



Evaluation of Bus/Bicycle and Bus/Right-Turn Traffic Delays and Conflicts

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EVALUATION OF BUS-BICYCLE AND BUS/RIGHT-TURN TRAFFIC DELAYS AND CONFLICTS

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16. Abstract This research evaluates conflicts and delays caused by interactions between buses, bicycles, and right-turning vehicles. Two concerns caused by these overlapping bus, bicycle, and automobile facilities are analyzed; the first concern is the number of bus-bicycle conflicts (as a proxy for safety) and the second concern is bus delay. Video data was collected and analyzed to quantify conflicts, travel time, and delay. For every bus passing through the study site, the mixed-traffic scenario that the bus incurs was categorized as one of 72 different combinations of bus, bicycle, and automobile interactions. Video count data was weighted according to seasonal, weekly, and hourly bicycle volume data to estimate the number of annual bus-bicycle conflicts. A regression analysis was performed to identify potential sources of delays. The results indicate that each bicycle crossing the intersection after the bus (within 60 feet of the bus) contributes to bus delay. No statistically significant delay was found from the bicycles stopped in the bicycle box, bicycles stopped behind the bicycle box, bicycles that crossed the intersection before the bus, or the presence of right-turning vehicles.			
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EXECUTIVE SUMMARY

This research evaluates conflicts and delays caused by interactions among buses, bicycles, and right-turning vehicles at a mixed-traffic corridor in Portland, OR. The study site has a near-side bus stop and a right curbside lane designated for buses and right-turning vehicles. Next to the bus/right-turn lane is a bicycle lane with a bicycle box ahead of the bus stop (i.e., between the intersection and the bus stop). This research examines two concerns caused by these overlapping bus, bicycle, and automobile facilities; the first is the number of bus-bicycle conflicts (as a proxy for safety) and the second is bus delay.

Video data was collected and analyzed to quantify conflicts, travel time, and delay. Special attention was paid to the way a bus operator encounters traffic when they are ready to cross the intersection. For every bus passing through the study site, the mixed-traffic scenario incurred was categorized as one of 72 different combinations of bus, bicycle, and right-turning automobile interactions. Histograms of traffic counts show the variation in complexity for traffic scenarios during peak hours and off-peak hours. Video count data was weighted according to seasonal, weekly, and hourly bicycle volume data to estimate the number of annual bus-bicycle conflicts.

A regression analysis was performed to identify potential sources of delays. The results indicate that each bicycle crossing the intersection after the bus (within 60 feet of the bus) contributes to bus delay. No statistically significant delay was found from the bicycles stopped in the bicycle box, bicycles stopped behind the bicycle box, bicycles that crossed the intersection before the bus, or the presence of right-turning vehicles.

Video analysis data was validated by TriMet bus stop data. This data was also used to produce heat map visualizations of bus speeds with respect to location and time of day. When buses do not have to stop to serve passengers, there is little evidence to suggest that the presence of a bicycle box contributes to delay.

A discussion of road treatments that could alleviate bus-bicycle delays and conflicts is presented, from the highest-investment/highest-return to a modest-investment/modest return option. Additionally, as cities seek to increase both cycling levels and bus efficiency, the methodology presented herewith can be used to generate quantitative and qualitative estimates of bus-bicycle conflicts.

1.0 INTRODUCTION

Cities have sought to alleviate traffic congestion and its associated environmental impact by encouraging cycling and transit use. The incremental development of cycling infrastructure and transit networks requires a rethinking of existing strategies and scrutiny of recent innovations. In general, most bus lines are routed on major streets and recommended bicycle routes are usually on low-speed neighborhood streets. However, multimodal networks will have challenging segments where bus routes, bicycle lanes, and motorized vehicles share space.

1.1 BICYCLE FACILITY IMPROVEMENTS

In 2010, Portland's City Council unanimously supported the Portland Bicycle Plan, with its ambitious goal of reaching a 25% cyclist mode share. Since the early 1990s, the city's investments in bicycle amenities have successfully achieved subsequent rises in cycling ridership (Birk and Gellar, 2006). In 2008, the city rolled out a new experimental traffic treatment, the right-angle bicycle lane extension (i.e., a bicycle or bike box). The most common application for the bicycle box is to place cyclists in front of right-turning vehicles, thus preventing right-hook conflicts (Dill, Monsere, and McNeil, 2012). Many of the city's bicycle boxes have been visually reinforced with green pavement marking, as is preferred by both motorists and cyclists (Dill, Monsere, and McNeil, 2012).

1.2 DECLINE IN BUS USE

While the bicycle network has been improving, Portland's public transit provider, TriMet, has been struggling with declining bus ridership and speeds (Figure 1.1). Not all modes of public transit have declined; MAX (light rail) ridership has increased during this period. Although many complex factors affect TriMet ridership, one major difference between bus and rail modes is average speed. MAX rail cars have averaged about 18.2 mph while buses average 13.7 mph, for 2015–2017 (TriMet, 2018). The quest to increase bus speeds—and plausibly, ridership—pushes transit agencies to find ways to reduce bus delays.

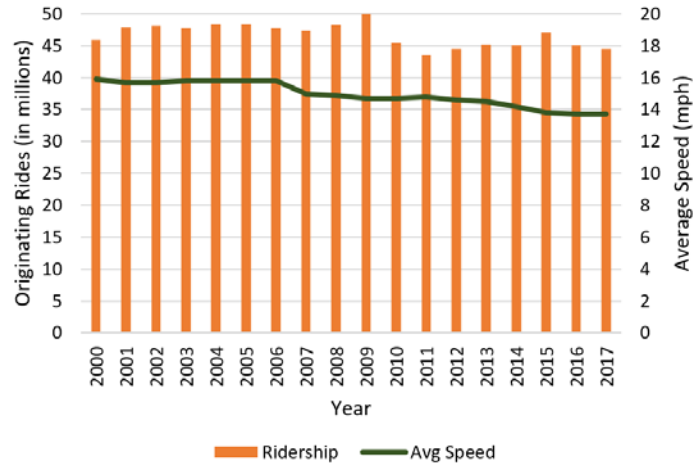


Figure 1.1: TriMet bus ridership and average bus travel speed

1.3 EVALUATION GOALS

In this context of growing bicycle ridership and slowing buses, it is important to study intersection designs that may need to be redesigned or updated. To the best of the authors' knowledge, there is no research that has addressed bus, bicycle, and automobile conflicts in the U.S. This research contributes a novel categorization of mixed-traffic conflicts, a methodology to estimate annual bus-bicycle conflicts, and regression results identifying statistically significant sources of delay. This new analysis of high-traffic, multimodal arterials can reveal patterns and insights useful in developing future design guidelines.

2.0 LITERATURE REVIEW

There remains much opportunity for research of bus-bicycle conflicts. In China, models have been proposed to estimate the number of conflicts as a proxy for safety, but this model is limited to mid-block stops, and are not applicable for stops near signalized intersections (Zhao et al., 2009; Lu et al., 2014). With regard for bus delay, studies have measured bus mean speeds with respect to particular bus stop designs; however, these studies also focus exclusively on mid-block stops (Zhao et al., 2014; Zhang et al., 2015).

Unfortunately, intersections pose the most challenges for bus-bicycle conflicts. In regards to bicycle safety, an Australian study found that 55% of bus-bicycle accidents take place at intersections (Ker et al., 2005). Another UK study shows that of all bus-bicycle conflicts, the most common cause was a bus overtaking a bicycle; that is, a collision resulting from a bus merging lanes in front of a bicycle (Pai, 2011). It is a collision primarily in the lateral direction, with the side/back of the bus striking the side/front of the bicycle. Another UK study found that on 30-40 mph streets, heavy goods vehicles (including buses) allotted less passing space to bicyclists than cars or vans (Parkin and Meyers, 2010).

