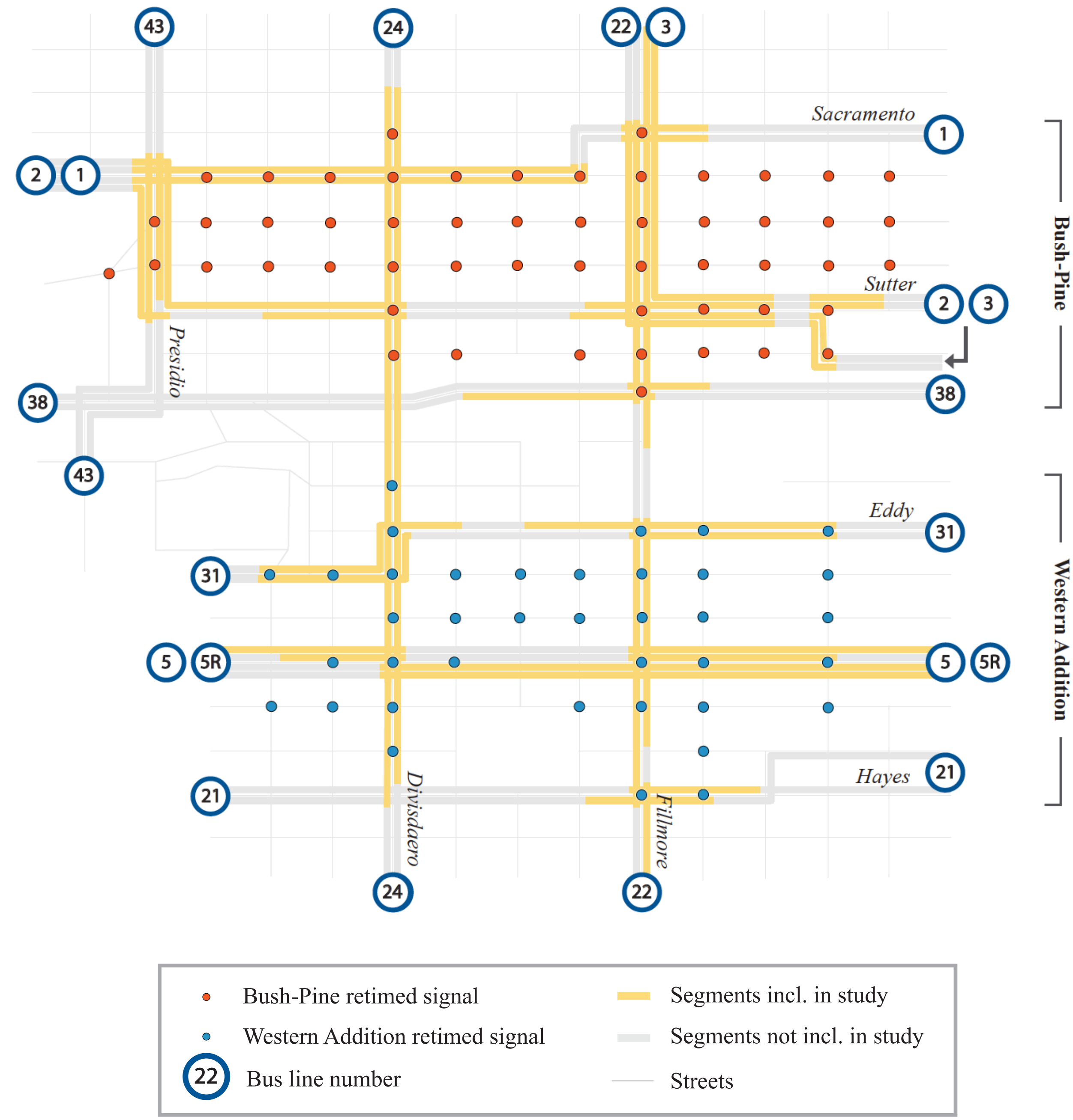


Figure 2: *Map of study section, showing studied stop-to-stop segments of 11 bus lines in the Bush-Pine and Western Addition areas.*

As shown below in Figure 2, Bush-Pine spans 7 streets north-south between Sacramento Street and Geary Boulevard, and 14 streets east-west between Masonic Avenue and Octavia Street. The study area includes 54 intersections with signals retimed on July 20 and 21, 2019. The Western Addition spans 8 streets north-south between Ellis Street and Hayes Street, and 10 streets east-west between Baker Street and Laguna Street. The section includes 36 intersections with signals retimed on April 30, 2019. See Appendix Exhibit 1 for a full map of both study areas with all street names delineated.

Time Period Parameters

	Western Addition	*Bush-Pine*
Before period	Jan 1 - April 29, 2019	Jan 1 - April 29, 2019
Retiming Date	April 30, 2019	July 20-21, 2019
After period	July 15 - December 20, 2019	July 22 - December 20, 2019

Figure 3: *Parameters outlining the Before and After study periods for the Western Addition and Bush-Pine travel segments. The Western Addition "After" study period does not being until July 15, because between June 1 and July 14, SFMTA was conducting a city-wide experiment with alternate TSP timing. For this reason, the travel time data from this time period is unusable for my research.*

SFMTA's Stop-to-Stop Travel Times portal on the Transtat website provides data on bus travel times between stops. The online tool allows me to compile all the bus travel data collected during the before- and after-periods. The travel times are measured excluding dwell times, meaning the times when passengers are boarding and disembarking. I collect and summarize the weekday trip data for three separate periods of the day: the AM peak period (7:00 – 9:00am), the PM peak period (4:00 – 7:00pm), and the Midday hours between those two (9:00am – 4:00pm). I exclude early morning hours and late-night hours, during which bus service tends to decrease significantly.

This study only analyzes data on SFMTA bus segments traversing retimed intersections the Western Addition and Bush-Pine. I ignore all segments that do not pass through these retimed intersections, as they do not relate to this study's goals. In total, I use data from 87 travel segments across 22 directional bus lines. To clarify, one bus line's inbound (IB) and outbound (OB) routes count as two separate directional lines.

For each travel segment, my objective is to quantify how much mean travel time and standard deviation changed after the traffic signal retiming. Increased travel times would lead to bus delays, and increased standard deviation would make bus arrival times more unreliable. Research has proven significant travel delays and reliability decreases to be a significant inconvenience for transit riders, and thereby present a serious concern for SFMTA. For this project, my goals are as follows:

Number of segments per line and direction

	Bus line name	Inbound	Outbound
1	1 California	5	5
2	2 Clement	5	5
3	3 Jackson	4	5
5	5 Fulton	4	2
5R	5R Fulton Rapid	2	2
21	21 Hayes	2	2
22	22 Fillmore	9	7
24	24 Divisadero	7	7
31	31 Balboa	4	6
38	38 Geary	1	1
43	43 Masonic	1	1

Figure 4: *Number of studied travel segments per bus line, in both the inbound and outbound directions. The circled numbers correspond with map symbols in Figure 2.*

1. to quantify each stop-to-stop segment's change in travel time and reliability,
2. to identify segments most impacted by the signal retiming, and
3. to use data trends and observations to theoretically explain such impacts.

This study's independent variables are bus line, direction, travel segment, and time of day. An important confounding variable in this analysis is the period of time between bus doors opening and closing at each stop, called dwell times. These dwell times can vary greatly depending on passenger density conditions, and if an elderly or disabled passenger needs more time to board or disembark. I control for this highly-varying factor by excluding dwell times in all stop-to-stop time calculations. Thus, in this study, stop-to-stop times are measured from when doors close at the first stop to when doors open at the following stop. Another confounder is the day of the week, because weekend service often differs from weekday service in rider demand and bus frequency. I study only weekday data, since weekend travel patterns tend to be less regular.

In my data analysis process, I perform statistical tests on data from the Transtat database. I separate the data into individual stop-to-stop segments of each bus line (n = 87), time of day (n = 3), and Before versus After (n = 2), totaling 522 different datasets to analyze. Using a Python program, I eliminate outliers, defined values beyond 3 times a dataset's inter-quartile range. The program calculates each set's mean and standard deviation values, then returns values for change in mean and standard deviation between the Before and After periods for each travel segment. This study focuses on three outcome measures, as follows: Mean Δ (in seconds), Mean % Δ (in percentage points), and SD Δ (in seconds).

When recording my results, I specify the bus line, direction, time of day, and number of observations for each dataset. I categorize the finalized results from all the travel segments into varying levels of improved or worsened bus service. Finally, I conclude whether the results demonstrate any time change patterns. I visually arrange these outputs in a color-coded route map, making them easier to understand spatially. Based on the map results, I pinpoint individual or consecutive intersections that seem to most negatively affect travel times and reliability.

3.2 Observational data and study

While working with SFMTA in August and September 2019, I performed a preliminary analysis of this same data. I used simpler statistical methods to determine median travel times and variability (measured as the 90th percentile minus the 50th percentile) of each travel segment. I then identified the most outstanding sections for increased travel time. By creating a map of the bus lines and highlighting these 'problem' segments, I was able to observe patterns in the results. Some intersections were included in multiple overlapping highlighted segments, spanning more than one bus line or multiple time periods. Based on this map, I chose two segments to observe

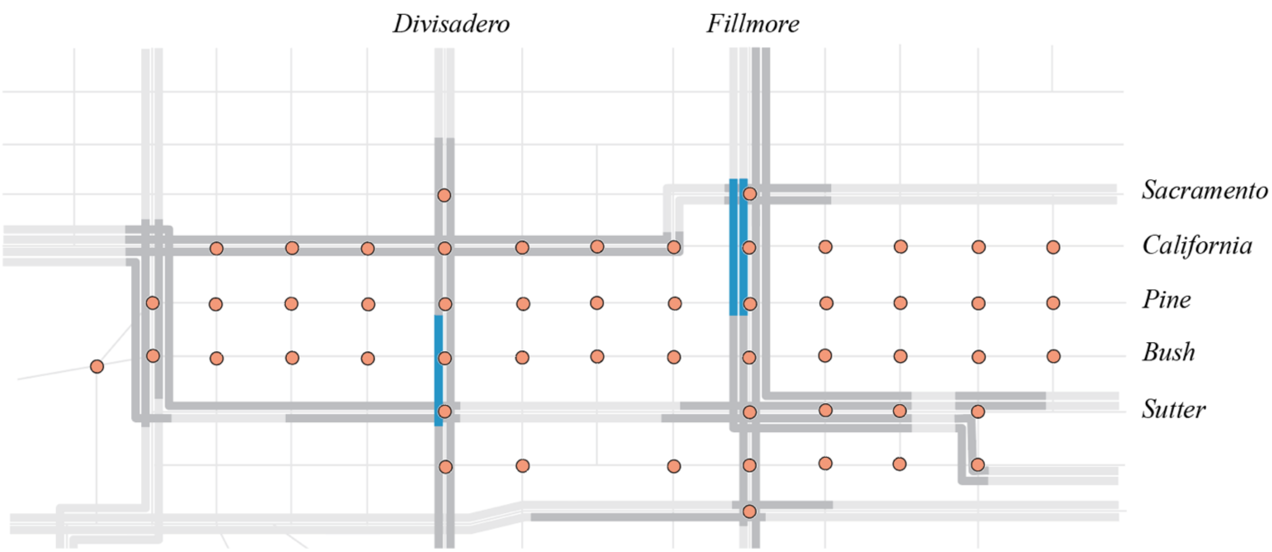


Figure 5: *Observed intersections on Divisadero St. and Fillmore St., highlighted in blue.*

in person. I looked for higher-traffic areas on high-ridership bus lines, as these segments are more crucial to riders' perceptions of Muni bus performance.

While performing these in-person observations, I looked for any signal timing issues or inconsistencies that could negatively impact transit efficiency. I chose 2 segments in Bush-Pine (denoted in Figure 5) that stood out for their extreme median time changes. These intersections and respective times of study are denoted below:

1. **Divisadero / Sutter and Bush**: September 18, 2:30 – 5:10 pm (Midday and PM Peak)
2. **Fillmore / California and Sacramento**: September 20, 7:35 am – 9:40 am (AM peak)

At both of these locations, I remained in one spot where I could adequately observe bus movements and traffic signals. During my observations, I took notes on the following, measuring all times using a stopwatch and noted the quantities in seconds:

- Each bus's arrival time at the first studied signal
- What signal each bus encountered at intersections (green, yellow, red)
- How long each bus waited at a red signal
- The signal timing cycles at each intersection and offsets between intersections

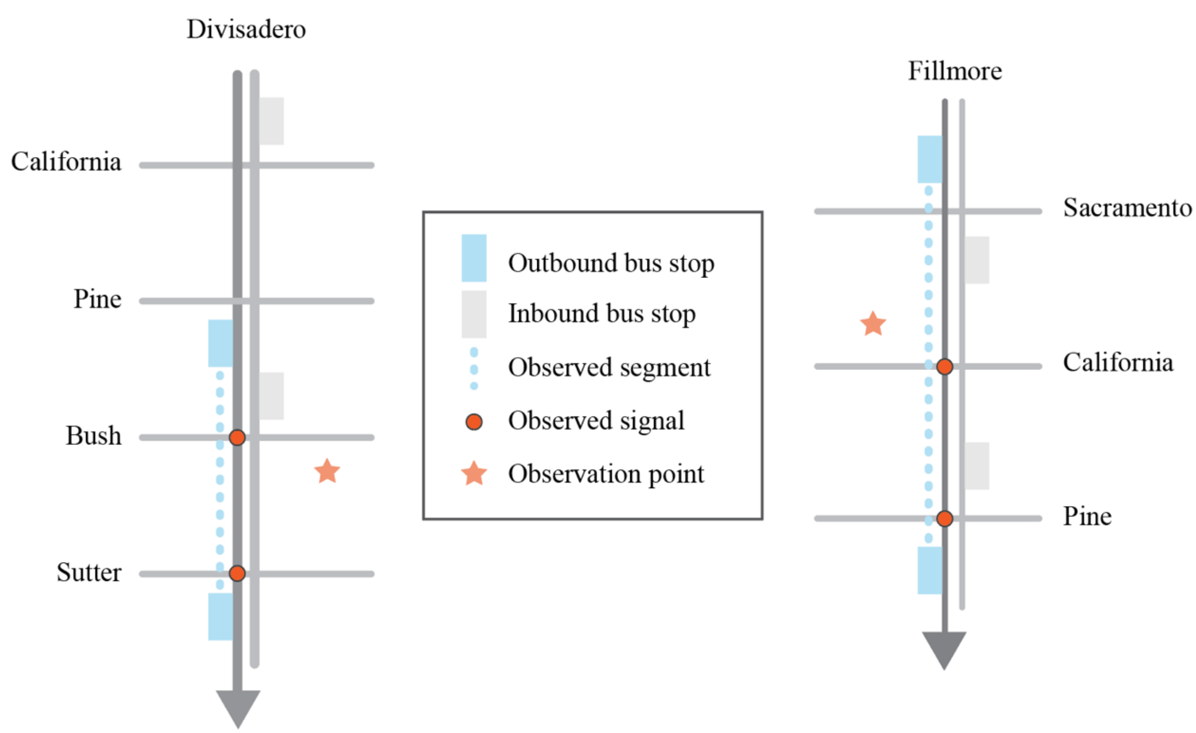


Figure 6: *Observation diagrams for Divisadero St. and Fillmore St., showing location of observed traffic signals and my observation location.*

My in-person observations add qualitative details and explanations that my quantitative analysis alone cannot explain. At these observation locations, which are depicted in Figure 6, I noted headway patterns – which represent a snapshot of service reliability – by marking the arrival times of every bus. Also, by noting the color of traffic signal that every bus encountered, and counting the stopping duration at red lights, I recognized patterns causing bus delays. For example, if buses repeatedly encountered red signals at the same intersection, I could see if signal offsets played a role in these patterns.

Lastly, by measuring signal cycles and offsets at each intersection, I can better understand interactions between buses, vehicles on cross-streets, pedestrians, and traffic signals. I set out to answer some questions and record any other notable street characteristics.

- Could green lights be extended on bus corridors without negatively impacting vehicular traffic on cross-streets?
- Do the offsets cause buses to encounter red signals much more often than they should, according to the green-to-red timing ratio?
- Do the bus stop locations (nearside vs farside) have any impact what signals buses encounter at each intersection?
- Is there anything unique about the area that influences traffic and/or pedestrian patterns?

With all these questions in mind, it is important to understand that every intersection in a city represents an individual case that cannot be simply examined or explained with statistics. Any given intersection has its own pedestrian, vehicular, and transit volumes for different times of the day, different attractions along its streets, and unique street designs and widths. Countless unique variables can impact a transit line's performance. Elements such as traffic density, street design, pedestrian patterns, and signal behaviors can affect a bus's interplay with people and vehicles sharing the roads.

4. Report on Findings

4.1 Summary of claim

By analyzing numerical data on bus travel times and patterns, I estimate how SFMTA's signal retiming affected Bush-Pine and Western Addition bus travel. Figure 7 below shows a basic summary of before-and-after changes across all studied bus segments. In the table, "ND" stands for "nominal difference" – for Mean Δ and Mean % Δ, they are segments whose changes are between –2 and 2; for SD Δ, the values are between –1 and 1. The "+" indicates an increase in mean travel time or standard deviation, and the "–" indicates a decrease. As the table shows, across all three time periods of the day, there were more increases in mean time and SD than decreases. The results of my statistical analysis support my hypothesis: signal changes negatively affected the majority of bus lines, both in mean travel time and SD. The results also suggest that certain bus lines experienced more serious performance changes than others.

Time Change Summary by Proportion

	Mean Δ (s)			Mean % Δ (% pts.)			SD Δ (s)		
	+	*ND*	–	+	*ND*	–	+	*ND*	–
AM Peak	0.60	0.17	0.23	0.62	0.11	0.26	0.61	0.21	0.18
Midday	0.55	0.30	0.15	0.59	0.22	0.20	0.48	0.33	0.18
PM Peak	0.51	0.17	0.32	0.55	0.13	0.32	0.45	0.24	0.31
Average	0.55	0.21	0.23	0.59	0.15	0.26	0.51	0.26	0.23

Figure 7: *Summary of the proportion of bus travel segments that changed in mean travel time and SD after pedestrian light adjustments. ND stands for "negligible difference", which is -2 < x < 2 for Mean Δ and Mean % Δ, and –1 < x < 1 for SD Δ.*

My numerical summary, combined with a spatial analysis, highlights specific travel segments with poor transit performance. These segments with the largest time increases represent intersections whose traffic signals might be inefficiently timed. In a later section, I discuss my in-person observations of two travel segments. By pairing numerical evidence with observed patterns, I speculate why these segments, and other similar sections, might have experienced such major increases in travel time. These problem segments, along with other slower and less reliable bus lines, present an important problem for SFMTA to fix because unreliable service drives away customers.

4.2 Problem segments

I use the methods described in Section 3.1 to measure bus performance across all travel segments in my prescribed study area. I categorize each segment's findings by bus line, direction, start and stop locations, and time of day. In tables similar to Figure 9, I summarize the before-and-after change in mean (in both number of seconds and percent change) and standard deviation (in seconds) for each travel segment.

	Stop-to-Stop Name	AM Peak			Midday			PM Peak		
1 California	***Inbound***	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Presidio to Baker	6.6	6.2	-2.3	0.4	0.4	2.3	-12.7	-9.6	-12.8
	Baker to Divisadero	-7	-12.1	1.5	-1.6	-3	-0.7	1.1	2	-1.9
	Divisadero to Pierce	6.7	9.6	0.2	7.1	9.1	-0.4	-5.5	-5.6	4.1
	Pierce to Sacramento	-2.5	-3.8	2.2	2.2	3.4	2.8	11.4	17.1	0.2
	Sacramento to Fillmore	5.8	11.2	-1.3	3.3	6.2	-0.3	-0.4	-0.7	-0.1
	Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Webster to Fillmore	4.7	9.1	4.3	5.6	10.3	3.3	5.5	10.6	3.2
	California to Pierce	5.1	9.9	-0.2	2.6	4.7	0.9	-3.6	-6.4	1.8
	Pierce to Divisadero	-7.3	-8.9	5.4	5.4	7.5	3.9	8.7	15.2	0.1
	Divisadero to Baker	-2.9	-5.8	4.2	-2.8	-5	3.3	-5.7	-10.2	2.6
	Baker to Presidio	-9.6	-10.5	-1.7	0.1	0.1	-0.7	3.2	3.5	-1.7

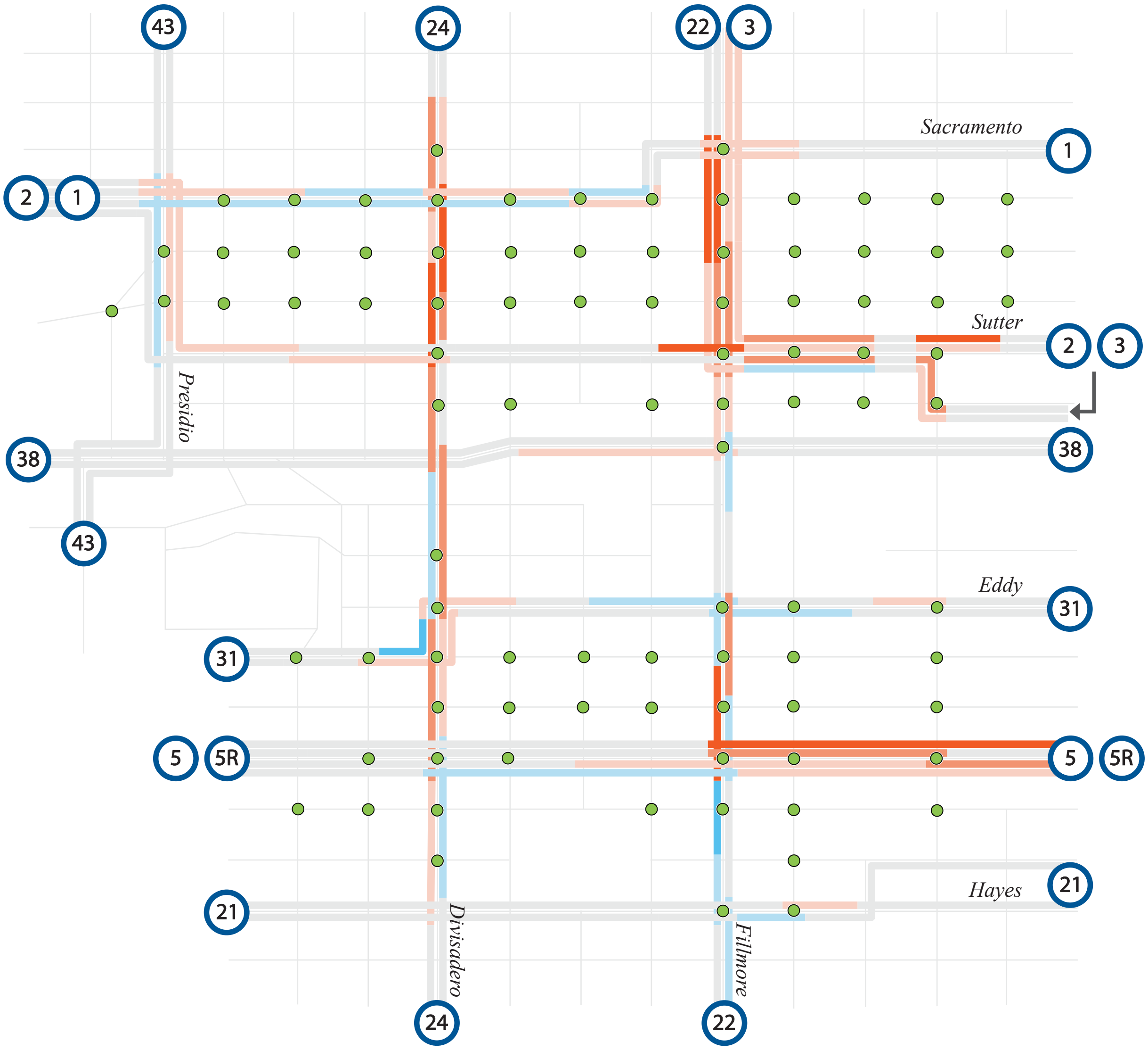
Mean Δ	***% Δ***	***SD Δ***
< –20	< –20	< –8
–10 to –19.9	–10 to –19.9	–4 to 7.9
–2 to –9.9	–2 to –9.9	–1 to –3.9
–1.9 to 1.9	–1.9 to 1.9	–0.9 to 0.9
2 to 9.9	2 to 9.9	1 to 3.9
10 to 19.9	10 to 19.9	4 to 7.9
20+	20+	> 8

Figure 8: *Table showing color-coded results for the 1 California line, along with the categorization system for mean change in seconds, mean change in percentage points, and standard deviation in seconds. Blue boxes represent decreases in mean time or SD; red boxes represent increases.*

To begin visualizing the comprehensive results of this study, I categorize all the results into separate strata according to their degree of change. By my categorization system, shown in Figure 8, the majority of results lie within the light red or light blue categories. These color groups represent the most minor increases and decreases in mean and standard deviation, respectively. Fewer segments are labeled with medium red and blue. Lastly, I reserve the dark red and dark blue categories for the most extreme increases and decreases, respectively. Grey represents segments whose Before-and-After differences were negligible (between –1.9 and 1.9 for Mean Δ and Mean % Δ, and between –0.9 and 0.9 for SD Δ). Refer to Appendix Exhibit 2 for full results tables for all study segments, similar to the example table above in Figure 8.

I plot the categorized data onto color-coded maps, which show results from all three study periods for Mean Δ (seconds), Mean % Δ (percentage points), and SD Δ (seconds). Figure 9 shows the AM Peak map for Mean Δ, and the rest of the results maps can be found in Appendix Exhibit 3. Using the color-coded results table, I select segments demonstrating worsened travel time across all time periods and multiple measures. Two of the most outstanding segments belong to the 24 Divisadero line. One is the IB segment from Bush Street to California Street, and the other is the OB segment from Pine Street to Sutter Street, which is discussed in the observations section later in this paper. The IB segment mean times increased more than 20s in all three time periods, representing a >30% increase for all times. The OB segment's mean measures increased 20-33 seconds for all periods of the day, representing a 35-60% increase for each time period. Additionally, I identified the southbound segment on Fillmore Street from Sacramento to Pine Street for its significant AM Peak mean increases. I discuss this Fillmore segment and the Divisadero OB segment in further detail in Section 4.4. Histograms comparing the before-and-after data distributions for these travel segments are in Appendix Exhibit 4.

AM Peak: Mean Δ



Travel time changes (seconds)		Map symbols
Worsened segments	Improved segments	
2 to 9.9	< –20	– 1.9s to 1.9s change / segment not included in study
10 to 19.9	–10 to –19.9	Retimed signal
>20	–2 to –9.9	24 Muni bus route number

Figure 9: *Map showing changes in mean travel time during the AM Peak study period.*

Figure 10 below demonstrates a histogram of Midday data from the 24 Divisadero OB segment from Pine Street to Sutter Street, one of the segments described previously. The blue bars show the distribution of travel times before SFMTA's pedestrian signal changes, while the red bars show the distribution from afterwards. According to the blue graph's bimodal distribution, approximately 35-40s and 55-65s were the most common amounts of time it took for buses to travel from Pine to Sutter. As this stop-to-stop segment spans two city blocks (and thus two signalized intersections), the shorter interval (35-40s) possibly indicates a bus passing through 2 out of 2 green lights. The longer interval (55-65s) perhaps indicates a brief stop at one red light. Meanwhile, the red graph's distribution shows one clear peak at around 75-85s, which possibly represents a very long stop at one signal, or stops at both red signals. This type of data visualization reveals telling trends, but is difficult to fully interpret without real-world observations to prove them. Such evidence will be discussed later in this paper.

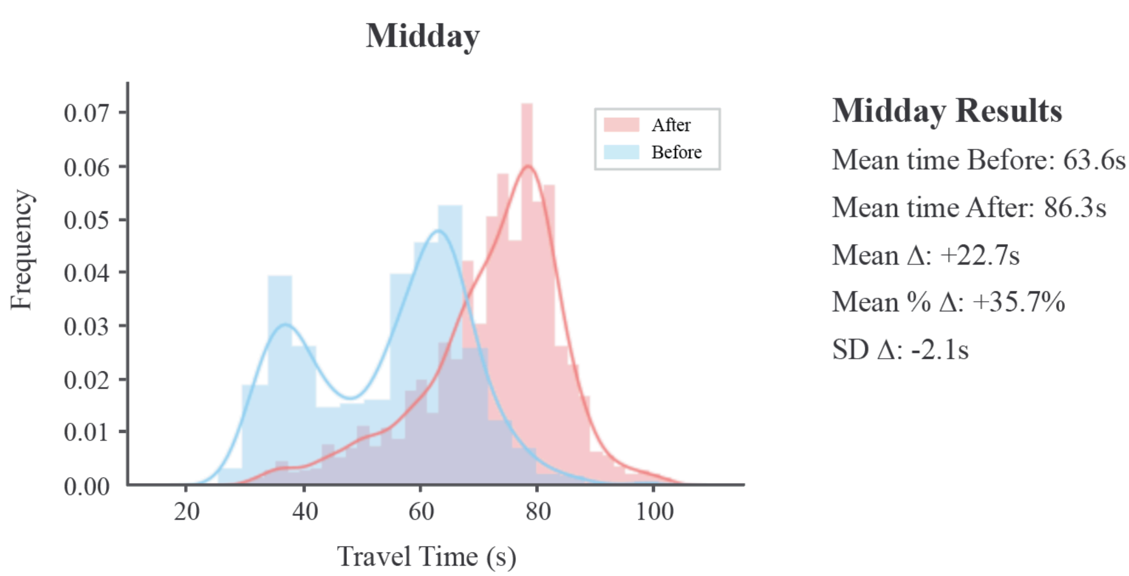


Figure 10: *Histogram of 24 Divisadero OB Pine to Sutter data, showing the Midday Mean distribution shift between Before and After the signal timing changes.*

4.3 Bus lines overview

All nine color-coded maps show more red segments than blue ones. Based on segment visualizations such as the one in Figure 10, I conclude that SFMTA's signal retiming project improved pedestrian safety at the expense of bus efficiency and reliability. Over half of all bus segments worsened in both mean travel time and standard deviation. Even though some segments showed improvements (i.e. decreased mean time and SD), they were not enough to counter the negative effects of worsened segments. Figure 11 below shows proportions of changes per bus line, categorizing each travel segment's before-and-after change simply as an increase, a decrease, or no change. The full graphs, including Mean % Δ and SD Δ results, are shown in Appendix Exhibit 5.

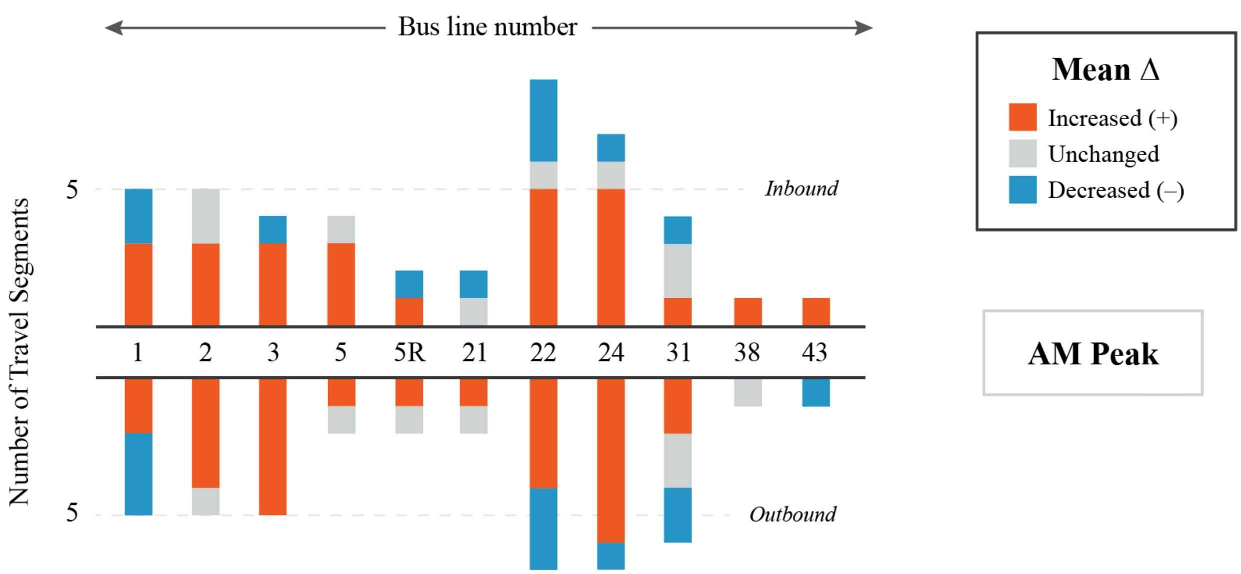


Figure 11: *Number of segments per bus line with increased, decreased, and unchanged travel times for the AM Peak study period. The upper bars represent inbound segments, and the lower bars show outbound segments.*

Clearly, as this figure shows, some bus lines (22 Fillmore, 24 Divisadero) include many more studied travel segments (n = 16 and n = 14, respectively) than other lines wherein n = 2 (38

Geary, 43 Masonic). Some bus lines in this study traverse long segments of streets with a dozen or more retimed intersections. Meanwhile, others simply pass through a couple of retimed intersections on the study area's borders. Because of this sample-population discrepancy, I am unable to conclude which bus lines experienced more slowdowns than others. Furthermore, the summary data from individual segments cannot simply be added up to quantify line-wide performance throughout the retimed study area. Unfortunately, no data tracks each bus's travel time from one end of the overall study area to the other end.

My solution is a visual summary of every segment's change; each square represents one travel segment. Figure 12 shows the results for mean change in seconds, categorized by bus line, with inbound and outbound segments combined. Each square in the figure represents one studied stop-to-stop segment. Figure 13 shows a summary of these results, combining all bus lines together in the first three columns, which represent the three different study periods of the day. The wide leftmost column shows all results aggregated across all time periods. The same figures for percent change in mean and for standard deviation can be found in Appendix Exhibit 6.

These two figures more clearly show the degree of travel time changes across different categories, allowing for a better view of performance by line. For example, according to Figure 12, the 1 California line experienced relatively minor changes, both positive and negative, across all time periods of the day. These mild changes seemingly balance each other out, suggesting that SFMTA's signal retiming project did not strongly influence this bus line's performance. On the other hand, both the 22 Fillmore and the 24 Divisadero show fewer improved sections than worsened ones. For the latter bus line, many of the mean increases are in the moderate-to-severe category across all time periods of the day.

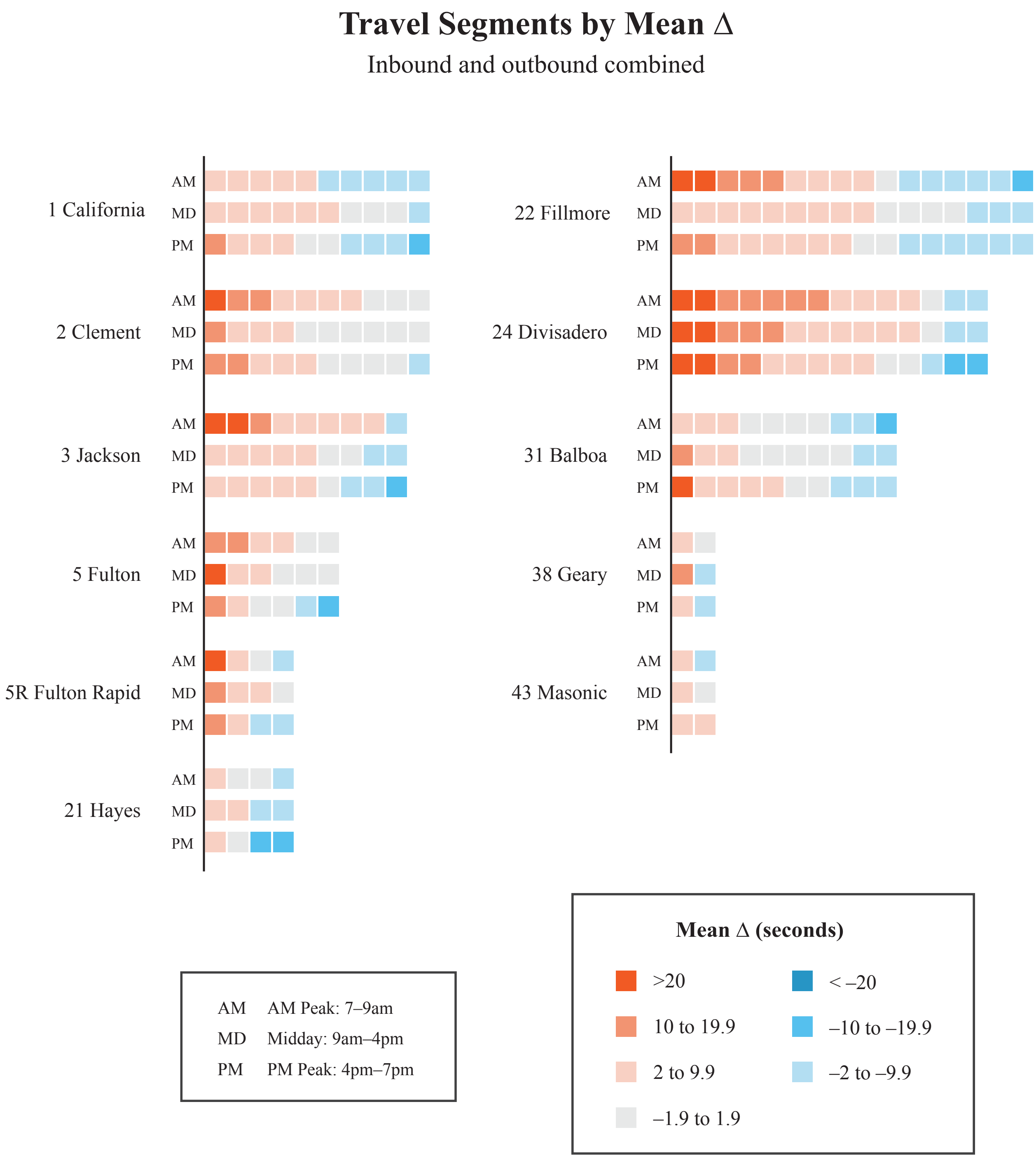


Figure 12: *All travel segments per bus line, organized by level of performance change as per mean travel time. The three rows of squares per bus line denote AM Peak, Midday, and PM Peak results from top to bottom.*

Curiously, the number and severity of slowdowns for the 24 Divisadero seems to decrease throughout the day. This same trend is reflected in the summary diagram in Figure 13, where we can see that the AM Peak column has the highest number of red squares overall, and the most moderate-to-severe mean increase segments as well. The PM Peak column, meanwhile, demonstrates the reverse, showcasing the highest number of blue squares.