Many U.S. studies on bus-bicycle conflicts evaluate road configurations, including shared bus-bicycle lanes, contraflow bus lanes and left-side bicycle lanes, and the ability of these designs to mitigate conflict (DeRobertis and Rae, 2001). From these existing configurations, cities seeking to enhance their multimodal networks can refer to real-world results to inform their design guidelines (Hillsman, Hendricks, and Fiebe, 2012).

Interactions between bus operators and cyclists may vary between countries; therefore, geographically specific data is valuable. To the authors' knowledge, there are no U.S. studies quantifying bus-bicycle conflicts and delays or evaluating the safety concerns of overlapping bus and bicycle facilities.

3.0 STUDY SITE

3.1 INTERSECTION DESCRIPTION

The intersection at SE Madison and Grand connects two one-way streets: Madison travels westbound and Grand travels north. The bus-bicycle conflict stems from Madison's two rightmost lanes. The curbside lane serves as a bus lane and a right-turn lane with prohibited turn on red. One lane to the left is a designated bicycle lane with striping and portions of green pavement marking.

Three bus routes serve the nearside bus stop on the right sidewalk. For the morning peak hours, it is not uncommon to have two buses located at the stop at the same time or for a bus to be stopped behind cars queueing for the right turn. The right-lane queueing may prompt the bus operator to serve passengers further back from the intersection, just upstream of the bus stop. After servicing the stop, buses must then merge into the central through lane to continue their routes. Depending on the position of the bus when it serves the stop, the bus will either merge before the intersection or while passing through the intersection. Bus and bicycle facilities are shown in Figure 3.1 and Figure 3.2.

The bicycle box allows stopped bicycles to be readily visible to buses or right-turning cars. However, the bicycle box is only employed when cyclists are stopped at a red light. If a cyclist approaches the intersection during a green light, their bicycle path will gradually merge, in the intersection, from a central lane to the rightmost side of the road. When a bus has finished serving passengers, it must merge from the right-side lane to the center lane. Since buses serve passengers at varying distances from the bus stop (due to traffic queuing), the area of potential bus-bicycle conflict is about 160 feet long (highlighted in red, Figure 3.2). In effect, the bicycle box addresses right-hook conflicts with right-turning vehicles, but still leaves cyclists vulnerable in bus-bicycle conflicts. The conflict area is the result of overlapping bus and bicycle paths, at and in the intersection.

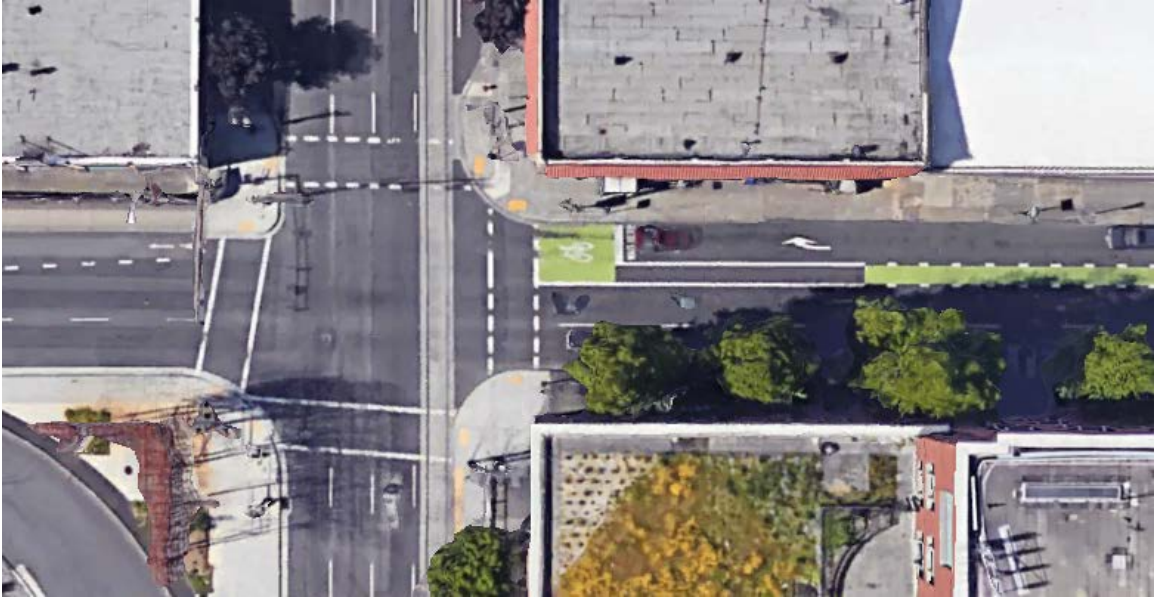


Figure 3.1: SE Madison & Grand, satellite image from Google Earth

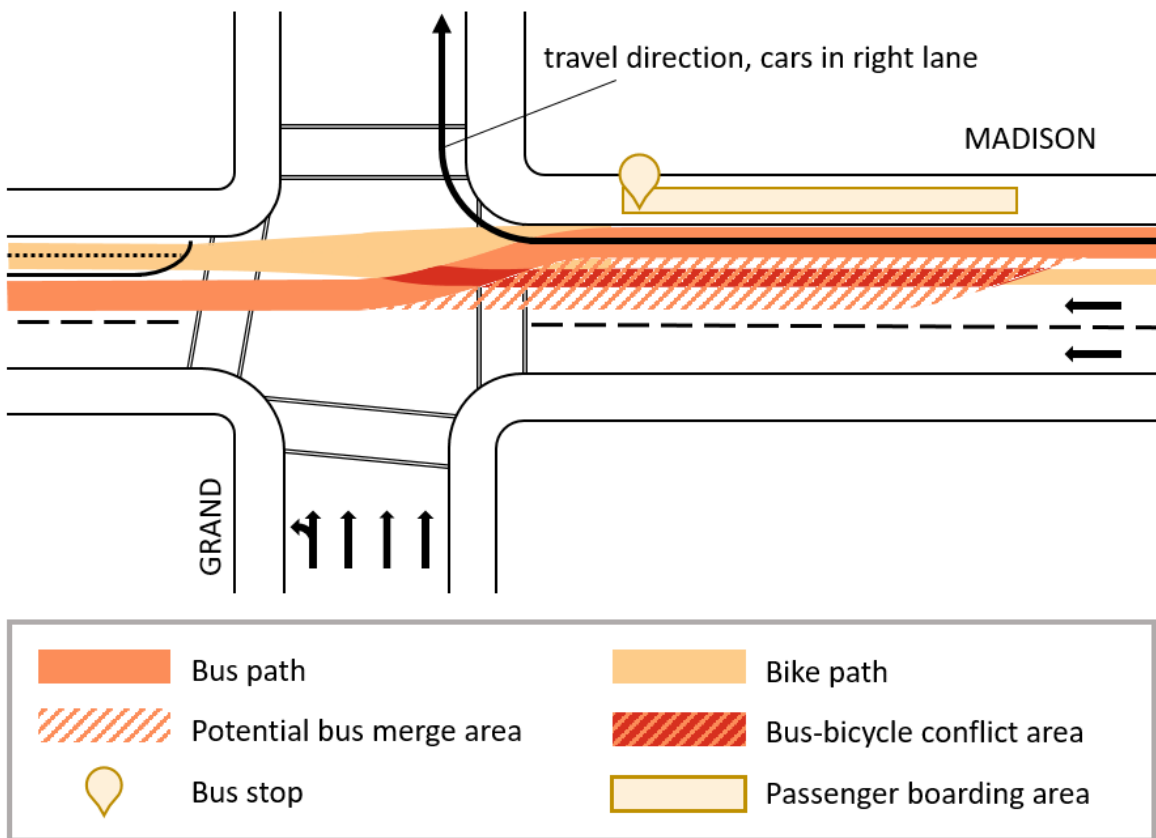


Figure 3.2: SE Madison & Grand, conflict diagram

3.2 SITE HISTORY

3.2.1 Bike Network

The Hawthorne Bridge underwent major improvements in 1999: sidewalks were widened, ramps with conflicting traffic closed, and merging conditions improved (Birk, 2003). Hawthorne is Portland's most heavily cycled bridge. The intersection of Madison and Grand is the closest intersection to the westbound Hawthorne bridge access and is a key arterial for automobiles, transit, and bicycles. Madison received cycling upgrades in 2010: a green bicycle box and green thermoplastic striping.