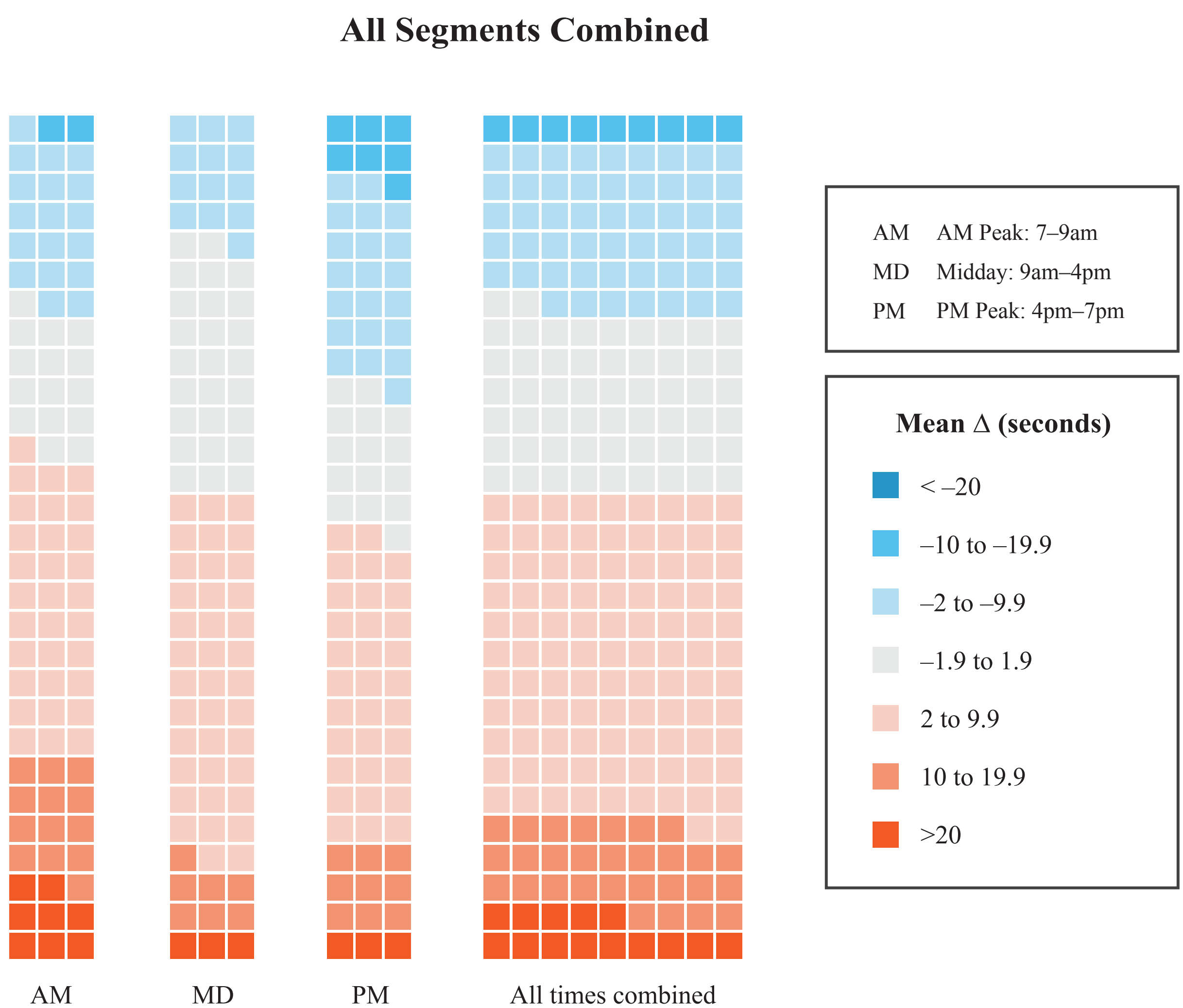


Figure 13: *All travel segments combined, categorized by degree of positive (i.e. increased) and negative (i.e. decreased) change.*

4.4 Intersection observations

As explained earlier, I observed bus interactions with traffic signals in two areas, based on my identification of "problem" intersections in my SFMTA preliminary data analysis:

1. Divisadero and Sutter, Divisadero and Bush (September 18, 2019) – part of the 24 Divisadero route in the outbound direction
2. Fillmore and California, Fillmore and Pine (September 20, 2019) – part of the 3 Jackson route in the inbound direction and the 22 Fillmore route in the outbound direction

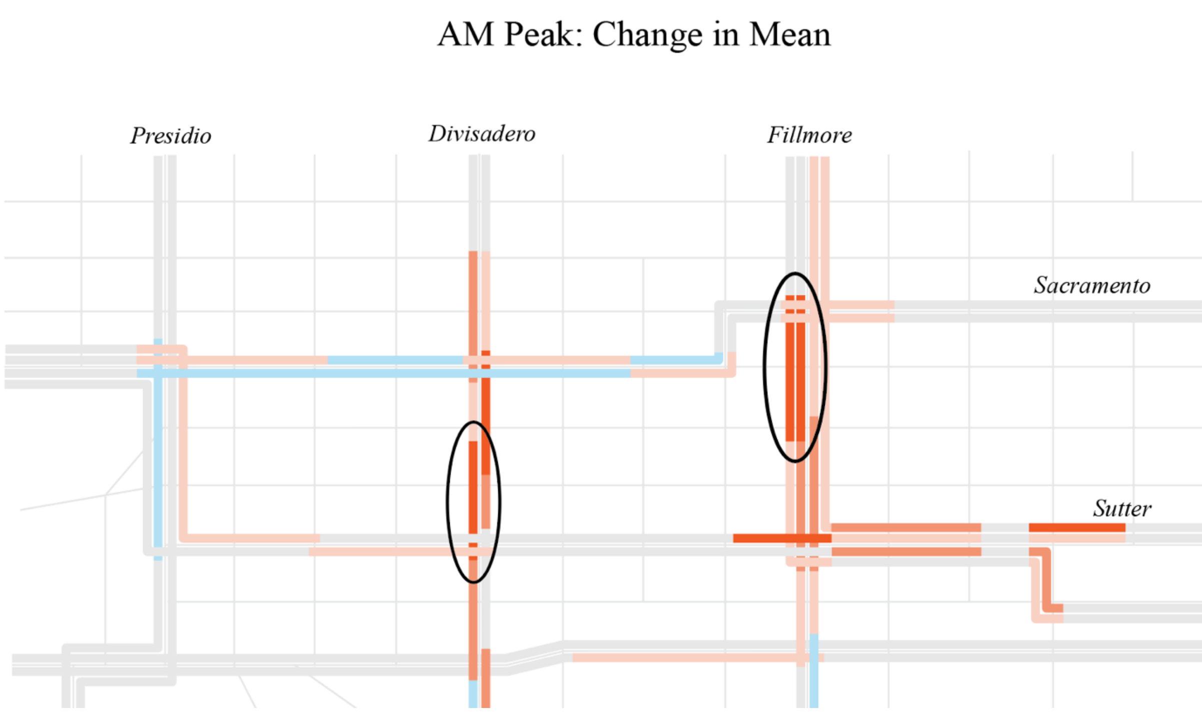


Figure 14: *Divisadero and Fillmore observed segments, shown on the AM Peak Mean Δ results map.*

When I completed this study's data analysis portion, I confirmed that these travel segments experienced severe mean travel time increases. I flagged the Divisadero travel segment for poor travel time performance across all three time periods of the day, whereas the Fillmore segment only demonstrated worsened performance during AM peak hours. In the following sections, I explain my observations of bus and traffic signal patterns at Divisadero St. and Fillmore St., as well as my proposed causes of worsened bus efficiency. I support this discussion with street design, bus headway, and signal offset visualizations.

4.4.1 Divisadero Outbound: Pine to Sutter Segment

The Divisadero study area yielded alarming results, demonstrating how dyssynchronous traffic signals can cause notable transit delays in a localized region. As shown in Figure 15, I observed the outbound 24 Divisadero travel segment spanning from Pine Street (far-side stop) to Sutter Street (far-side stop), crossing through two signalized intersections at Bush Street and Sutter Street. I made my observations between approximately 2:30pm and 5:15pm, which includes both Midday and PM Peak study times. This mean time increase is meaningful to SFMTA because the 24 Divisadero bus is a high-ridership commuter line. For this reason, travel delays in this area negatively impact many everyday customers who depend on the 24 Divisadero for their commutes. Figure 15 shows the layout of this study area and the position from which I made my observations.

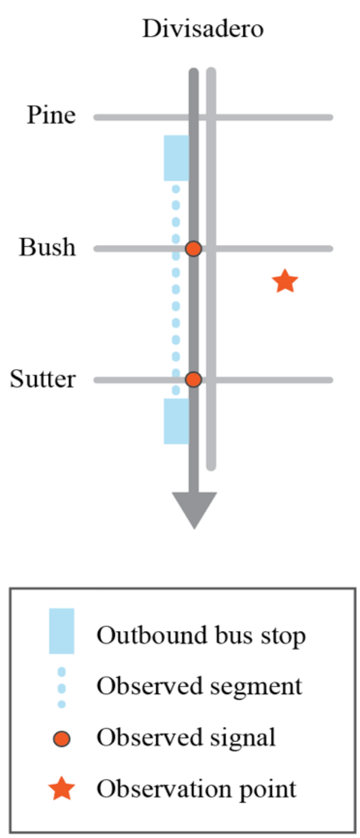


Figure 15: *Diagram of studied intersections and observation location on Divisadero St.*

Figure 16 shows bus headways and the signals encountered by each of 17 observed 24 Divisadero outbound bus. Each vertical pair of circles and lines represents one bus traveling in order through the two intersections. The time of arrival, expressed on the horizontal axis, denotes the time that each bus approached the Bush Street intersection.

The bottom circle represents the first signal at Bush Street, and the top circle represents the second signal at Sutter Street. A blue circle means a green traffic signal, and a red circle means a red signal. A grey circle stands for a missed observation, meaning that I was too distracted taking note of inbound buses and was unable to note an outbound bus at a red light.

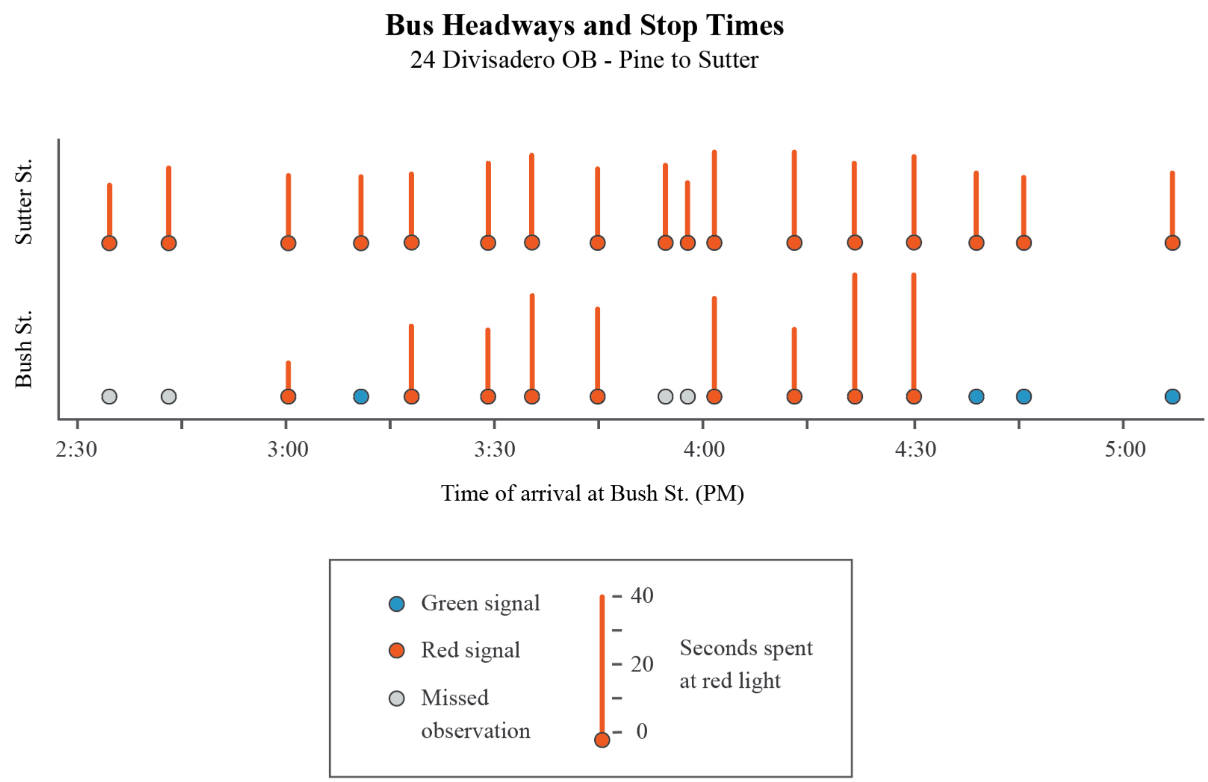


Figure 16: *24-Divisadero bus headways and traffic signals at Bush and Sutter, showing times spent stopped at red lights.*

My observation of the outbound direction reveals the somewhat inconsistent arrival of buses to the Bush Street intersection. The average of headways during this 2.5-hour observation period is 9 minutes, and most headways fall within 2 minutes of this standard gap. However, there are notably long gaps between the 2:43 and 3:01 buses (18 minutes) and the 4:46 and 5:07 buses (21 minutes). Meanwhile, the three buses between 3:54 and 4:02 (4 minutes apart on average) demonstrate a good example of bunching.

More importantly to this study, Figure 16 demonstrates an abnormally low green-to-red signal ratio. I cannot calculate an accurate signal ratio based on the Bush Street intersection data, due to the number of missed observations. However, it is obvious that most buses in this almost 3-hour study period encountered a red signal at Bush Street and Sutter Street. More pointedly, all 17 observed buses stopped at a red light at Sutter Street. This consistent pattern likely caused this segment's increased median travel times.

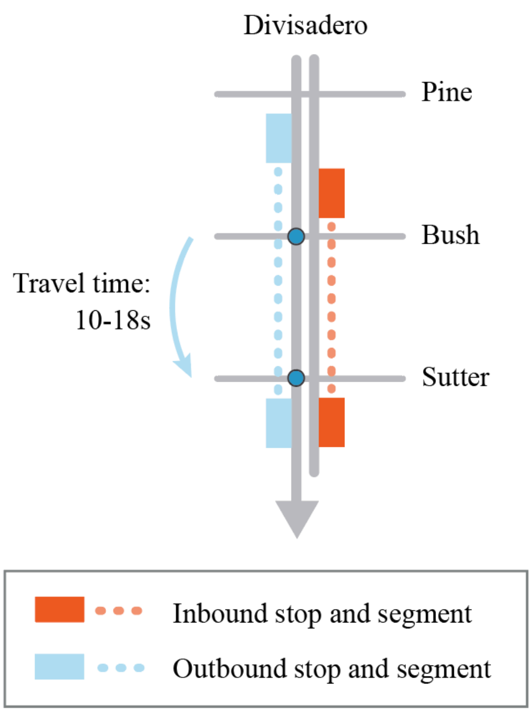


Figure 17: *Inbound and outbound segments passing through Bush and Sutter intersections on Divisadero.*

The top row of red bars in Figure 16 shows that every bus stopped at Sutter Street for a similar length of time. For this set of 17 observations, the mean number of seconds spent waiting at Sutter St. was 18.5 seconds, with a standard deviation of 3.1 seconds. Interestingly, the number of seconds spent waiting (or not waiting at all) at Bush Street did not seem to influence a bus's wait time at Sutter. This figure alone does not present all the information needed to form a hypothesis, however; a closer look at these two intersections' signal timing explains more.

Figure 17 represents the inbound and outbound 24 Divisadero segments that pass through the Bush and Sutter intersections. On the outbound side, a bus took somewhere between 10 and 18 seconds to travel between the two signalized intersections. This duration was measured from the start of the Bush St. intersection (or, if a bus was stopped, the moment the red signal turned green) until when the bus stopped at Sutter Street. The varying number of cars in front of a stopped bus is why this wide variation exists. If a bus traveled through Bush Street on an already green signal, it took about 10 seconds to reach a stop at Sutter. However, if the bus was stopped behind 2 cars at Bush, it took an extra 8 seconds from the time the signal turned green to when the bus crossed the intersection line, since each car took a few seconds to start moving and accelerate.

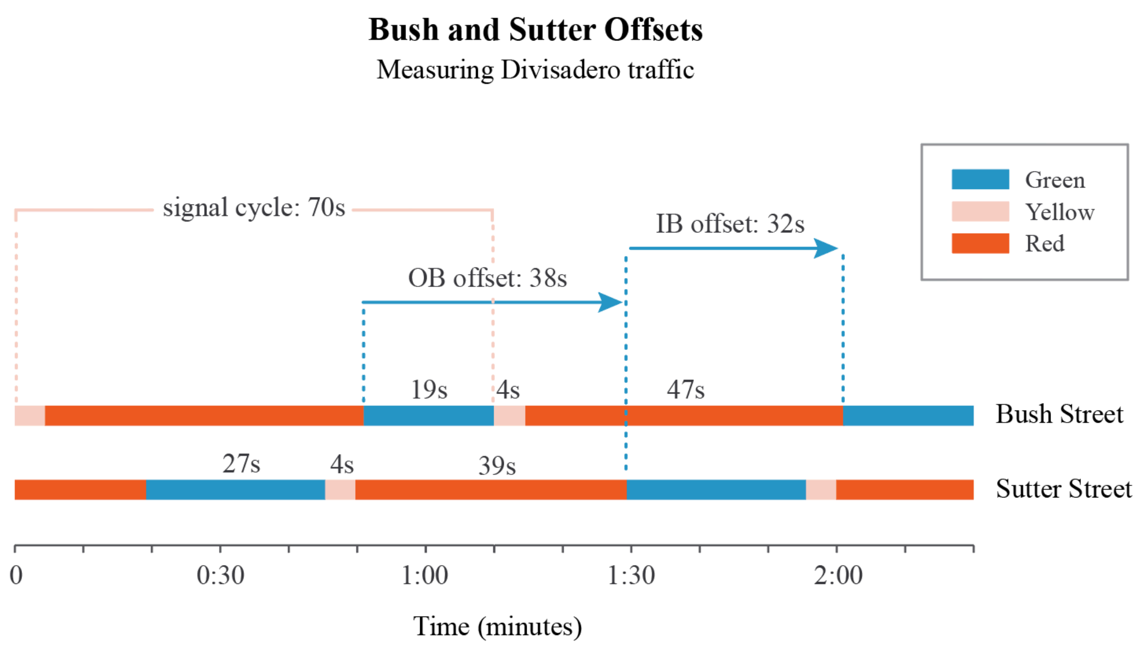


Figure 18: *Signal offsets for Divisadero Street traffic passing through Bush Street and Sutter Street intersections.*

Signal offsets between intersections are a crucial part of signal cycles' influence on traffic performance. Figure 18 represents the signal cycles and offsets for Divisadero/Bush and Divisadero/Sutter. Every signal cycle (the combination of green, yellow, and red signal durations per repetition) lasted 70 seconds at both intersections. The offsets (measured as the start of one green period to the start of the green at the next intersection) are 38 seconds from Bush to Sutter and 32 seconds from Sutter to Bush. During my observations, I focused on outbound buses as part of the study, but I also took note of inbound bus patterns as a useful comparison. From my vantage point, it was very difficult to observe Sutter Street signals for inbound buses, but I did find that 9 out of 17 observed buses stopped at a red signal at Bush Street.

We can consider the first half of a 4-second yellow signal mean “go” and the second half to mean “stop”, since a bus driver will only continue through a yellow light if there is enough time to pass through safely. According to this approximate measure, the green-to-red ratio at Bush is 21s to 49s. In other words, the “go” period for vehicles traveling on Divisadero Street in both directions across Bush Street is 30% of a 70-second signal cycle. For the Sutter Street intersection, this ratio is 29s to 41s, meaning the respective “go” period is 41.4% of a signal cycle. These ratios, compared with my observation samples, reveal a seemingly counterintuitive picture of probability. For example, why did every single outbound bus stop at a red signal at Sutter St., if the green-to-red ratio implies a 41% chance of encountering a green light?

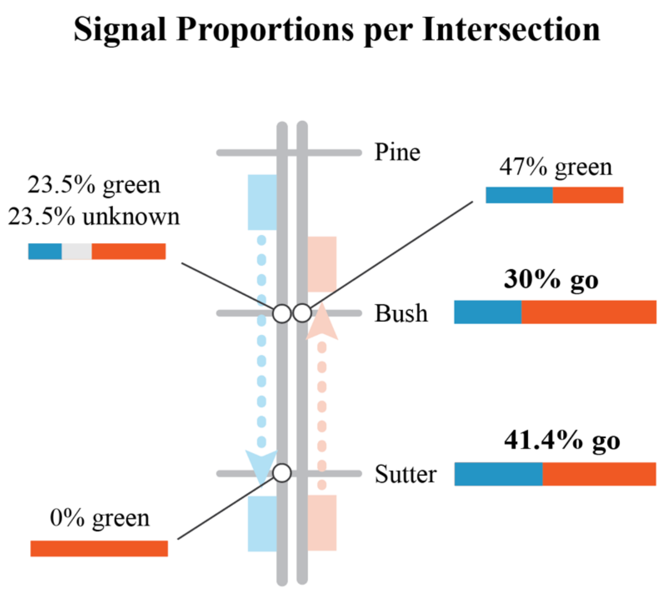


Figure 19: *Green-to-red ratios, or probability of encountering a “go” period, at Bush St. and Sutter St. while traveling on Divisadero St. in either direction.*

The southbound 38-second offset makes it extremely unlikely for a bus to catch a green signal at Sutter Street. If a bus is stopped at Bush, that means once the Bush signal turns green, the bus takes 10-18 seconds to reach the next intersection, as explained previously. The 38-

second offset ensures that this bus would still wait at least 20 seconds at Sutter. If a bus traveled directly through a green light at Bush, it would still encounter a red light by the time it arrived at the Sutter intersection. Additionally, there would have been other cars waiting at the Sutter queue in front, causing the bus further delays at that intersection. In short, in most circumstances, regardless of whether the bus encounters a red or green signal at Bush Street, it will still have to stop at Sutter Street.

To consider this situation further, how could these offsets be shifted to hypothetically produce a more efficient outcome? I present two alternative cycle alignments in Figure 20; I use a 14-second one-block travel time as an approximate baseline for the offsets. Alignment B demonstrates a counterproductive offset shift, whereas Alignment A achieves an optimal result for both inbound and outbound buses. These examples highlight the importance of signal progressions and stop placements in localized traffic design. For demonstrative purposes, I model a hypothetical world where the streets I am studying are completely independent from nearby streets and their offsets.

Offsets can either benefit or hinder transit on both directions on the street, depending on bus stop placements. If a bus traveled down a corridor with no bus stops, a green wave progression could only benefit one travel direction at best, while either providing no benefit or greatly deterring the other direction's flow. Fortunately, a bus stop acts as a 'reset' function between a bus and proximate signal cycles. When a bus pulls over to load and unload passengers, this process's duration varies greatly, depending on how many passengers are involved in the transition. If no passengers are boarding or disembarking, then the stop duration is 0 seconds, but if an individual with disabilities needs accessible boarding, then the process can take considerably more time. The somewhat randomized stop duration thus interrupts a bus's synchronous rhythm with the arterial's (main street's) signal progressions. Upon leaving the bus top, the bus's probability of encountering a green light is similar what the green-to-red ratio predicts, regardless of the signal it encountered at the previous intersection.

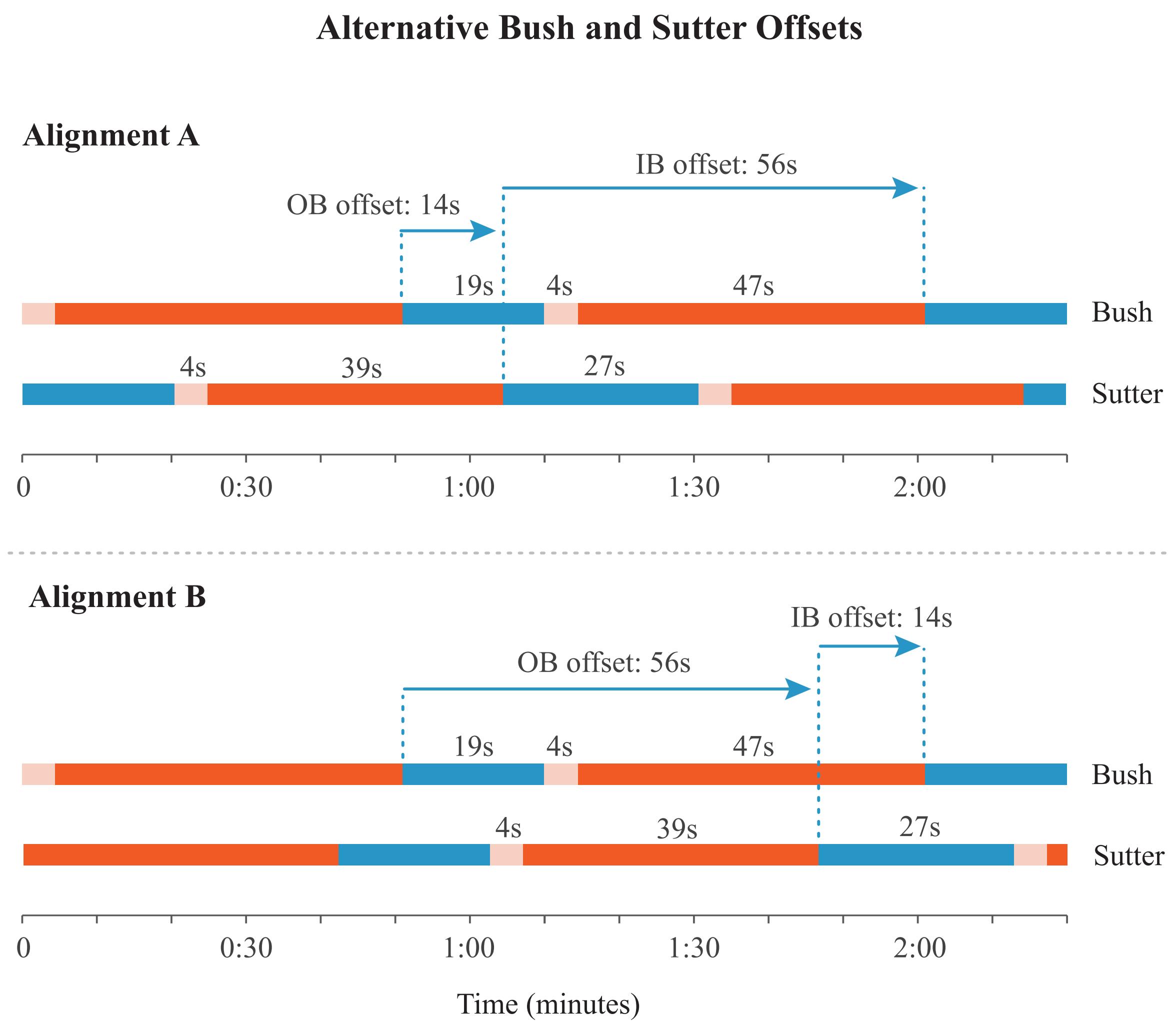


Figure 20: *Hypothetical alternative signal alignments between Bush St. and Sutter St., with the resulting offset lengths shown for each direction. Alignment A represents a beneficial shift, whereas Alignment B would be inefficient.*

In this specific case, the inbound near-side stop at Sutter acts as the bus's 'reset' before it crosses the Sutter intersection and approaches Bush Street. Figure 21 displays these segments again for ease of reference. For reasons explained in the paragraph above, the inbound bus has about a 30% probability of catching a green light at Bush. The northbound Sutter-to-Bush offset thus does not negatively influence an inbound bus's performance within this travel segment. On the other hand, the southbound Bush-to-Sutter offset undoubtedly affects an outbound bus's time performance. Based on this reasoning, the signal alignment between Bush and Sutter street should focus on helping outbound buses pass through Sutter unimpeded.

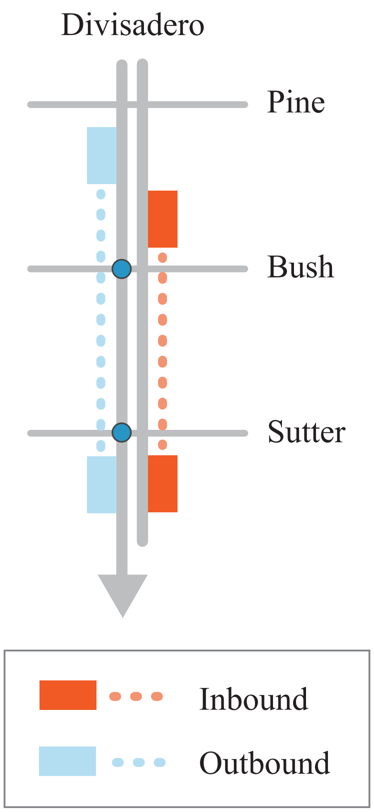


Figure 21: *Inbound and outbound segments on Divisadero.*

Referring back to Figure 20, Alignment B achieves the opposite of this goal. The outbound buses would still encounter a red signal almost every single time, and would therefore stop for about 40 seconds each time. Again, inbound buses would not be heavily impacted by this signal alignment. Meanwhile, Alignment A would allow virtually every outbound bus to pass through a green signal at Sutter Street.

These proposed alignments simply show the relationship between signal timing and stop placements using a specific location example. In real-world situation, one segment's traffic performance depends on a complex network of interconnected streets and multi-directional signal progressions. Transit engineers must consider thousands of factors when designing timing arrangements street by street. One travel segment flagged for slower transit performance might be necessary for more efficient performance in other segments in the same transit line.

4.4.2 Fillmore Street: Sacramento to Pine

My Fillmore observations further proved how traffic signals can disrupt a predictable bus schedule. This southbound travel segment starts at Sacramento Street (near-side stop) and ends at Pine Street (far-side stop). Because every bus stopped for passenger boarding at the Sacramento Street stop, I decided to leave the Sacramento street signal out of my observations; recall my earlier explanation of bus stops as 'reset' functions.

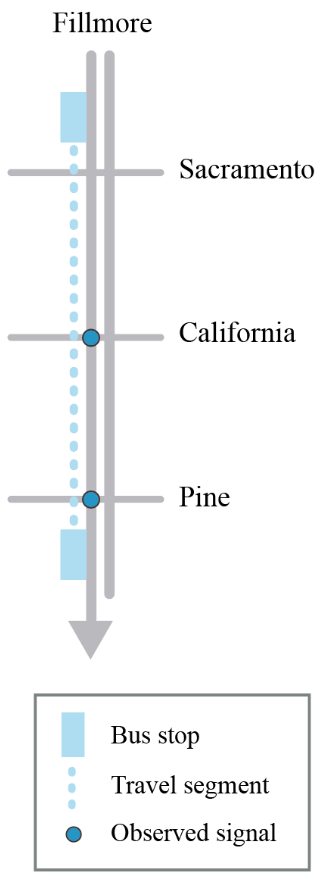


Figure 22: *Diagram of studied intersections and observation location on Fillmore St.*

Both the 3 Jackson inbound and the 22 Fillmore outbound lines include this segment, so I noted buses from both lines during my observations. Like the 24 Divisadero, the 22 Fillmore is another important commuter line, so these transit delays are crucial to riders' perceptions of SFMTA performance. I made my observations for two hours between 7:35am and 9:40am, which encompasses most of the AM Peak period (7-9am) and extends over half an hour into the Midday period (9am-4pm).

My data analysis confirmed the Sacramento-Pine segment as a problem for AM Peak mean travel time change, but my in-person observations partially contradicted this finding. As shown in Figure 23, between 7:35am and 8:50am, almost every outbound bus traveled through two green lights in a row at California Street and Pine Street. This observation was initially alarming to me because it represented a properly working green-wave progression. This directly contrasted the results, which claimed this segment experienced dramatic slowdowns after the timing changes. However, after 8:50am, suddenly almost every single bus encountered a red light at both California and Pine Street. This abrupt change only lasted for about 15 minutes, until the buses started encountering green lights again after 9:05am.

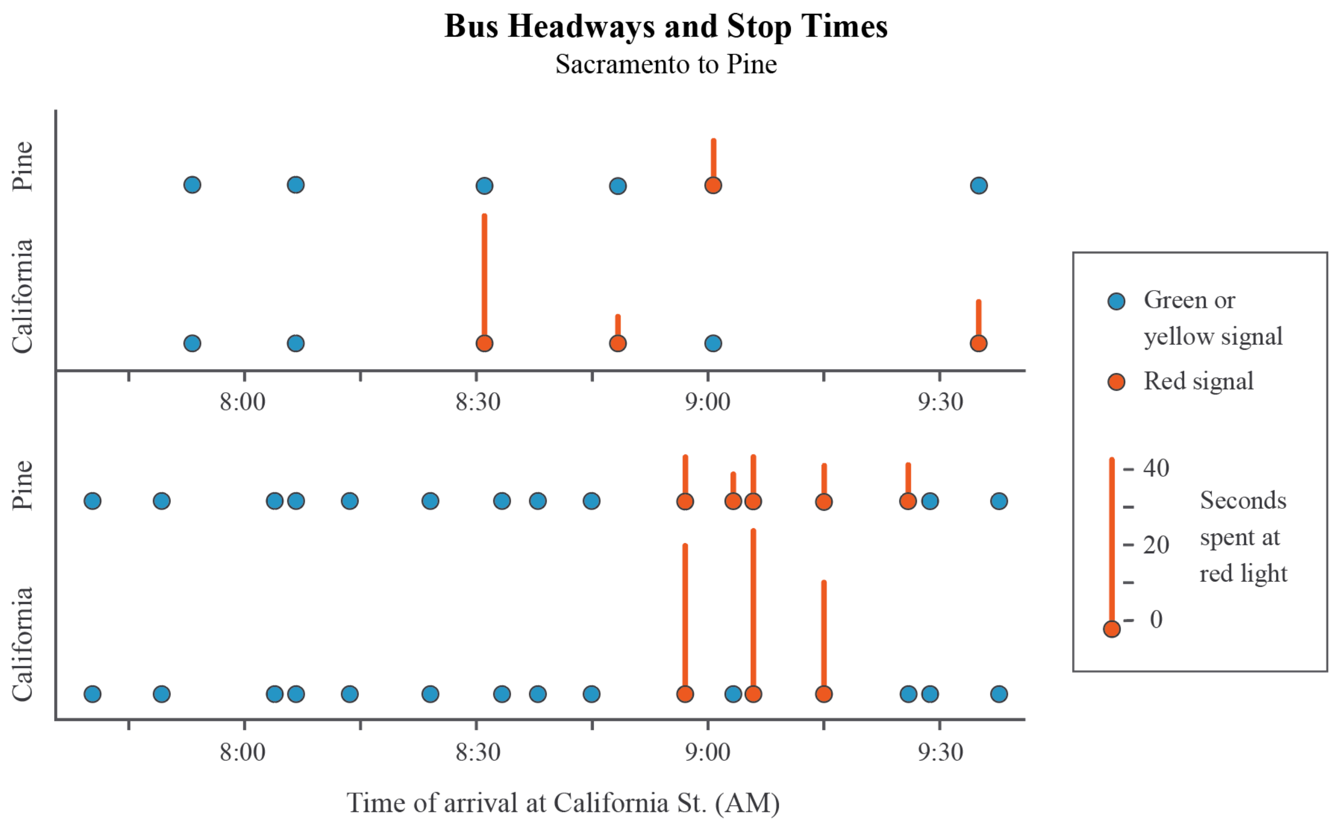


Figure 23: *22-Fillmore bus headways and traffic signals at California and Pine on Fillmore.*

Figure 24 represents offsets between Sacramento, California, and Pine Street during the two different timing phases that I observed. Programming A denotes the first signal setting, featuring an efficient green-wave progression for southbound vehicles. Programming B represents the brief period in which the offsets 'reversed' between Sacramento and California. The primary offset changed to 4 seconds in the opposite direction, from California towards Sacramento. The signal offset between California and Pine was the same as in Programming A.

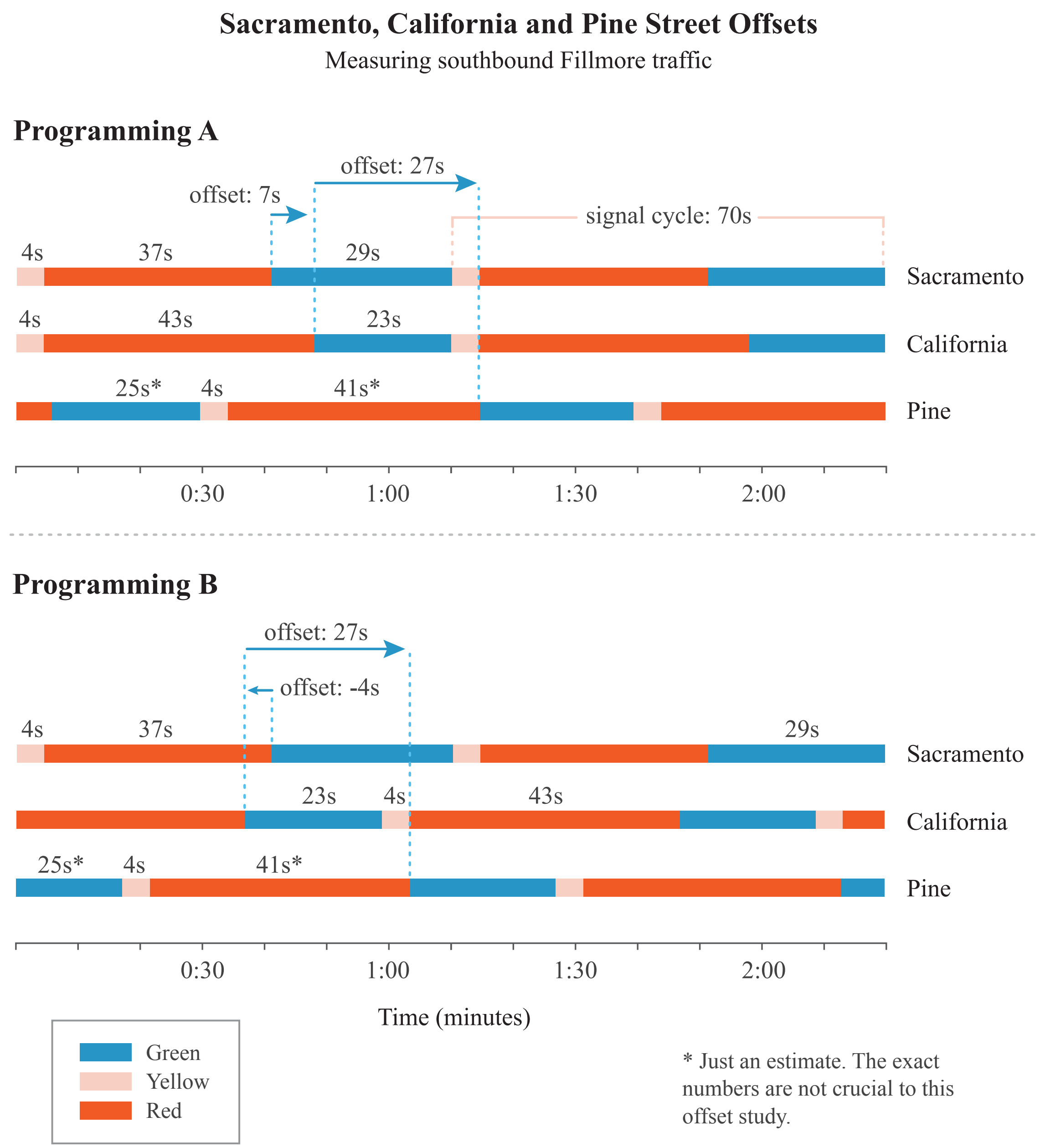


Figure 24: *Signal offsets for southbound Fillmore Street traffic passing through Sacramento, California, and Pine Street intersections.*

Buses typically took about 15-20 seconds to travel from Sacramento to California and about 17-23 seconds to travel to Pine Street, depending on whether the bus stopped at California. Figure 25 shows bus travel patterns, demonstrating why the Programming A system allowed for consecutive green passes whereas Programming B resulted in substantial delays. The

Programming A system allowed almost every bus to pass through California Street unimpeded, which then allow them to catch the green signal at Pine Street. However, any bus leaving Sacramento would encounter a red signal at California under the Programming B system.

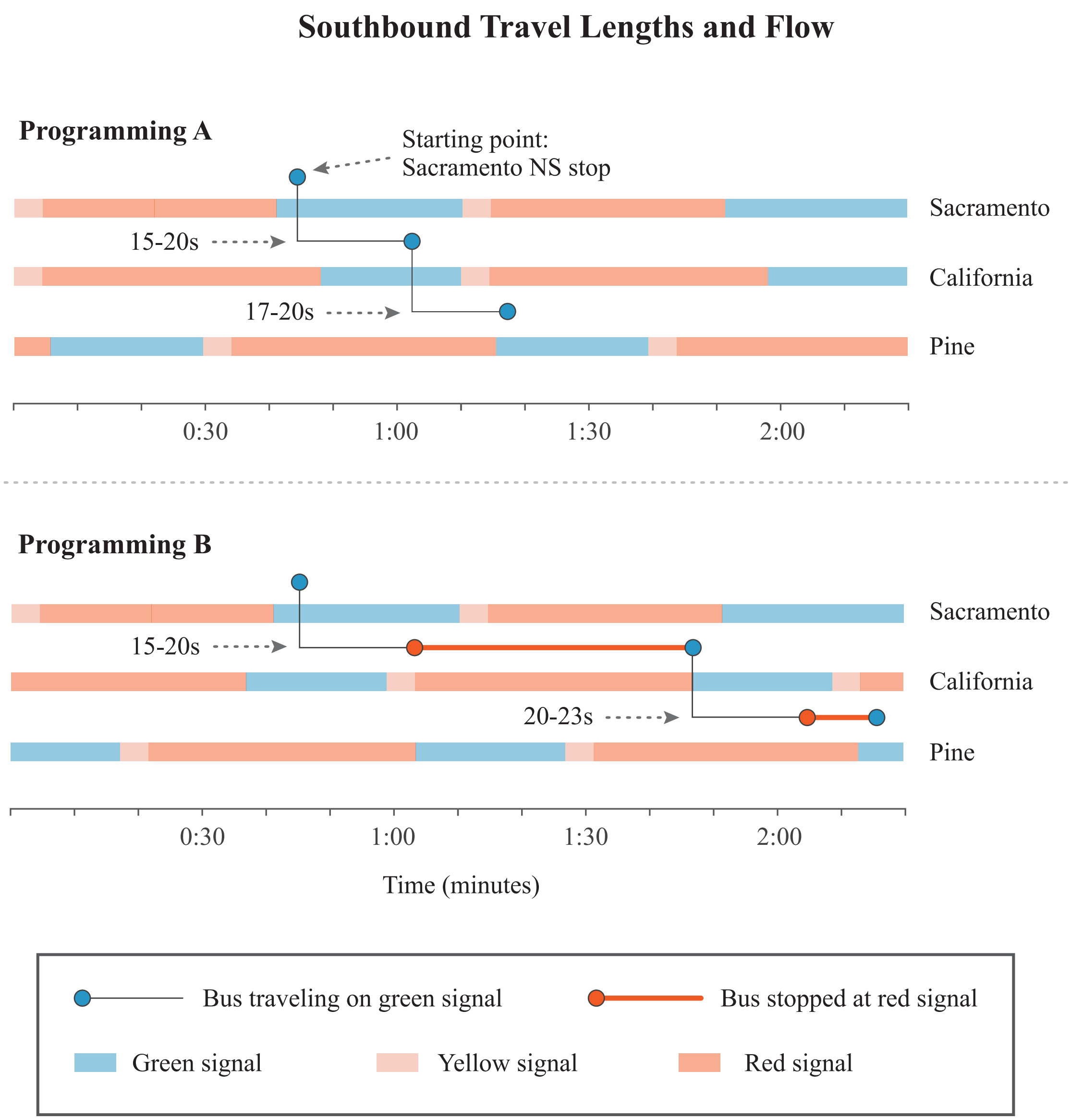


Figure 25: *Southbound bus patterns, demonstrating an optimal green-wave progression in Programming A and an inefficient traffic flow in Programming B. These diagrams are simplified, operating on the assumption that the buses start out near the beginning of the green period at Sacramento. In the case of Programming A, if a bus starts from Sacramento closer to the end of the green period, it could encounter a red signal at California and have to wait 30+ seconds (as demonstrated by the 8:31am 3 Jackson bus).*

As clearly shown in Figure 25, Programming A benefitted transit whereas Programming B hindered efficiency. On this particular morning, Programming A represented a significant portion of the AM Peak period (7:35-8:50am). I cannot speak for the signal timing before 7:35am, but I can confirm that Programming B didn't begin until 10 minutes before the AM Peak period ended. Programming B's brevity does not explain the AM Peak's severe travel time increases. Even more confusingly, the signal timing change only lasted for 15 minutes, and occurred at a seemingly random time of day.