3.2.2 Bus Network

Three bus routes, (2, 10, and 14) serve the morning commutes into downtown. The bus stop onsite, stop 3633, has been in operation since 1999; that same year, the first round of cycling improvements was completed. During peak bus service, stop 3663 often has buses scheduled to arrive concurrently or with only a one to two-minute headway.

3.2.3 Pavement Markings

A combination of graphic road markings is utilized on the pavement. The graphic layout of the street can have positive effects on a cyclist's perception of safety (Hunter, 2000). Indeed, a stripe is what demarks and upgrades a bicycle-accessible shoulder to a designated bicycle lane. Where there are more bicycle lanes, there are higher levels of commuting (Pucher, Komanoff and Schimek, 1999). Additionally, studies have shown that the use of bold demarcation is also vital for the efficacy of a bicycle box (Dill and Voros, 2003).

The bicycle box on Madison has solid green thermoplastic background with a white bicycle symbol on top. To prevent vehicle encroachment, the bicycle box has a bold stop bar and the words "WAIT HERE" painted underneath. The bicycle lane is solid green for most of the block leading up to the intersection. Although painted bicycle lanes are received favorably, the effects of pavement markings on cyclist behavior are still being reviewed. A follow-up study to Portland's 1997-1999 trial implementation of colored bicycle lanes found that after a bicycle box was installed, bicyclists turned their heads less to scan surrounding traffic conditions (Hunter et al., 2000). At this study site, the area directly in front of the bus stop but before the bicycle box has a break in the green pavement marking; there are only white boundary stripes. This design graphically cues bicyclists that the uncolored section of the bicycle lane is not a bicycle-exclusive zone. However, while this break in color prompts cyclists to pay attention, it does not run the length of the potential conflict area.

3.2.4 Bus Operator Perspective

TriMet considers routes 2, 10, and 14 as high-risk routes. Some bus operators prefer to avoid these challenging assignments, as their job performance is contingent on avoiding traffic violations and complaints. Other operators thrive on this challenge, as it allows

them to showcase their skills and become more proficient operators. A factor that compounds the impact of deficient geometric designs is the seniority basis of route assignments, which rotate on a 90-day cycle. Hence, the experienced operators can elect to drive less-challenging routes and a less-experienced operator may consequently drive a difficult one. The researchers interviewed a TriMet operator to get their opinion about the challenges presented in the study. The operator mentioned that they had been driving with TriMet for just over one year before driving route 2. The operator described the challenge of merging across a bicycle lane into a through-vehicle lane: “It’s hard to judge [a merge] when you have that much going on. Bicycles want to challenge buses and cars don’t want to let you in” (Gillette, 2018).

3.2.5 Relevant Traffic Statutes

Merging buses into traffic is not a new challenge for operators. In Oregon, the Oregon Revised Statutes (ORS) address transit vehicles merging away from service stops. ORS 811.167 states that a vehicle must yield to a bus with its left turn signal on pulling away from a service stop (Public Technology Ltd., 2017). At TriMet, the buses are also equipped with an operator-activated illuminated yield sign on the rear to amplify the signal to other road users that the bus is merging back into traffic. Use of this light varies by operator: some use it every time they merge away from a stop, and others use it on an as-needed basis. However, even if the operator does not activate the yield sign, all vehicles (including bicycles) are required to yield to the bus merging into traffic from a service stop.

4.0 METHODOLOGY

4.1 CATEGORIZATION OF TRAFFIC SCENARIOS

The scenarios that a bus encounters were categorized by the surrounding traffic conditions in two different lanes, the right curbside lane and the bicycle lane. The combination of bicycles, buses, and cars queuing in these two lanes is relevant because it affects the location that a bus serves passengers and, consequently, the location from which a bus can begin to merge into the center lane.

The traffic conditions in the bicycle lane are categorized in terms of relative location and movement status. For example, bicycles may be stopped or bicycles may be in motion. A cyclist may overtake the bus or cross the intersection after the bus. The activity in the lanes varies from moment to moment; for this study, the traffic conditions were categorized at the time a bus was ready to leave the stop.