After further consultation with SFMTA traffic engineers, I discovered that Programming A was the correct signal system, as confirmed by the agency's signal timing archives. Programming A outlined the timing not only for the AM Peak period, but for the entirety of the Midday period as well. According to an SF Go engineer, the switch to Programming B was unintended by all means, implying that it was caused by a glitch in the system (Tang 2019). Even with careful programming, sometimes technological errors can interfere with transit performance.

5. Discussion of Results

5.1 Overview

As previously discussed, a breadth of transportation literature reviews the individual issues encompassed in this current study. Previous research addresses various possible pedestrian safety measures (Gårder 2004; Leden, Gårder, and Johansson 2006; Keller et al. 2011), including extending crossing times (Arango and Montufar 2008; Fitzpatrick, Brewer, and Turner 2006; Amosun et al. 2007; Li 2013). However, these studies have not examined their unavoidable effects on local and city-wide traffic patterns. Other literature has modeled TSP systems for more reliable and efficient transit (Truong, Currie, and Sarvi 2017; He, Head, and Ding 2014; Memoli et al. 2017; Wahlstedt 2011; Skabardonis and Christofa 2011), but these studies do not consider the limiting factor of extended pedestrian intervals. Likewise, a third subset of studies has established a strong relationship between bus reliability and ridership (Nakanishi 1997; Tyrinopoulos and Antoniou 2008; Cantwell, Caulfield, and O'Mahony 2009; Kittelson 2013; Benezech and Coulombel 2013; W. Chen and Chen 2009; Chakrabarti and Giuliano 2015; Rietveld, Bruinsma, and van Vuuren 2001), but does not examine the reliability issue in tandem with pedestrian crossing delays.

Some studies have set out to examine network-wide traffic relationships, taking multiple components of road-user behavior and traffic signal timing into consideration. While older research (Herman and Prigogine 1979; Olszewski, Fan, and Tan 1995) presents somewhat unrealistic models unsupported by empirical data, more recent studies have demonstrated results based on simulations and data, defining a relationship between traffic density and flow within given traffic networks (Geroliminis and Sun 2011; Du, Rakha, and Gayah 2016; Daganzo and Geroliminis 2008; Thonhofer et al. 2018; Di Gangi et al. 2016). Building upon these model-based studies, this current study examines network-wide traffic relationships from a different perspective. This study supports a large-scale data analysis with qualitative evidence, using two high-traffic travel segments as case studies.

Before beginning my research, I expected that SFTMA inadvertently worsened bus travel times and reliability by extending pedestrian crossing times. Previous literature on inter-network traffic effects (Gartner and Wagner 2004; Daganzo and Geroliminis 2008) supported this hypothesis, explaining that prolonged red signals disrupt traffic flow and cause transit delays. I hypothesized correctly that more than half of all study segments increased in both average travel time and standard deviation. My field observations, however, add depth to this otherwise simple conclusion. In this study, I demonstrate how stop placement, signal timing, and special street characteristics collectively define transit performance across individual intersections. Previous literature either examines signal effects on transit efficiency from a broad city-wide standpoint, or analyzes individual components of pedestrian safety and transit efficiency without researching their residual network effects. My research attempts to bridge the divide in this literature by accounting for all these factors. I use both quantitative and qualitative measures to more holistically evaluate SFMTA's experiment with longer pedestrian crossings.

5.2 Travel time changes and implications

My findings supported my decrease-in-efficiency prediction for both mean and standard deviation, across all three study periods of the day. Copious research proves a causal relationship between bus reliability and ridership; riders highly value reliability when considering their transportation options (Nakanishi 1997; Tyrinopoulos and Antoniou 2008; Cantwell, Caulfield, and O'Mahony 2009; Kittelson 2013). Such studies define reliability as unpredictable and longer-than-expected wait times (Rietveld, Bruinsma, and van Vuuren 2001). Based on this evidence, increased Muni travel times are likely correlated with ridership changes in demand.

Due to limitations on available data, this study approaches the reliability question from a different angle, using mean and standard deviation of stop-to-stop travel times to measure transit performance. In this study, transit efficiency generally worsened across all measures, with some areas showing more extreme time increases than others. Travel time increases, along with increases in standard deviation, would make the After-Period transit performance more unreliable than it was before the pedestrian signal changes. Because riders make bus route decisions based on how they perceive service reliability (Chakrabarti and Giuliano 2015), I can infer that these travel time increases could worsen ridership opinions of SFMTA bus performance, possibly decreasing ridership over time.

One study makes an important note that many transit riders depend on multiple bus lines to reach their destinations. If riders experience frequent delays in one segment of their trip, they could choose to take a different route (Chakrabarti and Giuliano 2015). This change could have two likely outcomes, the first being the more favorable: the rider switches to another bus line, if available and convenient, which does not decrease transit ridership. However, ridership is negatively impacted if there are no reasonable alternatives, and the rider decides on a mode other than public transit.

My statistical analysis of travel data yielded numerically accurate results, but these results could not explain efficiency problems on a per-intersection level. Existing literature demonstrates this drawback of pure data analysis when it focuses primarily on city-wide causes of unreliability. Such studies (Saberi et al. 2013; Tyrinopoulos and Antoniou 2008; Cantwell, Caulfield, and O'Mahony 2009) do not mention how signal timing or pedestrian interactions hinder transit performance on a micro level. To address this gap, my field observations helped explain physical factors leading to large statistical changes.

5.3 Signal timing in practice

This study proves that unaccompanied data reaches limitations in real-world problem solving. In this research project, my analysis of travel time data gives me a statistically reliable summary of bus line performance. However, without the in-person observations to complement the analysis, this numerical summary would fail to provide much insight or useful information.

Simple measures of average travel time and standard deviation do not explain travel inefficiencies on an intersection-by-intersection basis. Since every travel segment has unique traffic and street design properties, each case's traffic inefficiencies has its own causes and solutions.

By studying observational analyses in detail, I encounter various traffic engineering challenges that previous studies have explored. As mentioned earlier, several studies have discussed problems and hypothetical solutions regarding unreliable on-time performance, stop placement in relation to intersections, and transit priority signal timing strategies.

5.3.1 Stop placement: near-side vs. far-side

In Section 4.4, I discuss near-side and far-side stop locations' relationship with signal cycles and bus efficiency. Existing studies have explained stop placements' importance using various approaches, including city-wide data analyses, micro-simulations, mathematical modelling, and small-scale case studies. Research by Ceder, Butcher, and Wang (2015) and Furth and SanClemente (2006) focused on stop placement in areas with uneven topography, which is applicable to much of hilly San Francisco's terrain. In modeling data on a city-wide scale, however, both studies fail to explain how stop placement can benefit or delay traffic in specific street design scenarios, such as those involved in this current study.

Different studies evaluating near-side and far-side stop effects on bus travel times have produced conflicting results. Diab and El-Geneidy (2015) concluded that near-side stops generally cause more delays than far-side stops, whereas Wang et al. (2013) claimed the opposite. Meanwhile, Liu and Jian (2019) demonstrated that the efficiency of stop placement depends on the stop's distance from the nearest traffic signal. My case studies of Divisadero and Fillmore Street neither disprove nor agree with these studies' results. My findings in these specific, localized examples demonstrate that stop placement, as an individual factor, does not directly correlate with delay times.

Aforementioned literature focused mainly on city-wide data and simulations, combining results from thousands of travel segments into simplified conclusions. On the other hand, this study's observations explain how a bus stop's location factors into signal timing of consecutive intersections. A bus stop's efficiency within a travel line depends entirely on both signal progressions and stop placement on both sides of the street. In order for a travel segment to function with minimal delays, traffic signals must coordinate with stop locations.

5.3.2 Signal offsets and green-wave progression

Time-efficient traffic flows on signalized arterials have been thoroughly modeled and studied in engineering literature. Gartner and Wagner (2014) emphasized that carefully-timed signal coordination is crucial to having efficient urban street networks. Kong et al. (2011) and Ye et al. (2014) both proposed bi-directional green wave models using passive TSP, optimizing efficiency both ways on signalized arterials. Gettman et al. (2007), Duerr (2000), and Yang and Ding (2017) all presented active TSP variations on actuated green wave methods, wherein intelligent signals adjust cycles to accommodate incoming transit vehicles.

My intersection observations support Gartner and Wagner's ideas on signal coordination. I observed bi-directional green wave progression at Fillmore Street during the Programming A cycles, supporting the literature on this timing method's efficacy (Kong et al. 2011; Ye et al. 2014). As SFMTA's pedestrian retiming project focused on passive instead of active TSP, I hypothesize that actuated signals would improve transit flows on higher-traffic streets (Gettman et al. 2007; Duerr 2000; Yang and Ding 2016).

On a larger scale, so-called perfect traffic efficiency is impossible to achieve. Recalling the 24 Divisadero outbound example, where every bus encountered a red light at Sutter: the simple-seeming fix would be adjusting offsets between Bush and Sutter Street. Since that segment's inbound direction is unimpacted by local signal offsets, a more optimal alignment nice green-wave progression would greatly benefit outbound efficiency. However, in a real-world situation, adjusting one offset can throw the rest of the system out of balance. Not only do these offsets affect Divisadero traffic, but they also affect the offsets and cycles for all the surrounding cross-streets. Additionally, green-wave progressions are very difficult to time while considering where hundreds of near-side and far-side bus stops are located. Allowing green-wave progression for one side of the street will often cause delays for the other side of the street, depending on the spacing and location of an arterial's bus stops.

In reality, signal timing is highly complicated because traffic flows on all intersecting streets are interdependent. As such, an efficiency improvement in one area will result in a drawback in another area. Adjusting one intersection for more efficient traffic flow can greatly disrupt traffic coordination on adjacent intersections, prompting a domino effect in which the entire system loses its synchronous cohesion.

5.3.3 Special zones and impacts on transit

Sometimes, special circumstances present significant limitations for traffic timing. In section 4.4.1, I outline signal alignment shifts that could improve the 24 Divisadero line's efficiency. However, I do not propose shortening the red signal periods for a very important reason. The Divisadero area I studied is part of a hospital zone, meaning that there are additional traffic rules that protect pedestrians. The UCSF Medical Center covers a 5-block area centered around Divisadero Street, starting at Bush Street and extending southwards until Geary Street.

Hospital zones already require longer crossing times to allow mobility-impaired pedestrians to walk safely. In this specific case, however, political pressure played an additional role in the area's signal timing. In May 2019, 77-year-old Galina Alterman was killed in a traffic accident at the Divisadero and Sutter Street intersection (Rubenstein 2019). Following this tragic event, pressure from both city government and community groups urged SFMTA to allow even more crossing time around this area. This Divisadero Street case exemplifies how local politics and unique street characteristics can further conflict with traffic performance.

5.4 Research limitations

In addition to this pedestrian problem, bus unreliability represents a very complex problem for transportation agencies to fully solve without suffering losses in at least one area of operations. In the event that travel times and variability worsen in certain areas, e.g. because of a signal system adjustment, a transportation agency cannot simply alter its scheduling to account for these changes. SFMTA does make quarterly adjustments to its bus scheduling based on current travel time conditions. However, adding time to a schedule upsets riders, who consider transit less appealing with any additional delay above 30 seconds. According to SFMTA Transit Priority Team Manager Michael Rhodes (personal communication, 2019), an 10% reduction in travel time per trip results in an estimated 5% ridership increase, and the converse is true as well. In addition to this complication, if SFMTA adds more time to a bus schedule, it must add another bus to offset the time losses for riders. Running one extra bus costs an additional $1 million per year, and those extra funds are not always available. The alternative is to run a bus line less frequently, making the service less attractive to riders and causing crowding (Rhodes 2019).

I was unable to account for some confounding factors in this study, including irregular school and holiday traffic patterns, segment length differences, and non-regular timing cycles. AM Peak and Midday data likely vary with volumes of school-age riders, which fluctuate while school is in or out of session. I used percent change in mean travel time to show changes' severity, but did not calculate the amount of change per travel distance or number of retimed signals. Lastly, some intersections may not be programmed with the same signal cycles whether or not pedestrians are crossing the street. The two locations that I observed had regular signal timing, meaning that signal cycles remained constant even in the absence of crossing pedestrians. I cannot confirm that all the intersections in this study follow the same rule.

In this study, I measure changes in mean travel time and standard deviation per stop-to-stop travel segment. The available Transtat data only provided datasets by individual travel segments, and not for extended lengths of bus lines. For this reason, I could only use these independent segments' summary measures to approximate reliability. This study does not claim that these statistical values directly represent on-time transit performance. On-time performance is dictated by how much a bus's actual arrival deviates from its prediction. Other studies in this field have used variation in headway times as a more accurate measure of bus reliability (Buchanan and Walker 2002; X. Chen et al. 2009; Saberi et al. 2013). Because of dataset limitations, this study is unable to confirm any system-wide changes in either on-time performance or bus headways. Still, longer travel times in each travel segment, especially paired with greater variation, undoubtedly worsen on-time performance by making arrival times more difficult to predict.

Clearly, various participants in the transportation scene play vital, overlapping roles in this central issue. Within this interwoven network of internal and external factors, increasing pedestrian crossing times constitutes only one part of the overall solution. However, my research focuses on SFMTA's crossing time extension project specifically. For this reason, this study uses lengthened crossing times to represent a safety improvement. As explained earlier, previous literature proves that this change improves pedestrian safety. However, this one solution is far from holistic, and I do not claim it to be an overall representation of pedestrian safety. Keeping this in mind, I emphasize that this extended crossing time project does not represent an end to pedestrian fatalities.

5.5 Takeaways and next steps

More detailed studies of vehicular movements, bus service, and traffic signals in San Francisco could address some of the above limitations. SFMTA could benefit from re-examining the signal malfunction I observed at Fillmore Street. That could mean carrying out additional in-person observations, or it could mean looking for technical errors in the implementation process. Ultimately, further investigations should determine when that specific error occurs, how to fix it, and whether that error exists at other intersections. Additional SFMTA research can determine why some lines got worse than others, and what factors influence this. Confounding factors could include more crowded arterials for transit, busier cross-streets for vehicles, or heavier pedestrian traffic in areas such as shopping districts. For identified problem segments, further research should model how to make San Francisco signals more efficient while accounting for surrounding traffic.

This study demonstrated that SFMTA's signal timing changes, to allow longer walk signals, increased Muni bus travel times and standard deviations for the majority of individual travel segments. However, more research is needed to quantify system-wide effects on on-time performance. Taking this a step further, future studies could study how this decreased reliability impacted SFMTA ridership over time. Beyond that, future studies on bus reliability should account for transit-signal elements as described in this paper, such as signal offsets in relation to stop placement.

6. Conclusion

This study found that on a whole, SFMTA failed to maintain their level of bus service after their pedestrian signal changes. However, certain stop-to-stop segments did decrease in travel times and standard deviation. My case study highlights what real traffic components should be considered when retiming traffic signals. In this study, my observations and subsequent analysis showed that signal alignment issues and system flaws can cause transit delays. In-person observations clarify our understanding of transit performance, but that may not always be possible with limited manpower and resources.

One central takeaway is that statistical data cannot fully capture the nuances of a large-scale traffic system. Transit does not operate independently from complex surrounding urban factors. When studying traffic efficiency, a total focus on quantitative results can obscure crucial qualitative insights. Cities represent problems in disorganized complexity, as famously described by Jane Jacobs. On this note, public transit undoubtedly enhances urban mobility, environmental sustainability, user equity, and traffic mitigation. In order to promote transit ridership and achieve these benefits, SFMTA strives for maximum reliability and efficiency. Nonetheless, while using this data to optimize transit, people's safety must remain an utmost priority – saving pedestrian lives matters more than saving a few seconds in transit.

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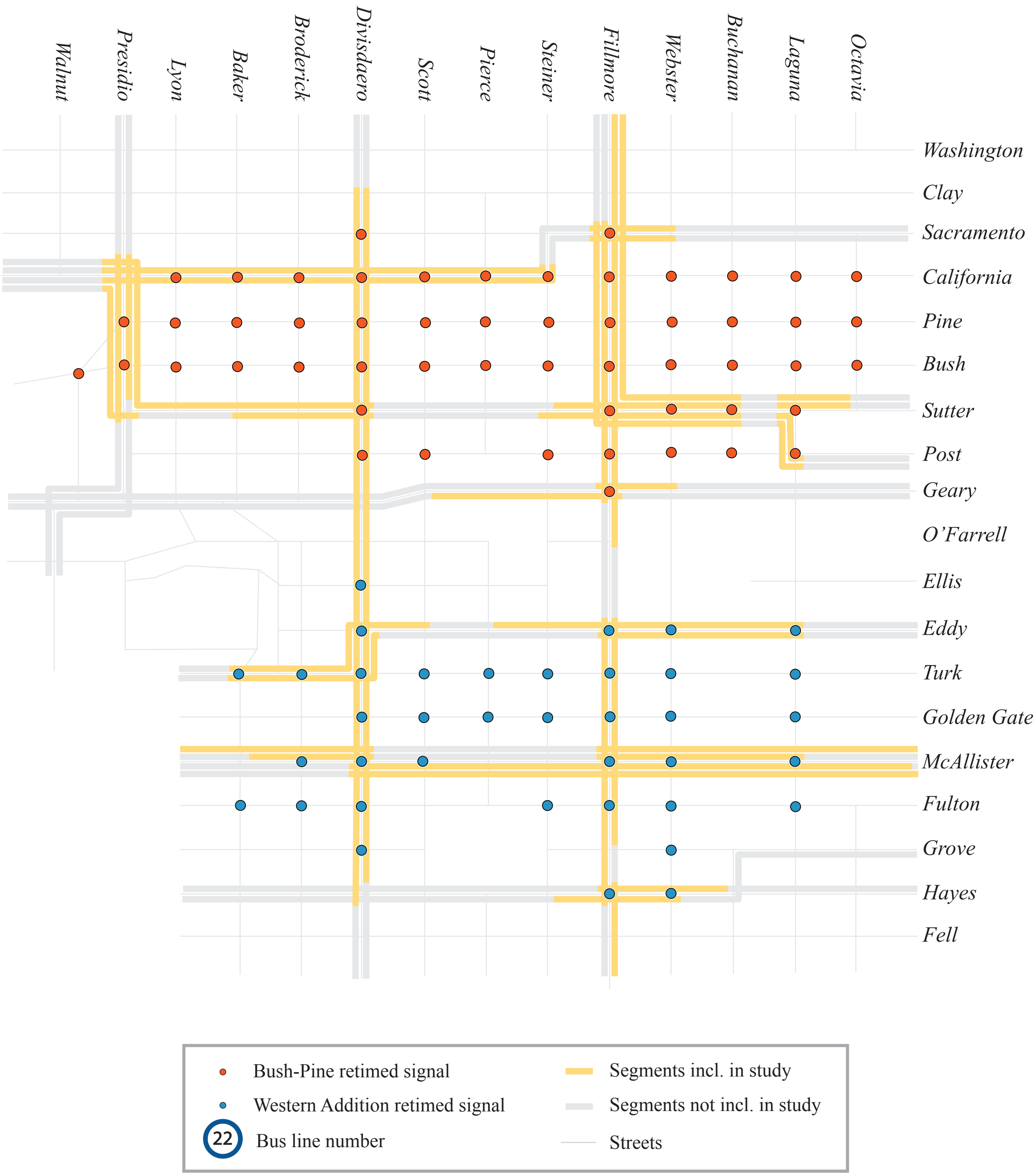
Appendix Exhibit 1. Street Names Map