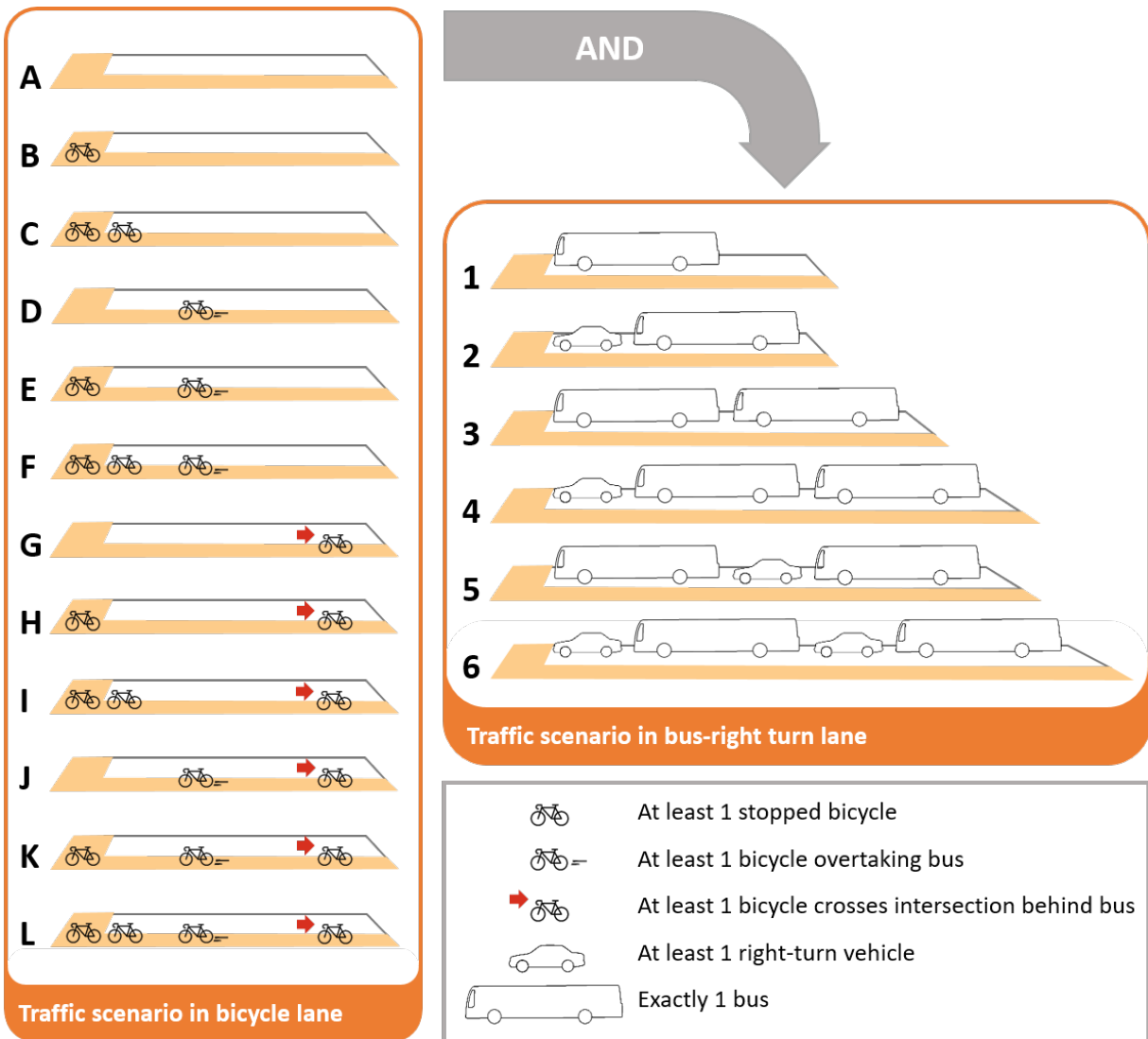


Figure 4.1: Categorization schematic

4.1.1 Bike Lane Conditions

Figure 4.1 shows the conventions of categorizing the traffic scenarios. Conditions A–L reflect the activity in the bicycle lane. Four bicycle conditions were identified: bicycle stopped in box, bicycle stopped in lane, bicycle overtaking bus, and bicycle crossing intersection after bus. As noted in the key, a bicycle icon in the figure represents one or more bicycles. There was a small number of occurrences where a skateboarder, electric scooter user, or motorized board user was using the bicycle lane. In these cases, they were counted as bicycles.

4.1.2 Bus-Right Turn Lane Conditions

Scenarios 1–6 reflect the activity in the right curbside lane. A bus might be at the bus stop, behind a right-turn vehicle, behind a bus, or behind buses and right-turning vehicles. As noted in the key, a car icon in the figure represents one or more right-turning vehicles. When two buses arrive at the intersection, the first bus would be classified with scenario 1 or 2, and the second bus would be classified with scenarios 3–6.

4.1.3 Ranking Complexity

The traffic scenarios A–L and 1–6 were ordered in terms of their increasing demand of judgement on the bus operator. For example, in the “A” category, the bus has no bicycles anywhere near it. This is clearly the simplest scenario for the bus operator. In the “B” category, there is at least one bicycle stopped in the bicycle box in front of the bus, clearly visible. Bicycle(s) in the “C” category are stopped in the bicycle box and overflowing into the peripheral bicycle lane. “D” category has at least one moving bicycle in the bicycle lane, overtaking the bus. Categories “E” and “F” are combinations of the aforementioned variables.

4.1.3.1 Defining Bicycle Box

For this study, the bicycle box is defined as the entire width of the right-angle extension, including the area in line with the bicycle lane. For our intersection, this definition is congruent with the study site’s installation of thermoplastic. Figure 4.2 shows bicycles (i) and (ii) counted as in the bicycle box, and (iii) as in the bicycle lane.

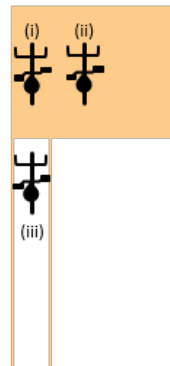


Figure 4.2: Distinction of bicycle box, in solid color

The “G” scenario has a bicycle behind the bus when crossing the intersection. A bicycle less than 60 feet behind the bus was considered to be part of the bus’s traffic scenario; 60 feet was chosen because it is 1.5 times the length of a bus. When located within a distance of 60 feet, the presence of bicycle(s) forces a critical judgement call from the bus operator. The operator must judge the length of the gap and check to see whether the cyclist is yielding or intending to overtake the bus. When bus operators intend to merge away from the right lane, they are forced to make these assessments quickly, with the

weight of their judgement directly bearing on a cyclist's safety. For these reasons, any category with a bicycle behind the bus (G-L) is ranked as more complex than bicycles in front of/overtaking the bus. Similarly, traffic scenario components 1-6 are ordered from least complex to more complex.

4.2 QUANTIFICATION OF DELAYS

For every bus that traveled through the study site, bus delay was calculated in two different ways. The first calculation was for gross delay: the time interval from which the bus enters the study area to the time it leaves the intersection. The second calculation is for travel delay. Travel delay is the gross delay minus the time spent serving the bus stop and minus the time spent waiting for a green light.

$$D_G = t_l - t_e \tag{4-1}$$

where: D_G is the gross delay
 t_l is the time a bus leaves the intersection
 t_e is the time a bus enters the area of study

$$D_T = D_G - t_s - t_w \tag{4-2}$$

where: D_T is the travel delay
 t_s is the time interval spent servicing the bus stop
 t_w is the time interval spent waiting for a green light

4.3 STUDY AREA BOUNDARIES

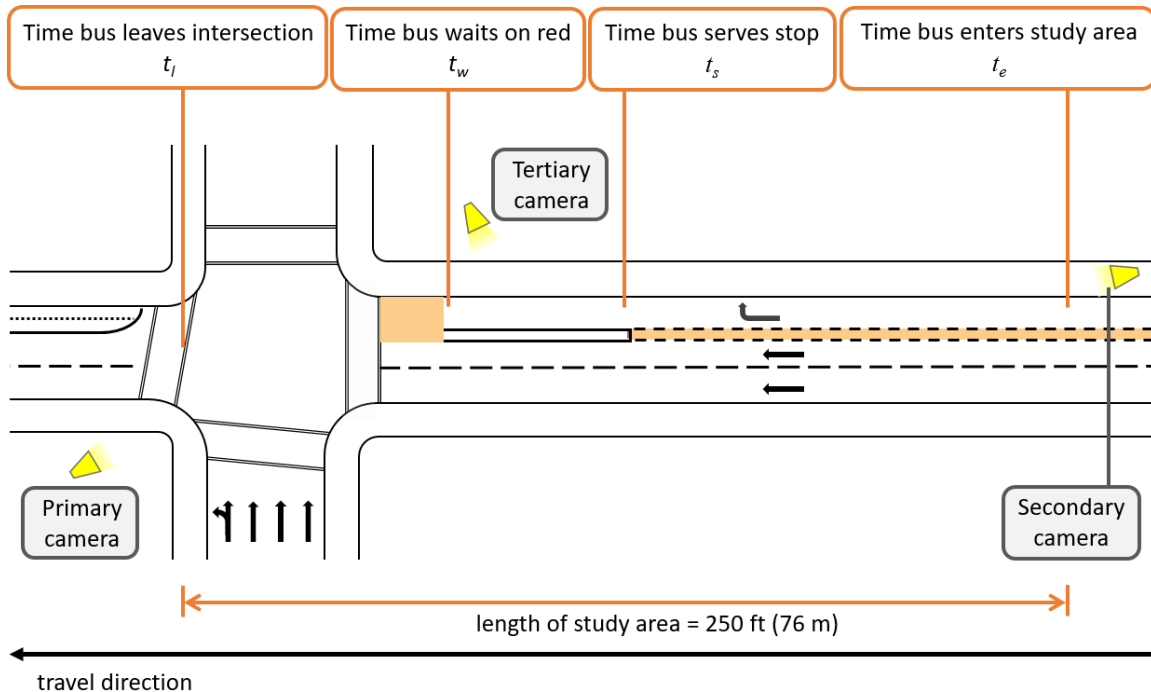


Figure 4.3: Times used to calculate delay

The confines of the study area are shown in Figure 4.3. The eastern edge of the study area is just within the scope of the primary video camera lens, and the end of the study area is the inner edge of the west pedestrian sidewalk. To calculate the time interval spent in serving the stop (t_s), a time stamp was recorded when the bus started serving the bus stop, and another when the bus finished serving the bus stop. Recording the start and end of bus service proved to have several nuances, but the video footage (see Figure 4.4) offered four observable proxies: turn signal, bus kneeling/rising, doors opening/closing, and time buffers after stopping/starting.