Appendix Exhibit 2. Stratified Results Tables

1 California

Stop-to-Stop Name	AM Peak Mean Δ	AM Peak % Δ	AM Peak SD Δ	Midday Mean Δ	Midday % Δ	Midday SD Δ	PM Peak Mean Δ	PM Peak % Δ	PM Peak SD Δ
Inbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Presidio to Baker	6.6	6.2	-2.3	0.4	0.4	2.3	-12.7	-9.6	-12.8
Baker to Divisadero	-7	-12.1	1.5	-1.6	-3	-0.7	1.1	2	-1.9
Divisadero to Pierce	6.7	9.6	0.2	7.1	9.1	-0.4	-5.5	-5.6	4.1
Pierce to Sacramento	-2.5	-3.8	2.2	2.2	3.4	2.8	11.4	17.1	0.2
Sacramento to Fillmore	5.8	11.2	-1.3	3.3	6.2	-0.3	-0.4	-0.7	-0.1
Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Webster to Fillmore	4.7	9.1	4.3	5.6	10.3	3.3	5.5	10.6	3.2
California to Pierce	5.1	9.9	-0.2	2.6	4.7	0.9	-3.6	-6.4	1.8
Pierce to Divisadero	-7.3	-8.9	5.4	5.4	7.5	3.9	8.7	15.2	0.1
Divisadero to Baker	-2.9	-5.8	4.2	-2.8	-5	3.3	-5.7	-10.2	2.6
Baker to Presidio	-9.6	-10.5	-1.7	0.1	0.1	-0.7	3.2	3.5	-1.7

2 Clement

Stop-to-Stop Name	AM Peak Mean Δ	AM Peak % Δ	AM Peak SD Δ	Midday Mean Δ	Midday % Δ	Midday SD Δ	PM Peak Mean Δ	PM Peak % Δ	PM Peak SD Δ
Inbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Presidio to Presidio	0.5	0.5	0.7	0	0	0	-0.4	-0.3	-3.9
Baker to Divisadero	3.6	4.5	-1.9	1	1.2	0.3	2.5	3	1.4
Steiner to Fillmore	0.1	0.2	-2.3	-0.4	-0.8	-1.1	-0.9	-1.8	0.1
Fillmore to Buchanan	11.9	22	6.1	8.3	13.1	6.6	10.4	14.8	9.8
Laguna to Laguna	12.8	21.3	1.3	4.8	7.6	3.7	3.4	4.9	1.7
Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Octavia to Laguna	3.3	8.9	2.8	2.3	5.9	1.4	3.7	9.5	2.8
Buchanan to Fillmore	8.4	11.5	3.4	0	0	0	-9	-12.6	-1.8
Fillmore to Steiner	21.6	43.5	3.9	1.2	2.8	1.7	-1.5	-3.4	2.3
Divisadero to Baker	0.7	1	1.4	0.6	0.8	0.5	0.6	0.8	1.1
Sutter to Presidio	9.3	9.4	2.6	10.7	10.6	-1.4	10.4	10.2	-2.3

3 Jackson

Stop-to-Stop Name	AM Peak Mean Δ	AM Peak % Δ	AM Peak SD Δ	Midday Mean Δ	Midday % Δ	Midday SD Δ	PM Peak Mean Δ	PM Peak % Δ	PM Peak SD Δ
Inbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Sacramento to Pine	23.3	30.9	9	2.3	2.1	2.3	9	8.1	-0.1
Pine to Fillmore	9.5	10.6	8.6	-4.5	-5.1	10.5	-3	-3.4	9.7
Fillmore to Buchanan	-3	-4.6	3.1	-0.2	-0.3	3.4	1.2	1.6	1.9
Laguna to Laguna	9.2	14.7	-0.3	8	12.7	2.9	2.1	2.9	-2.3
Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
Octavia to Laguna	33.1	86.9	8.4	3.5	8.8	1.7	2.9	7.4	2.6
Buchanan to Fillmore	12.4	17.4	1.8	-1.1	-1.5	5.1	-8.3	-11.8	-1
Fillmore to Pine	5.8	6.2	-9.3	-4.6	-4.2	4.5	-16.1	-13.4	1.3
Pine to Sacramento	7	13	3.7	4.1	6.4	-2.3	8.2	13.5	1.4
Sacramento to Fillmore	6.1	5.6	1.7	2.6	2.2	0.5	2.3	2	1.6

Mean Δ	***% Δ***	***SD Δ***
< –20	< –20	< –8
–10 to –19.9	–10 to –19.9	–4 to 7.9
–2 to –9.9	–2 to –9.9	–1 to –3.9
–1.9 to 1.9	–1.9 to 1.9	–0.9 to 0.9
2 to 9.9	2 to 9.9	1 to 3.9
10 to 19.9	10 to 19.9	4 to 7.9
20+	20+	> 8

Appendix Exhibit 2, continued

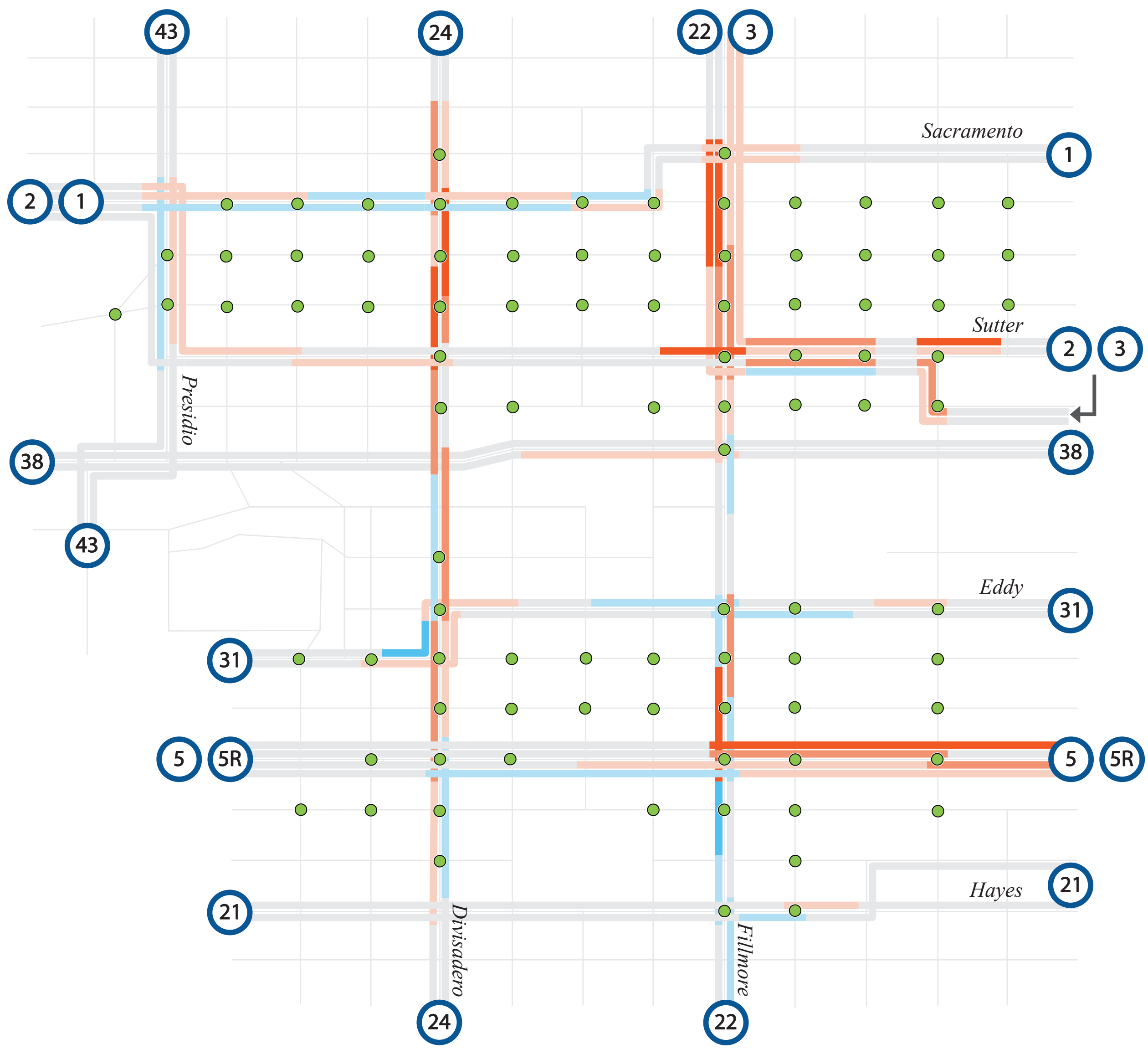
Route	Stop-to-Stop Name	AM Peak			Midday			PM Peak		
		Mean Δ	% Δ	SD Δ	Mean Δ	% Δ	SD Δ	Mean Δ	% Δ	SD Δ
5 Fulton	***Inbound***									
	Divisadero to Scott	1.5	2.9	-0.1	-1.4	-2.5	-1.6	2.5	4.4	-2.6
	Pierce to Fillmore	7.2	10.6	12.4	5.5	7.8	0.4	-3.1	-4.3	-9.7
	Fillmore to Laguna	6.6	9.5	3.1	-1.5	-2.2	2.8	-0.3	-0.4	-0.2
	Laguna to Gough	18.6	33.9	8.1	21.2	39.3	10.7	17.9	33.8	12.7
	Outbound									
	Laguna to Fillmore	16.9	17.7	-2.1	0.7	0.7	5	-12.4	-12.3	0.6
	Divisadero to Baker	0.4	0.7	-0.5	2.4	4.4	-2.4	-1.3	-2.1	1.1
5 Fulton Rapid	***Inbound***									
	Divisadero to Fillmore	-9.5	-7	4.7	2.8	2.2	1.6	4.2	3.3	-8.4
	Fillmore to Van Ness	9.1	3.1	-4.6	6.1	2.4	3.6	10.6	4.2	7
	Outbound									
	Van Ness to Fillmore	22.4	9.5	2.5	14	6	6	-5.8	-2.3	6.1
	Divisadero to Masonic	-0.1	-0.1	-2.1	-1.4	-0.8	-1.2	-3.1	-1.6	0.7
21 Hayes	***Inbound***									
	Steiner to Fillmore	1.4	3.1	2.3	2.1	4.7	2.3	4.4	9.8	1.3
	Fillmore to Webster	-4.6	-10.6	1.3	-5.1	-11.2	7.1	-13.4	-29.5	-1.8
	Outbound									
	Buchanan to Webster	2	5	2.8	3	7.3	2.8	1.8	4.3	2.2
	Webster to Fillmore	-0.9	-2.7	-0.8	-7.5	-17.6	-4	-10.3	-23	-4
22 Fillmore	***Inbound***									
	Oak to Hayes	-5.8	-7.4	-0.9	-2.6	-3.5	-0.2	-3.8	-4.3	0.7
	Grove to McAllister	-0.5	-0.9	-2.9	-0.8	-1.5	-2.3	-2	-3.7	-1
	McAllister to Golden G.	-6.3	-11.3	3.4	4.6	8	5.1	10.3	17.4	0.5
	Golden Gate to Eddy	14.3	20.4	-0.5	6.7	8.7	-0.1	7.4	9.3	-0.2
	O'Farrell to Geary	-5.6	-10.2	-2.4	4.1	7.7	3.1	-5	-9.1	1
	Geary to Sutter	7.4	14.7	0.2	7	12.7	1.7	5	8.9	-1.1
	Sutter to Pine	14.6	19.4	4.3	8.9	8.9	-2.9	0.2	0.2	3.6
	Pine to Sacramento	7.4	14.3	1.2	3.3	5.2	-1.3	8	13.2	0.3
	Sacramento to Jackson	4.4	4.5	1.3	4.4	4.2	-0.2	4.2	4	-0.4
	Outbound									
	Sacramento to Pine	23.9	33	8.5	5.7	5.7	-0.2	11.9	11.6	-3
	Pine to Sutter	16.9	23	8.7	1.7	2.4	8.1	2.9	4	8
	Sutter to Geary	6.1	11.8	12.6	8.6	15.5	4.8	9.1	15.9	5.4
	Eddy to Turk	-4.5	-7	-0.4	-9.2	-14.1	0.8	-9.3	-14	0.7
	Turk to McAllister	21.2	33.4	8.3	0.5	0.7	4.6	-9.7	-13.2	-2.6
	McAllister to Grove	-10.6	-18.8	3.1	-6.9	-12.1	-1.7	-3	-5.2	-0.5
	Grove to Hayes	-2.1	-4.8	-3.4	-1.9	-4	-1.3	1.2	2.3	0.1

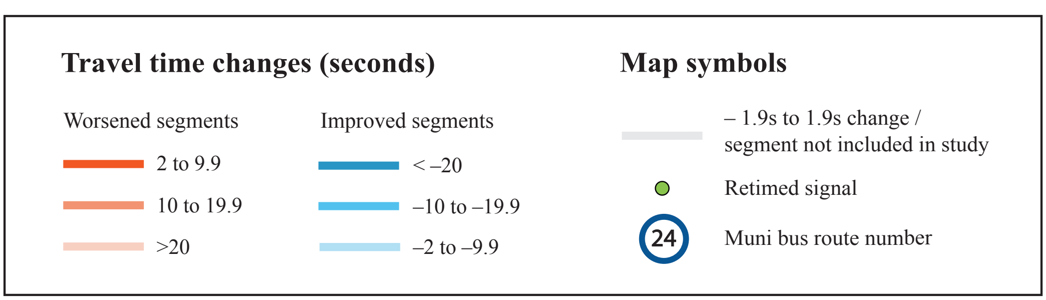
Appendix Exhibit 2, continued

Route	Stop-to-Stop Name	AM Peak Mean Δ	AM Peak % Δ	AM Peak SD Δ	Midday Mean Δ	Midday % Δ	Midday SD Δ	PM Peak Mean Δ	PM Peak % Δ	PM Peak SD Δ
24 Divisadero	***Inbound***	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Hayes to McAllister	-6.5	-6.7	0.9	-3.8	-3.8	4	-11.3	-11.1	-1.4
	McAllister to Eddy	4.3	6.1	-0.1	-1.1	-1.4	-1	-10	-11.9	3.9
	Eddy to Geary	12	10.5	4.6	17.3	16	9.8	3.1	3	7.3
	Geary to Sutter	-1.2	-1.6	2.4	12.9	18.4	3.5	13.6	20.6	4.9
	Sutter to Bush	19.7	49.6	9.2	9.4	19.3	5.3	3.3	6.5	1.9
	Bush to California	22.8	52.1	11.4	20.8	33.7	-0.6	23.5	38.3	-1.7
	California to Clay	9.8	18.9	3.2	7.5	13.2	3	0.9	1.4	3.9
	Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Clay to California	12	20.7	4	6.1	9.5	3.5	-0.3	-0.4	1.8
	California to Pine	4.1	10.3	8.9	6.2	15.5	6.7	8.1	20.4	6.3
	Pine to Sutter	20.5	48.5	0.1	22.7	35.7	-2.1	33.2	60.3	-1.3
	Sutter to Geary	11.5	14.5	-0.5	18.2	21.1	6.8	11.2	12.7	5.1
	Geary to Eddy	-2.4	-3	-0.1	-4.9	-6	1.2	-4	-4.5	0.4
	Eddy to McAllister	15	20.8	-6	6.4	8.3	-1.5	4.3	5	2.5
	McAllister to Hayes	5.1	6.6	-2.6	5.9	6.9	4.3	8.1	7.5	-4.1
31 Balboa	***Inbound***	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Baker to Broderick	0.2	0.6	-0.1	1.9	5.4	0.5	2.3	6.7	0.4
	Broderick to Divisadero	5	4.4	6.5	16.2	14.4	1.7	20.9	18.5	2.3
	Fillmore to Buchanan	-6.8	-9	3.4	-8.2	-10.3	2.1	-5.3	-6.7	3.2
	Buchanan to Laguna	-1.7	-3.3	0.8	0.5	1	0.9	-2.8	-5.4	0.9
	Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Laguna to Buchanan	3.8	10.9	2.4	5.6	15.6	3.3	3.3	8.7	2.2
	Buchanan to Fillmore	-0.2	-0.4	0	0.9	1.6	-0.2	-1.2	-2	0.2
	Fillmore to Pierce	-7.2	-10.4	-1.2	0.7	1	-0.3	1.3	1.8	-1
	Scott to Eddy	8.7	17.1	3.5	6.1	11.4	5.6	3.5	6.3	4
	Eddy to Broderick	-11.1	-19.2	4.5	-0.7	-1.2	0.2	4	7	-7.3
	Broderick to Baker	-1.7	-4.9	-2.7	-2.6	-6.7	-4.5	-7.2	-17.1	-8.5
38 Geary	***Inbound***	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Scott to Fillmore	6.2	6.2	5.6	10.4	10	5.5	6.9	6.2	0.7
	Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Webster to Fillmore	1.1	2	0.7	-2.6	-4.3	0.6	-5.6	-8.9	-1.9
43 Masonic	***Inbound***	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	Sutter to California	2.4	2.3	-0.5	2.6	2.4	0.5	9.1	9.1	-1.1
	Outbound	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*	*Mean Δ*	*% Δ*	*SD Δ*
	California to Sutter	-8.5	-8.1	0	0.5	0.4	0.9	4.7	4	0.2