Figure 4.4: Primary camera view of study area

4.4 CALCULATING TIME OF BUS SERVICE

Buses will signal right when serving the stop, and signal left to indicate when they intend to pull away for the stop. However, sometimes the turn signals were not visible to the camera, or were not used according to convention. Another proxy available was the rise and/or kneel of the bus. To increase accessibility, TriMet buses are kneeling buses; they lower slightly when passengers are boarding and rise when they are finished boarding. This small adjustment is usually discernible from the video, but not always. Another proxy is the opening and closing of doors. Lastly, after annotating several interactions, it was possible to reasonably assume a time buffer proxy: the start of service was recorded as two seconds after the bus stops at the bus stop, and the end of service as two seconds before the bus pulls away from the stop. If none of the aforementioned proxies were discernible from the footage from the primary camera, the secondary or tertiary camera could be referenced, and the hierarchy of observable proxies could be utilized from a different camera viewpoint. These different proxies were ranked in reliability according to their time stamp type (Figure 4.5) to provide consistency across data collections. For all 219 bus events, the time of service was calculable before the hierarchy was exhausted.

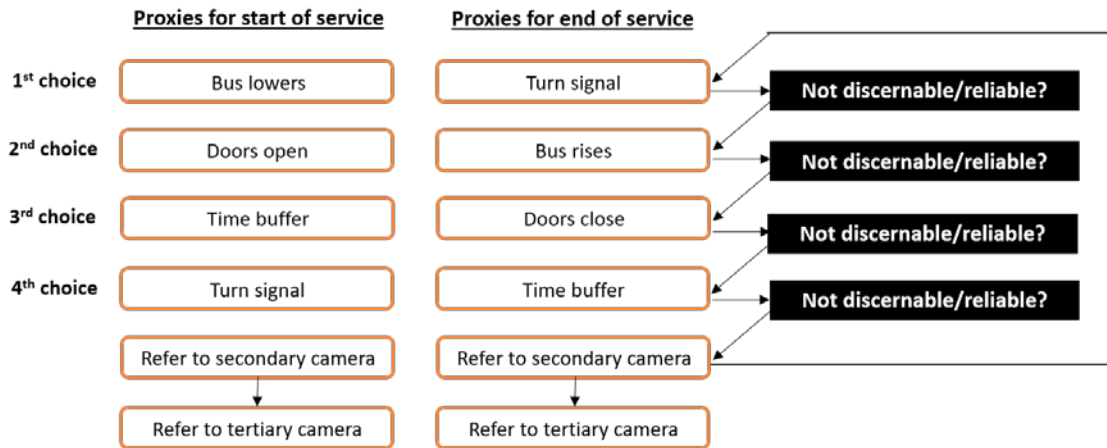


Figure 4.5: Hierarchy of utilizing service time proxies

4.5 VERIFICATION OF TIME OF BUS SERVICE

To validate the estimation of the service time, we used TriMet bus stop-level (BSL) dwell, with dwell being the amount of time between bus doors opening and closing. BSL data also provided additional information about the number of passengers boarding and alighting, including lifts.

5.0 RESULTS

The data was collected during a weekday in June, August, and September, when cycle activity is high due to sunny and dry weather. The first two hours, 6:30 a.m.-8:30 a.m., reflect peak (bus service) conditions, while 6 a.m.-6:30 a.m. and 8:30 a.m.-11 a.m. reflect off-peak bus service conditions. Specifically, for peak conditions, the bus stop onsite is scheduled to host a bus every 2.8 minutes. For off-peak conditions, a bus every 4.8 minutes. The grade at the site is slight (+2%) and the impact on bus acceleration is negligible at grades less than 3% (Furth and SanClemente, 2006).

TriMet provided data for bus stop #3633, including stops, arrival/leave times, dwell, ons, offs, and use of the lift.

5.1 JUNE DATA COLLECTION

The June data collection was conducted on a sunny, warm weekday. The study observed 65 bus events between 6:30 a.m.-10:30 a.m.

Table 5.1: June Mixed-Traffic Metrics

	Bicycle Flow (bicycle/hr)	Bus Flow (bus/hr)	Right-Turning Vehicles (veh/hr)
Peak Conditions	430	21	103
Off-Peak Conditions	190	12	166

5.1.1 June: Distribution of Traffic Scenarios

Each bus event was categorized according to the definitions presented in the Methodology Section 4.1. The distribution of scenarios is shown in the histogram below.

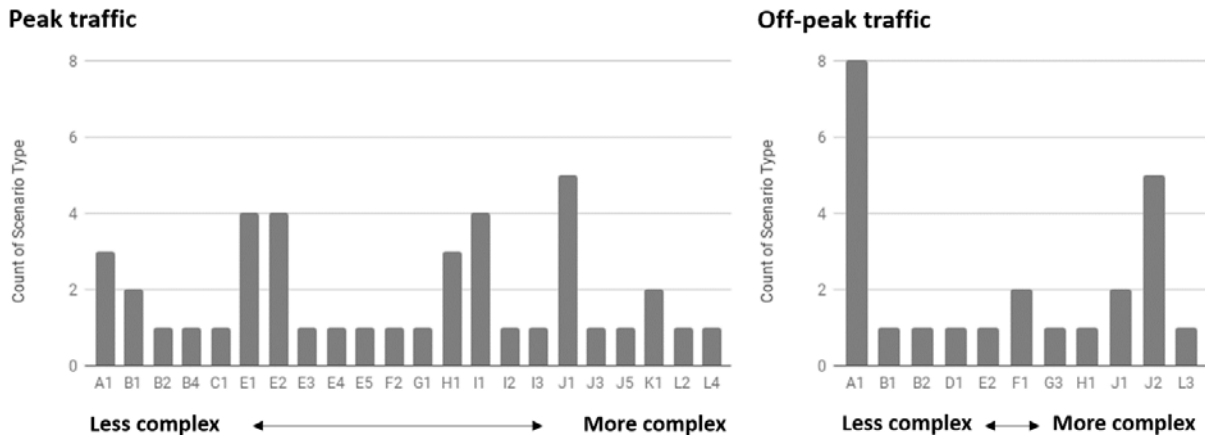


Figure 5.1: Traffic scenarios during peak and off-peak hours, June

5.2 AUGUST DATA COLLECTION

In July 2018, there were many wildfires in Oregon/California. As the thick smoke reached Portland, state and local health officials issued warnings against outdoor activities (Welch, 2018). Although some bicyclists were seen wearing masks, the smoke generally suppressed bicycle ridership. For this reason, a July data collection was not taken. By the time of the August data collection, the air quality was still extremely poor, but cycling numbers were closer to normal.

Another noteworthy condition is the start of Portland’s first e-scooter pilot in July. The e-scooter users who used the bicycle lane were still relatively small in number (4% of all bicycle lane users), and were counted as bicycles.

The August data collection was conducted on a sunny, warm weekday. The study observed 76 bus events from 6 a.m.-11 a.m.

Table 5.2: August Mixed-Traffic Metrics

	Bicycle Flow (bicycle/hr)	Bus Flow (bus/hr)	Right-Turning Vehicles (veh/hr)
Peak Conditions	259	20	80
Off-Peak Conditions	164	12	143

5.2.1 August: Distribution of Traffic Scenarios

Each bus event was categorized according to the definitions presented in the Methodology Section 4.1. The distribution of scenarios is shown in the histogram below.