Appendix Exhibit 3. Maps of Travel Segment Mean Time and SD Changes

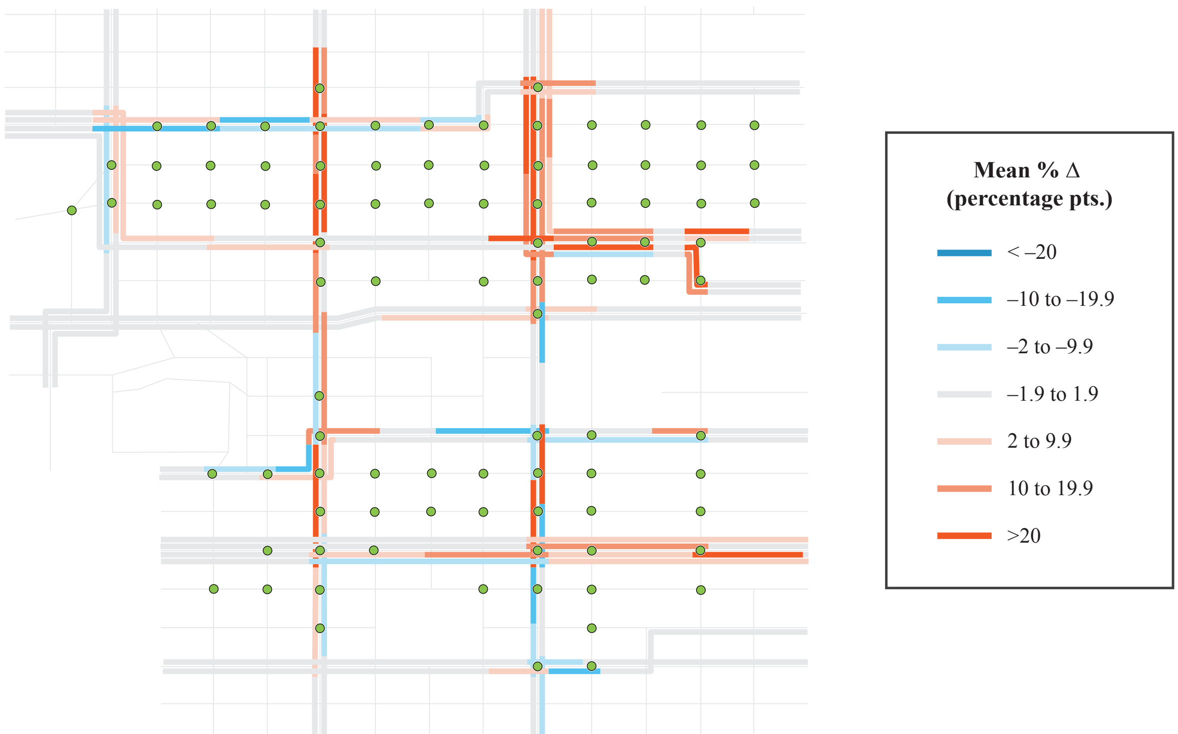
AM Peak: Mean Δ



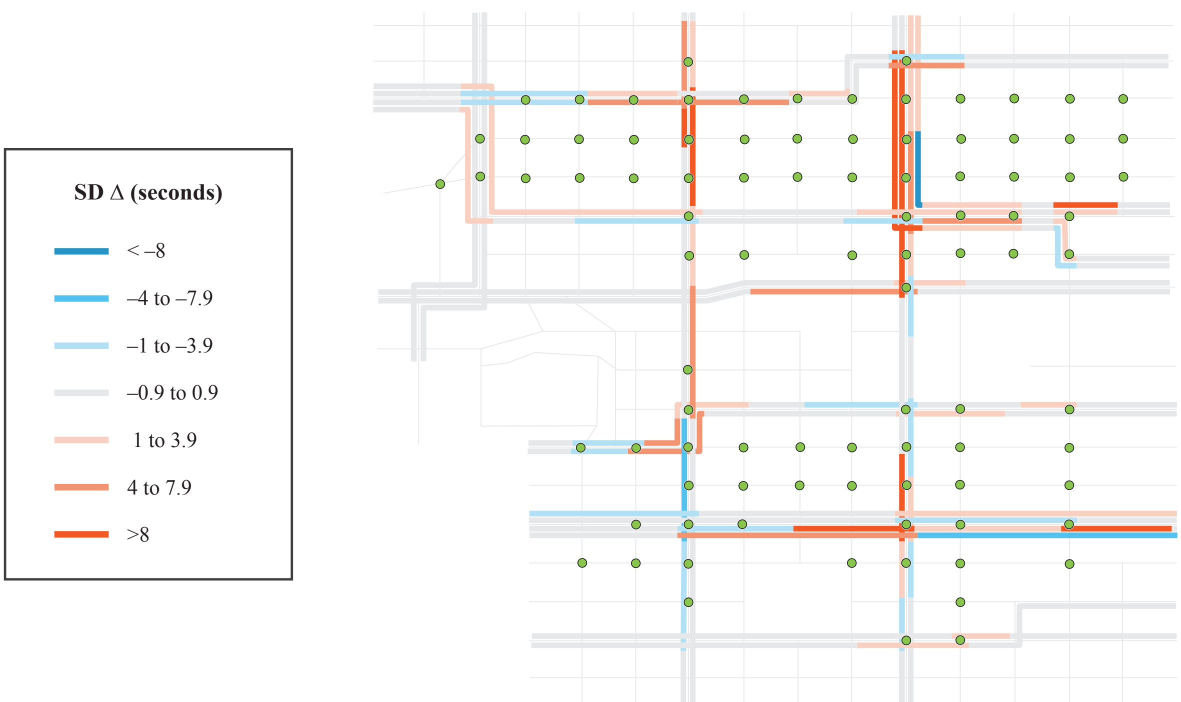


Appendix Exhibit 3, continued

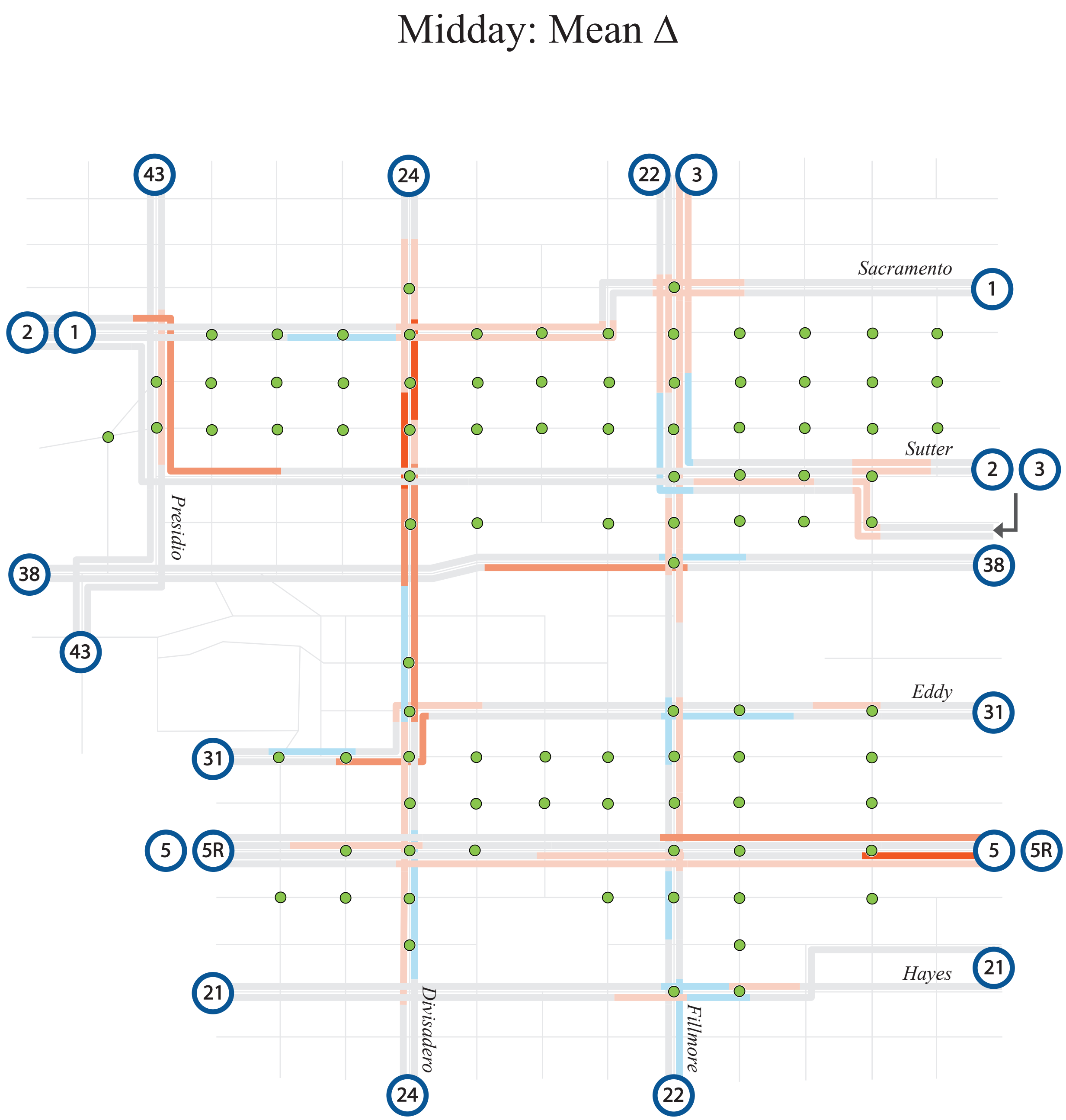
AM Peak: Mean % Δ



AM Peak: SD Δ



Appendix Exhibit 3, continued



Travel time changes (seconds)

Worsened segments

2 to 9.9

10 to 19.9

>20

Improved segments

< –20

–10 to –19.9

–2 to –9.9

Map symbols

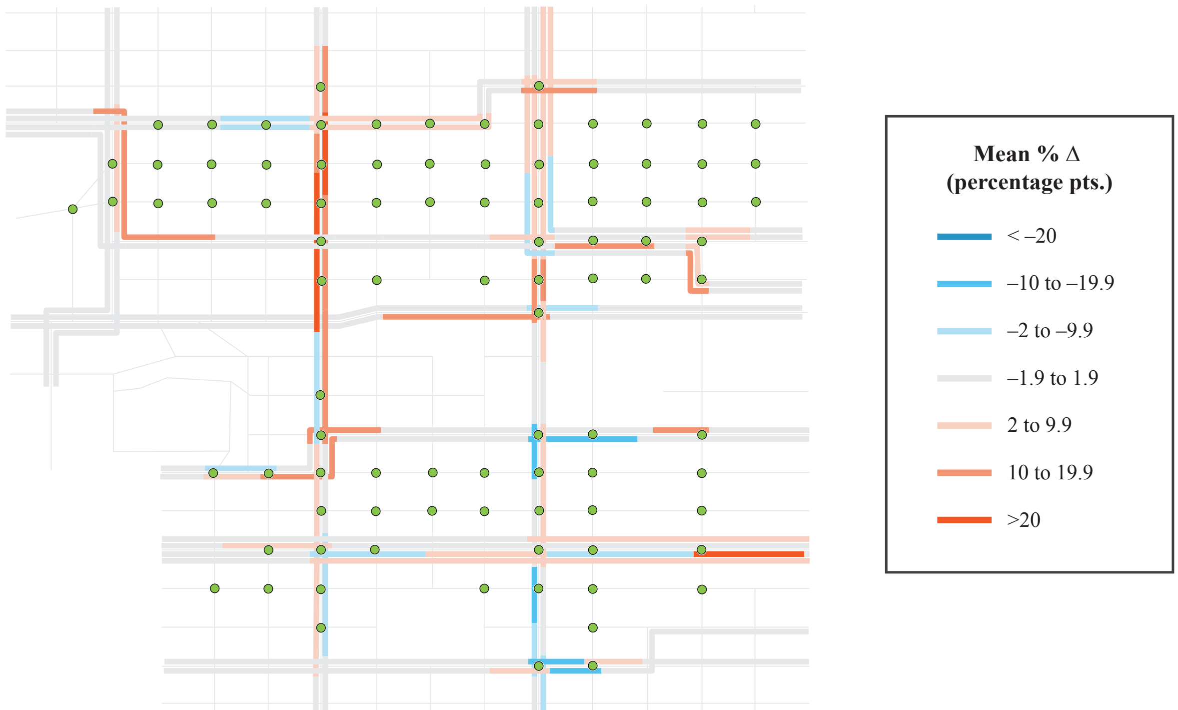
– 1.9s to 1.9s change / segment not included in study

Retimed signal

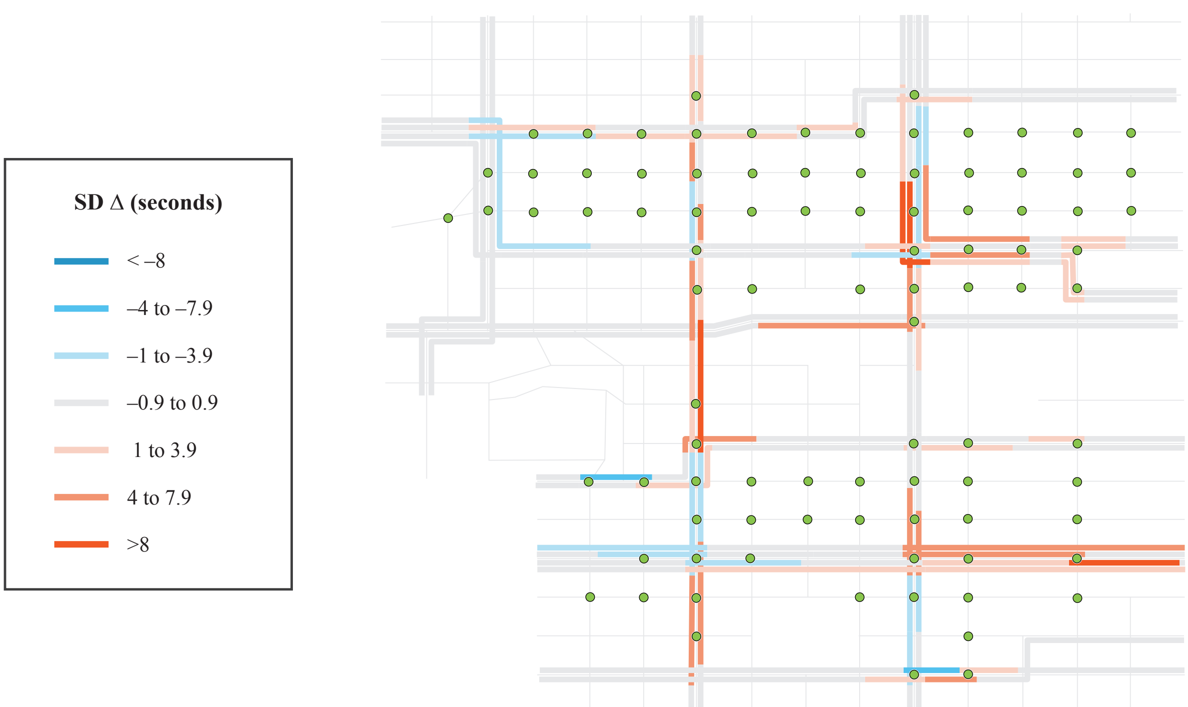
Muni bus route number

Appendix Exhibit 3, continued

Midday: Mean % Δ

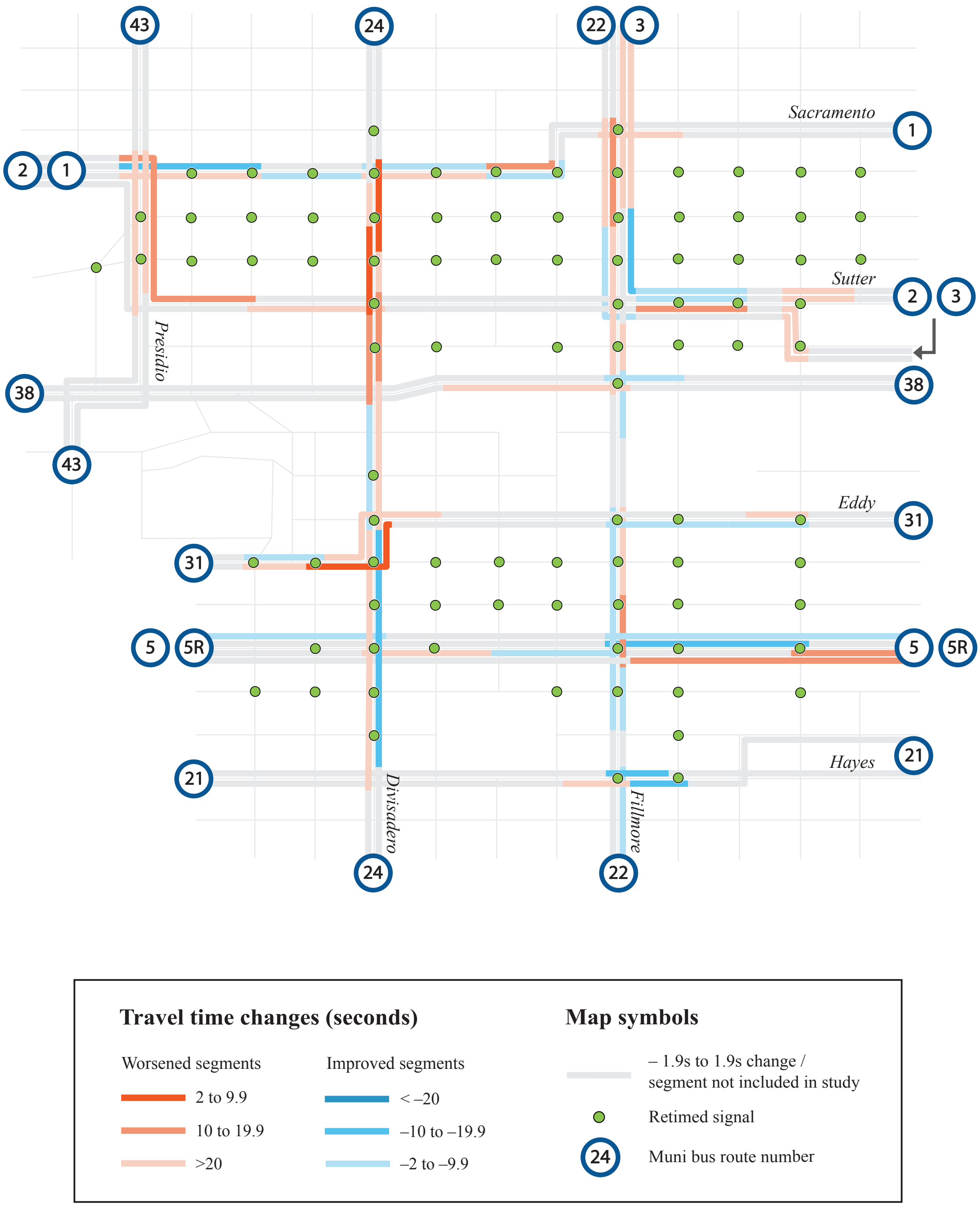


Midday: SD Δ



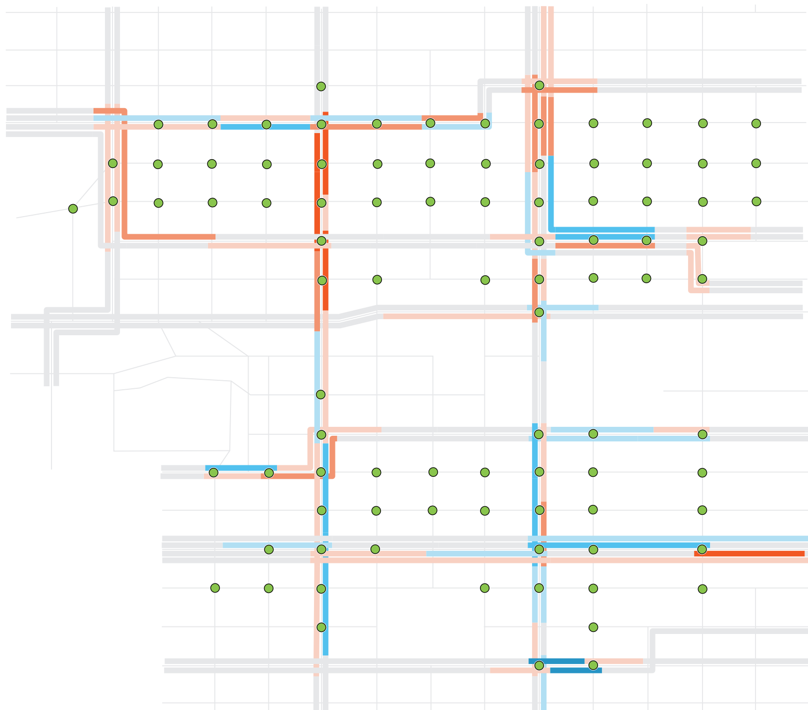
Appendix Exhibit 3, continued

PM Peak: Mean Δ



Appendix Exhibit 3, continued

PM Peak: Mean % Δ



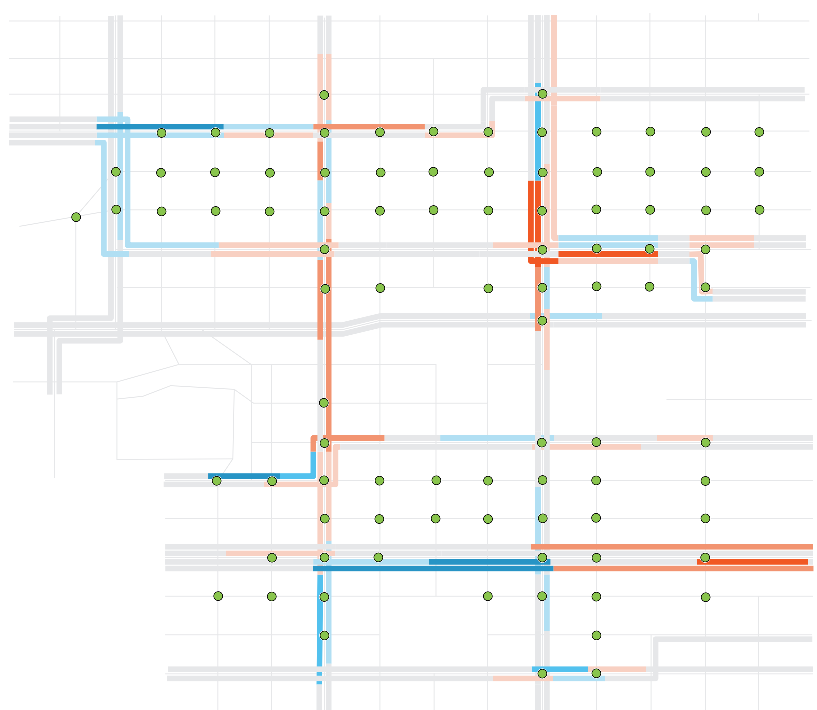
Mean % Δ (percentage pts.)

- < –20
- –10 to –19.9
- –2 to –9.9
- –1.9 to 1.9
- 2 to 9.9
- 10 to 19.9
- >20

PM Peak: SD Δ

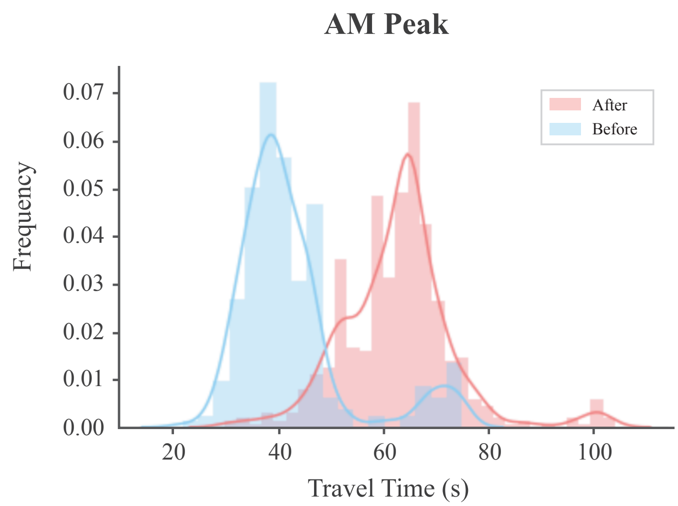
SD Δ (seconds)

- < –8
- –4 to –7.9
- –1 to –3.9
- –0.9 to 0.9
- 1 to 3.9
- 4 to 7.9
- >8



Appendix Exhibit 4. Problem Segment Histograms

24 Divisadero Outbound: Pine to Sutter



AM Peak Results

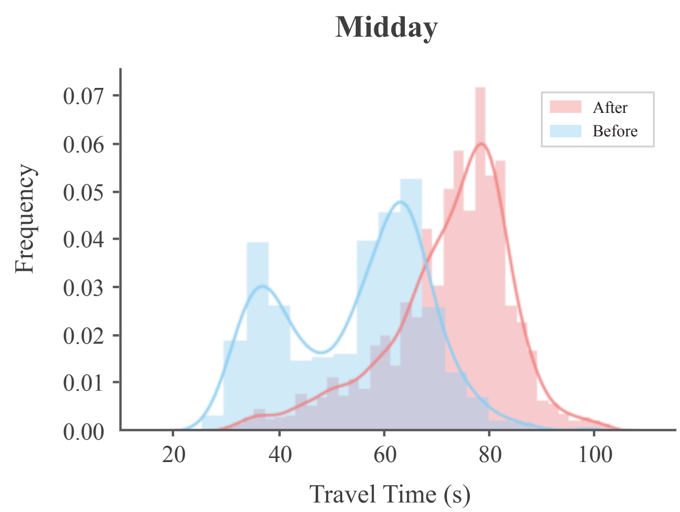
Mean time Before: 42.3s

Mean time After: 62.8s

Mean Δ: +20.5s

Mean % Δ: +48.5%

SD Δ: +0.1s



Midday Results

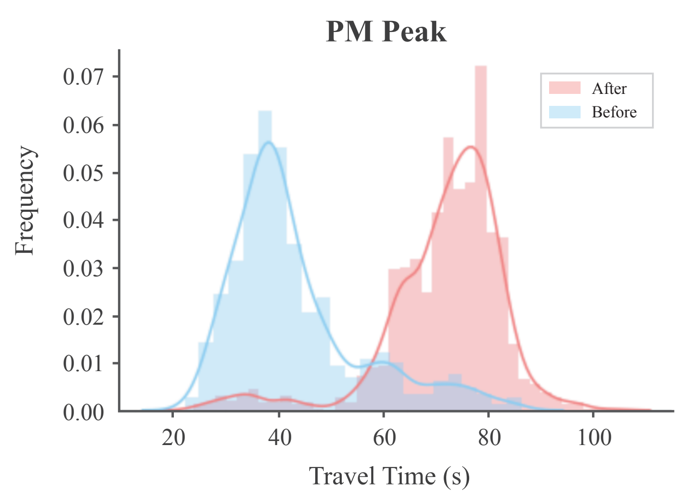
Mean time Before: 63.6s

Mean time After: 86.3s

Mean Δ: +22.7s

Mean % Δ: +35.7%

SD Δ: -2.1s



PM Peak Results

Mean time Before: 55.1s

Mean time After: 88.3s

Mean Δ: +33.2s

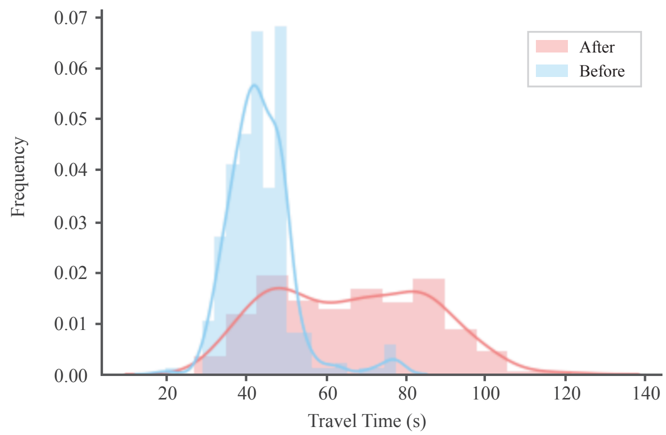
Mean % Δ: +60.3%

SD Δ: -1.3s

Appendix Exhibit 4, continued

24 Divisadero Inbound: Bush to California

AM Peak



AM Peak Results

Mean time Before: 43.8s

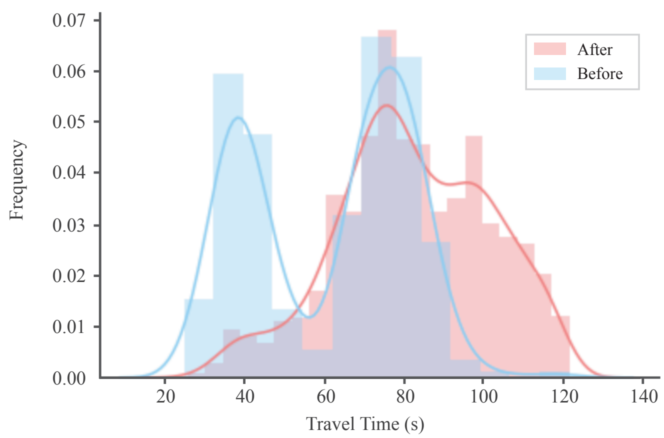
Mean time After: 66.6s

Mean Δ: +22.8s

Mean % Δ: +52.1%

SD Δ: +11.4s

Midday



Midday Results

Mean time Before: 61.8s

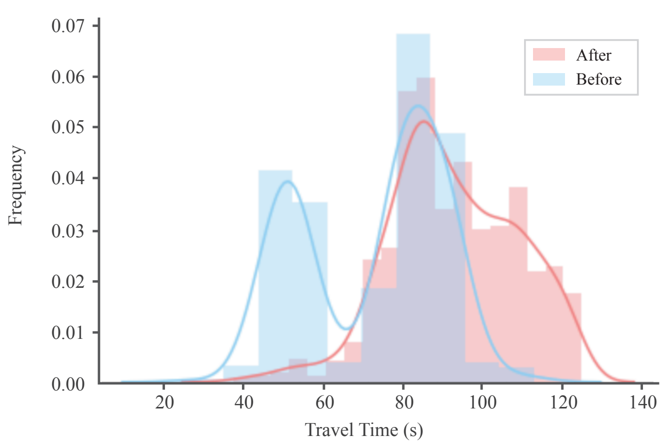
Mean time After: 82.6s

Mean Δ: +20.8s

Mean % Δ: +33.7%

SD Δ: -0.6s

PM Peak



PM Peak Results

Mean time Before: 61.3s

Mean time After: 84.8s

Mean Δ: +23.5s

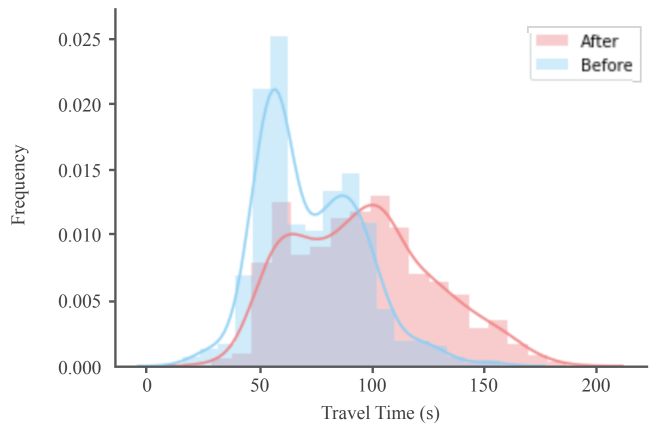
Mean % Δ: +38.3%

SD Δ: -1.7s

Appendix Exhibit 4, continued

Fillmore Street Southbound: Sacramento to Pine

22 Fillmore OB: AM Peak



AM Peak Results

Mean time Before: 72.5s

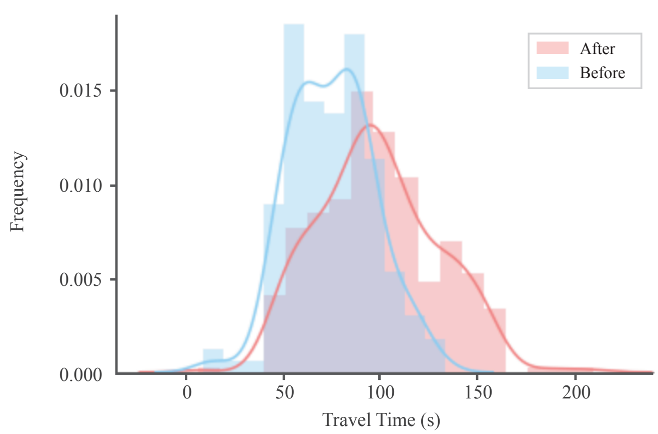
Mean time After: 96.4s

Mean Δ: +23.9

Mean % Δ: +33.0%

SD Δ: +8.5s

3 Jackson IB: AM Peak



AM Peak Results

Mean time Before: 75.5s

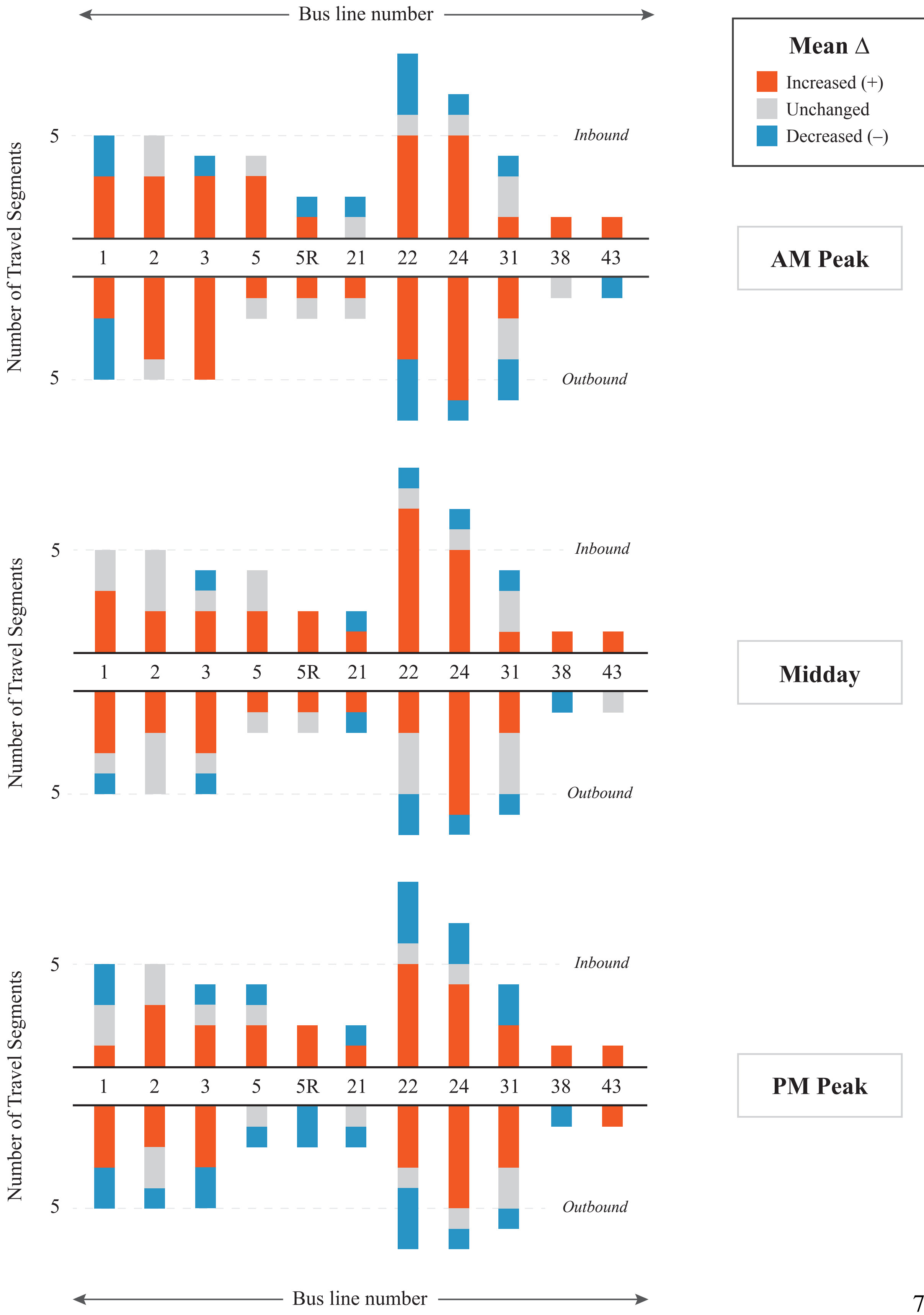
Mean time After: 98.8s

Mean Δ: +23.3s

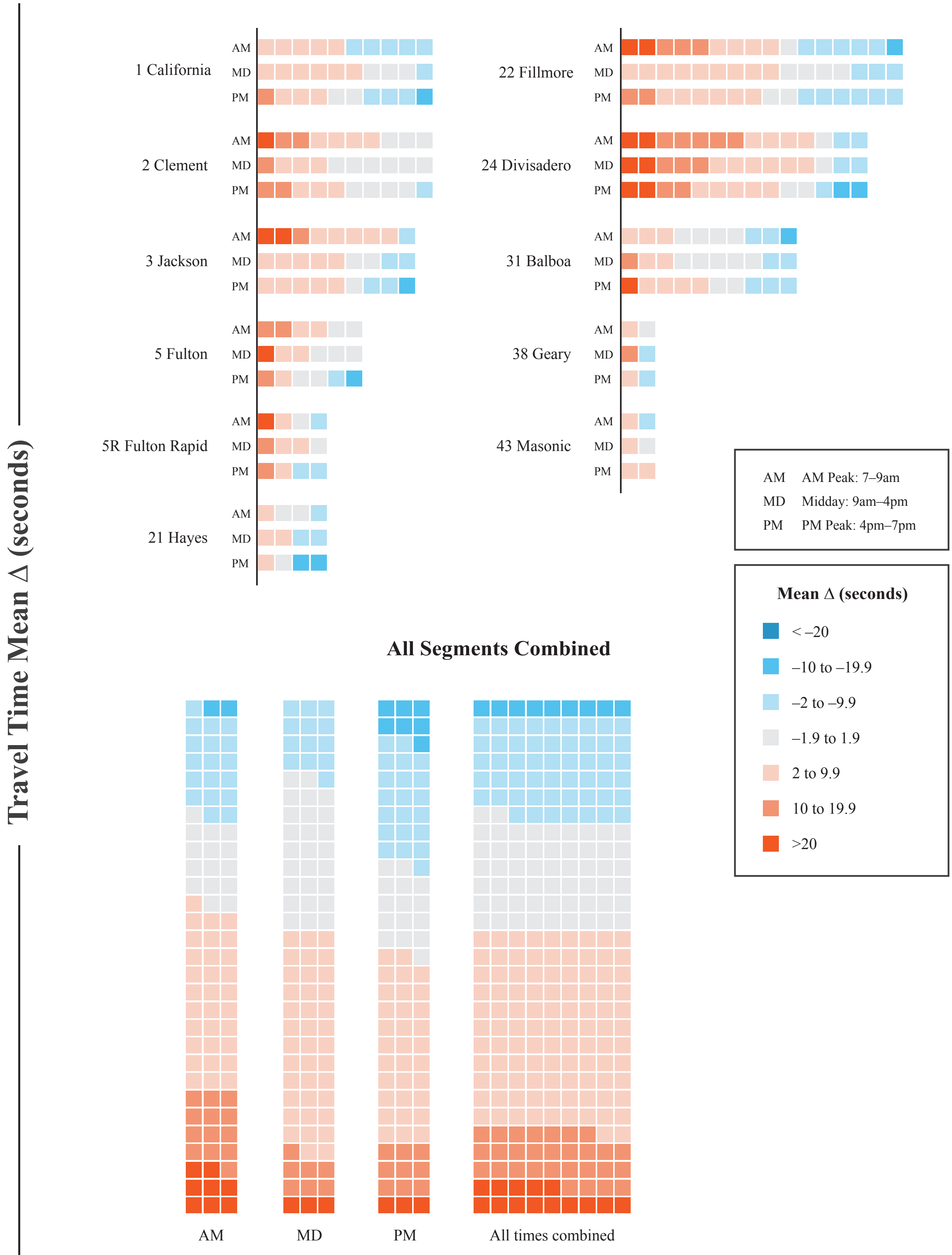
Mean % Δ: +30.9%

SD Δ: +9.0s

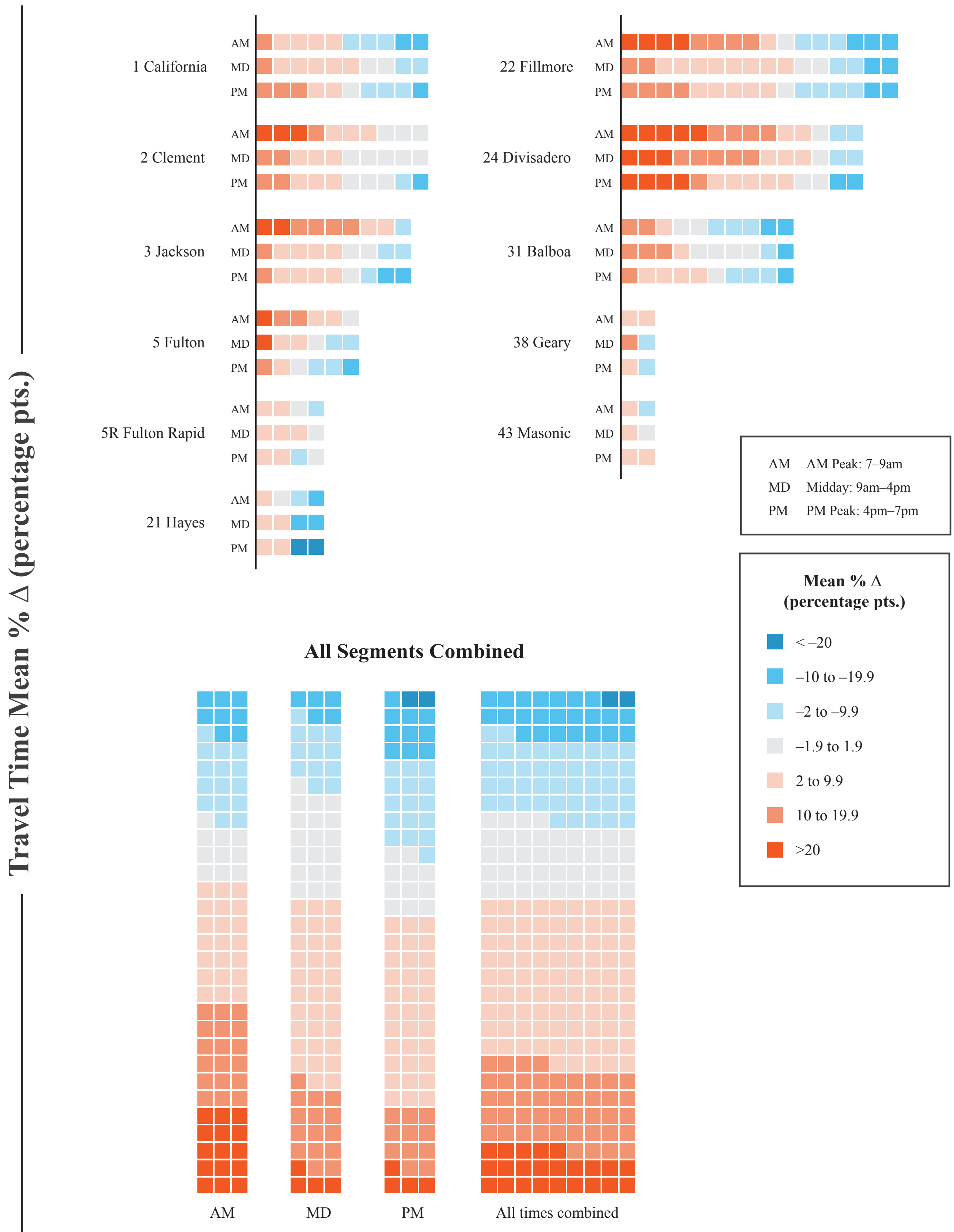
Appendix Exhibit 5. Number of Segments by + or – Mean Δ in Seconds



Appendix Exhibit 6. Travel Segment Summary Changes



Appendix Exhibit 6, continued



Appendix Exhibit 6, continued