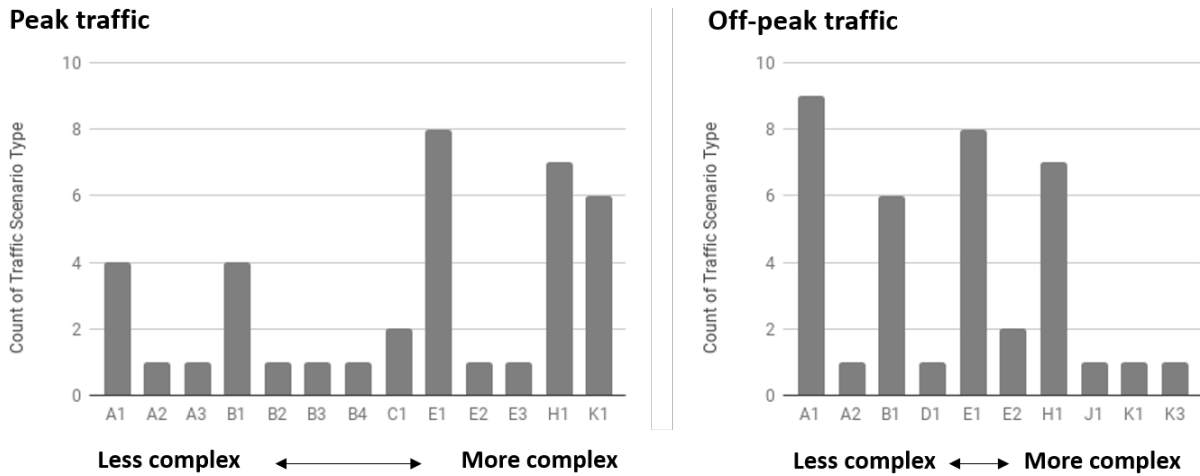


Figure 5.2: Traffic scenarios during peak and off-peak traffic hours, August

5.3 SEPTEMBER DATA COLLECTION

The September data collection was conducted on a sunny, warm weekday. The study observed 78 bus events between 6 a.m.-11 a.m.

Table 5.3: September Data Collection

	Bicycle Flow (bicycle/hr)	Bus Flow (bus/hr)	Right-Turning Vehicles (veh/hr)
Peak Conditions	310	21	93
Off-Peak Conditions	240	12	141

5.3.1 September: Distribution of Traffic Scenarios

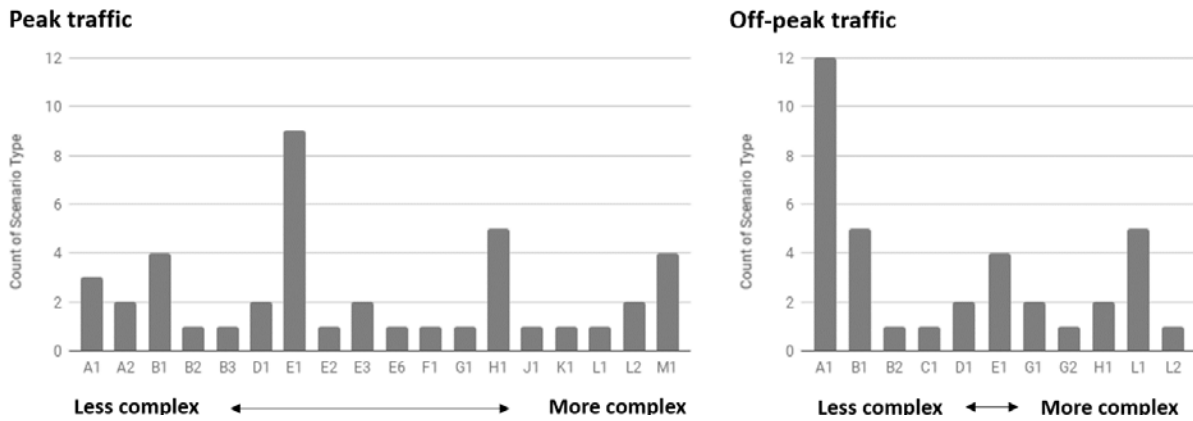


Figure 5.3: Traffic scenarios during peak and off-peak hours, September

5.4 AGGREGATE DATA AND ANALYSIS

The aggregate traffic conditions from our data collections are shown in Table 5.4. Our analysis included 219 bus events. Though the peak/off-peak distinction was determined by scheduled bus service, the bicycle traffic was also heavier during peak conditions. The number of cars in the right-turn lane was actually greater during the off-peak conditions.

Table 5.4: Aggregate Study Conditions

	Bicycle Flow (bicycle/hr)	Bus Flow (bus/hr)	Right-Turning Vehicles (veh/hr)
Peak Conditions	333	21	92
Off-Peak Conditions	199	12	148

5.4.1 VARIATION ON TRAFFIC SCENARIO TYPE

During the 14 hours of data collected, 33 of the possible 72 traffic scenarios occurred. As shown in Figure 5.4, the variation of traffic scenarios during peak traffic is broad. The off-peak traffic has less variation and a relatively high number of A1 scenarios, the scenario in which buses do not interact with right-turning vehicles or bicycles. However, high-complexity scenarios occurred in both peak and off-peak hours.

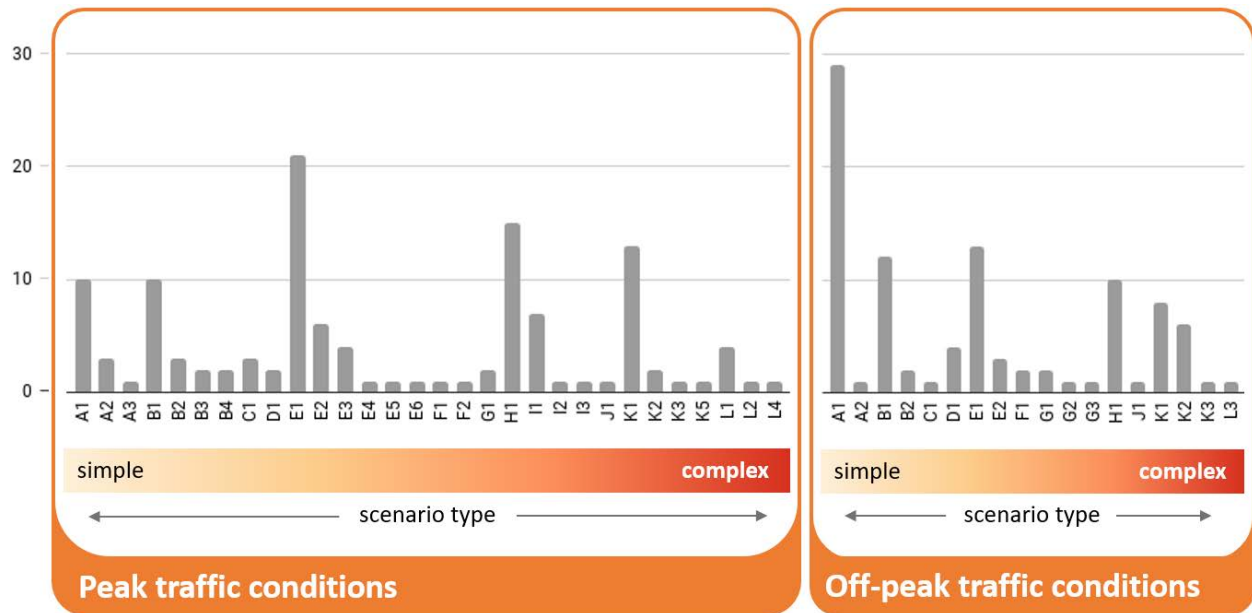


Figure 5.4: June traffic scenario distribution

5.4.2 Most Common Traffic Scenario Types

Table 5.5 is a summary of the seven most frequent traffic scenario types. To categorize complexity, a low rating was assigned to the traffic scenarios with no moving bicycles near the bus when ready to leave the stop (categories Ax–Cx, where x may be any number). A medium rating was assigned when all bicycles crossed the intersection in front of the bus (categories Dx–Fx), and a high label is assigned to any scenario that includes at least one bicycle crossing the intersection behind the bus (Gx–Lx).

According to the aggregate data analysis, during peak conditions a bus is most likely to encounter a medium-complexity traffic scenario, and during off-peak conditions a bus is most likely to encounter a low-complexity traffic scenario. However, medium- and high-complexity scenarios still occur during off-peak hours.

Table 5.5: Summary Statistics of Five Most Common Traffic Scenario Types

Rank of frequency of occurrences	Traffic scenario	Mean travel delay (sec)	Sample std. deviation	Occurrence rate, peak conditions	Occurrence rate, off-peak conditions	Complexity of bus-bicycle conflict
1	A1	19	5.78	8.2%	29.6%	Low
2	E1	25	6.16	17.2%	13.3%	Medium
3	H1	25	6.32	12.3%	10.2%	High
4	B1	22	2.59	8.2%	12.2%	Low
5	L1	24	6.24	10.7%	8.2%	High

5.5 THEORETICAL MODEL OF BUS-BICYCLE CONFLICTS

The bicycle arrivals were sorted into 15-minute intervals. Assuming a bicycle speed of 10 mph and a conflict zone of 160 feet, a bicycle is expected to be in the conflict area for 10.9 seconds. Assuming Poisson arrivals, the probability of a bus encountering a bicycle increases from 6- 8:45 a.m., and declines from 8:45 a.m.-11 a.m. (Figure 5.5). The highest probability for bus-bicycle conflicts occurs in the 15-minute interval before 8 a.m. and the 15-minute interval before 9 a.m. The observed frequency of conflicts confirms the assumptions applied to the theoretical model (Figure 5.6).

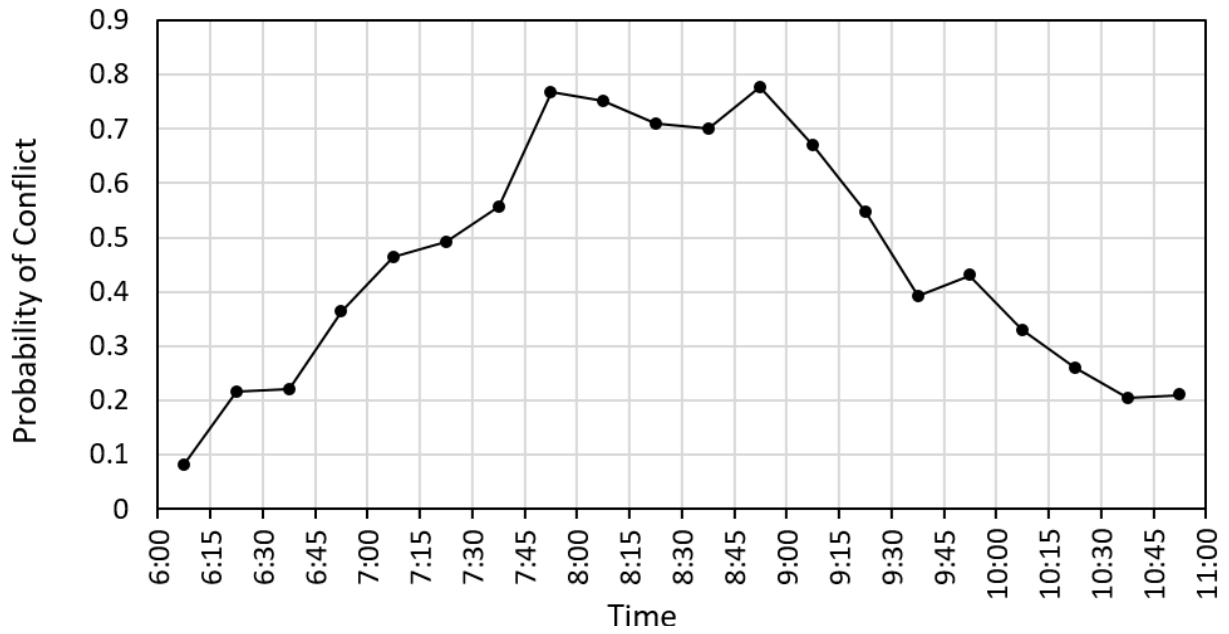


Figure 5.5: Probability a bus encounters a bicycle in the conflict area

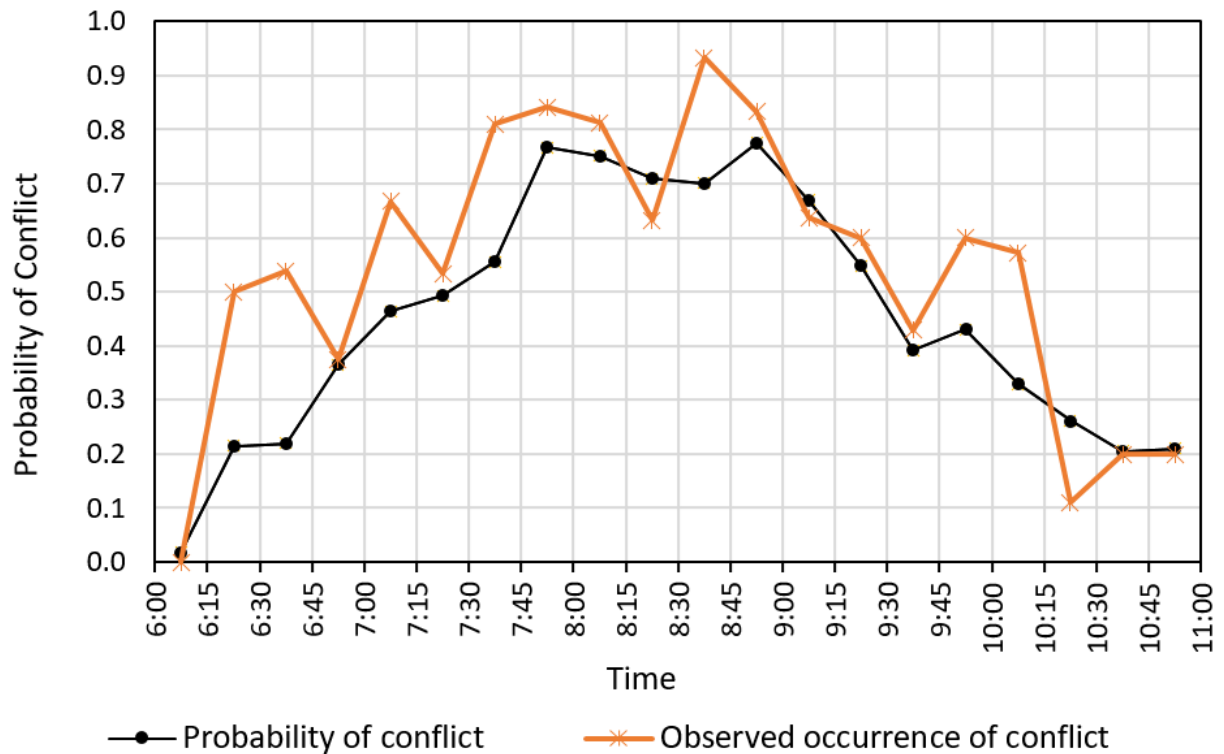


Figure 5.6: Theoretical probability and observed frequency of conflict

5.6 ESTIMATION OF ANNUAL BUS-BICYCLE CONFLICTS AT STUDY SIDE

The bicycle traffic on Madison and Grand flows directly to the Hawthorne Bridge, where there is a bicycle counter. There are no path nodes between Madison and Grand and the counter, so the westbound counter data can be referenced in this analysis. The bus traffic is relatively constant year-round, so the number of conflicts can be scaled according to the bicycle count variation. The bicycle counter has been in use since 2013, so its data can be used to calculate daily, weekly, and seasonal factors for bicycle traffic, adapting the well-known methodology used to estimate Average Annual Daily Traffic (AADT). The estimated annual number of high complexity (Gx–Lx) conflicts is over 11,000. Figure 5.4 is a link to a video example of a J1 type scenario, a high-complexity traffic occurrence.



Figure 5.7: QR link to high-complexity traffic scenario example

5.7 REGRESSION ANALYSIS

Multiple regression analyses were conducted to identify variables that have a significant impact on dwell times. Table 5.6 shows the final model with six significant variables.

- Stop: Binary variable equal to 1 if the bus services passengers
- Ons: Number of boarding passengers
- Offs: Number of alighting passengers
- Lift: Binary equal to 1 if the wheelchair lift was activated
- Number of bicycles behind bus
- Route 4: Binary equal to 1 if the bus served Route 4; 0 if routes 10 or 14.

Table 5.6: Regression Analysis Results

Variable	Coefficient	Standard Error	t-value	Relative Contribution
<i>Intercept</i>	0.907	1.896	0.478	—
Stops	8.792***	2.039	4.313	0.0973
Ons (Boardings)	2.771***	0.384	7.214	0.1650
Offs (Alightings)	0.899**	0.283	3.169	0.0545
Lift	34.445***	5.244	6.568	0.1155
Num. Bicycles Behind Bus	0.516*	0.278	2.127	0.0127
Route 4	-2.198*	1.032	-2.130	0.0069
* $p < 0.1$ ** $p < 0.05$ *** $p < 0.001$			Adjusted R-Square = 0.4365	

Many other variables were tested, but dropped due to insignificance, including: non-linear passenger movements, bicycles stopped in the bicycle box, bicycles stopped in the bicycle lane, number of bicycles, the number of right-turning vehicles, the number of buses, number of cars, and binary variables indicating “at least one” bicycle or car in each position. Routes 10 and 14 follow the same path beyond this stop and end shortly after entering downtown Portland while Route 2 follows a separate path.

5.7.1 Novel Findings

The only statistically significant variable related to traffic interactions was the number of bicycles behind the bus when crossing the intersection; each bicycle contributes 0.516 seconds of delay. Conversely, the bicycles stopped in the bicycle box, stopped in the bicycle lane, or overtaking the bus had no significant relationship with bus delay. In other words, the bicycles that cross the intersection in front of the bus do not significantly correlate with bus delay, regardless of their location (in front of the bus or peripheral) or condition (stopped or moving). These regression results should be considered with caution due to the low number of observations. Future studies are necessary to solidify or reject these preliminary findings.

5.7.2 Validation of the Regression Model and BSL Data

The video analysis observed several measurable factors: the number of bicycles, the number of right-turning cars, the traffic scenario – the methodology was designed to be objective and repeatable. However, the most nuanced variable to ascertain was the interval of time the bus spent serving the bus stop. The hierarchy of available proxies was described in the methodology, and once the TriMet bus stop-level (BSL) data was available, it could be compared to the video analysis estimates.

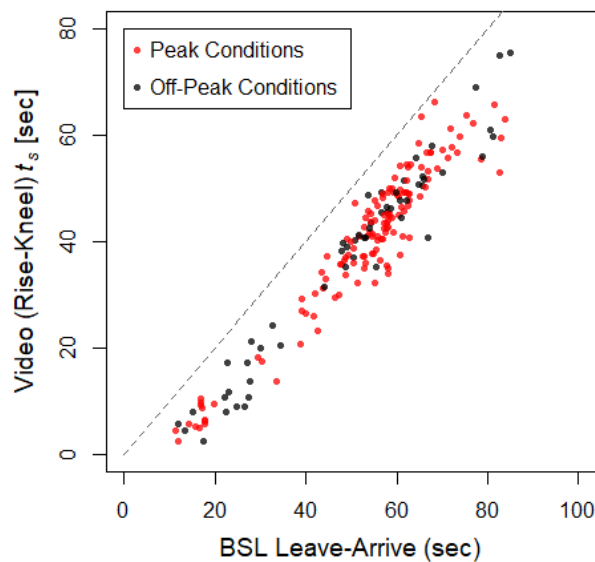


Figure 5.8: Correlation between video time of service and BSL leave-arrive time

In Figure 5.8, the scatter plot comparing BSL data and the video analysis show a strong correlation with a median offset of 12 seconds. This is an indication of the quality of the data collection effort. The 12-second offset is likely the result of how BSL data records arrive times and leave times. The resolution of BSL data is a 45-foot diameter around the bus stop (Figure 5.9) (Glick and Figliozi, 2017a). If, for example, a bus starts serving passengers while 20 feet behind the stop bar, when it is finished it may pull up closer to the intersection by 20 feet. However, TriMet’s BSL data would record the time spent waiting for a green light as dwell time. In these scenarios, $t_s \neq$ BSL dwell.

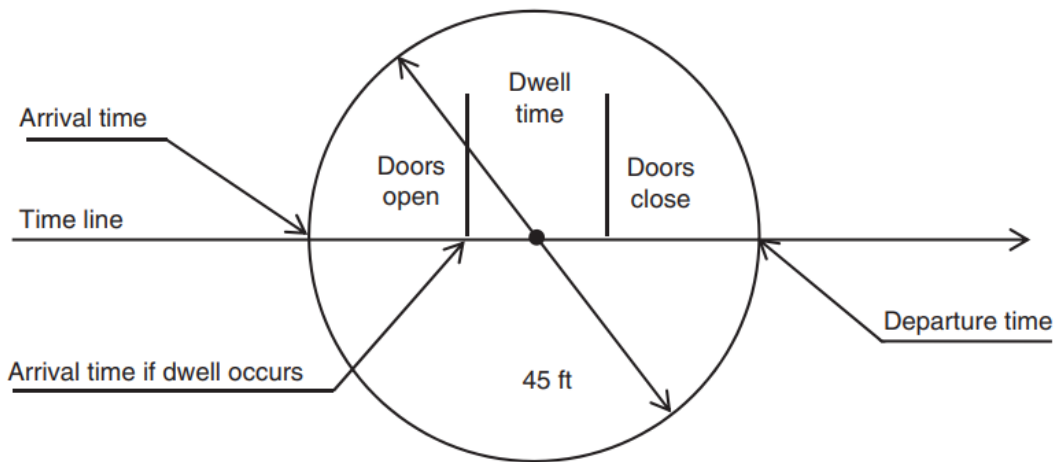


Figure 5.9: Resolution of BSL location data

5.8 HEAT MAPS

Another useful visualization tool for examining segments of streets are heat maps of bus speeds. These graphics show average speeds by location and time of day and can help identify areas of congestion, as indicated by slow speeds. Using buses as probes is not new and can give insight into the road segment (Stoll, Glick, and Figliozi, 2016; Glick and Figliozi, 2017b). The heat maps of the following three figures have vertical lines to mark the locations of important road features. From right to left, the same as the travel direction:

1. Beginning of the planter median prior to 7th.
2. Beginning of crosswalk of Madison and 7th (near-side)
3. End of crosswalk (start of intersection) of Madison and 7th
4. Beginning of crosswalk (end of intersection) of Madison and 7th
5. End of crosswalk of Madison and 7th (far-side)
6. Beginning of intersection of Madison and 6th
7. End of intersection of Madison and 6th
8. Beginning of bike box
9. Beginning of crosswalk (Madison and Grand)
10. End of crosswalk (start of intersection of Madison and Grand)
11. Beginning of crosswalk (end of intersection of Madison and Grand)
12. End of crosswalk of Madison and Grand

In Figure 5.10, the general behavior of buses can be seen during the morning commute. Buses are slowed by the intersection at 7th, and experience even slower speeds prior to the bike box before crossing Grand. Congestion is highest between 8 a.m. and 9 a.m.

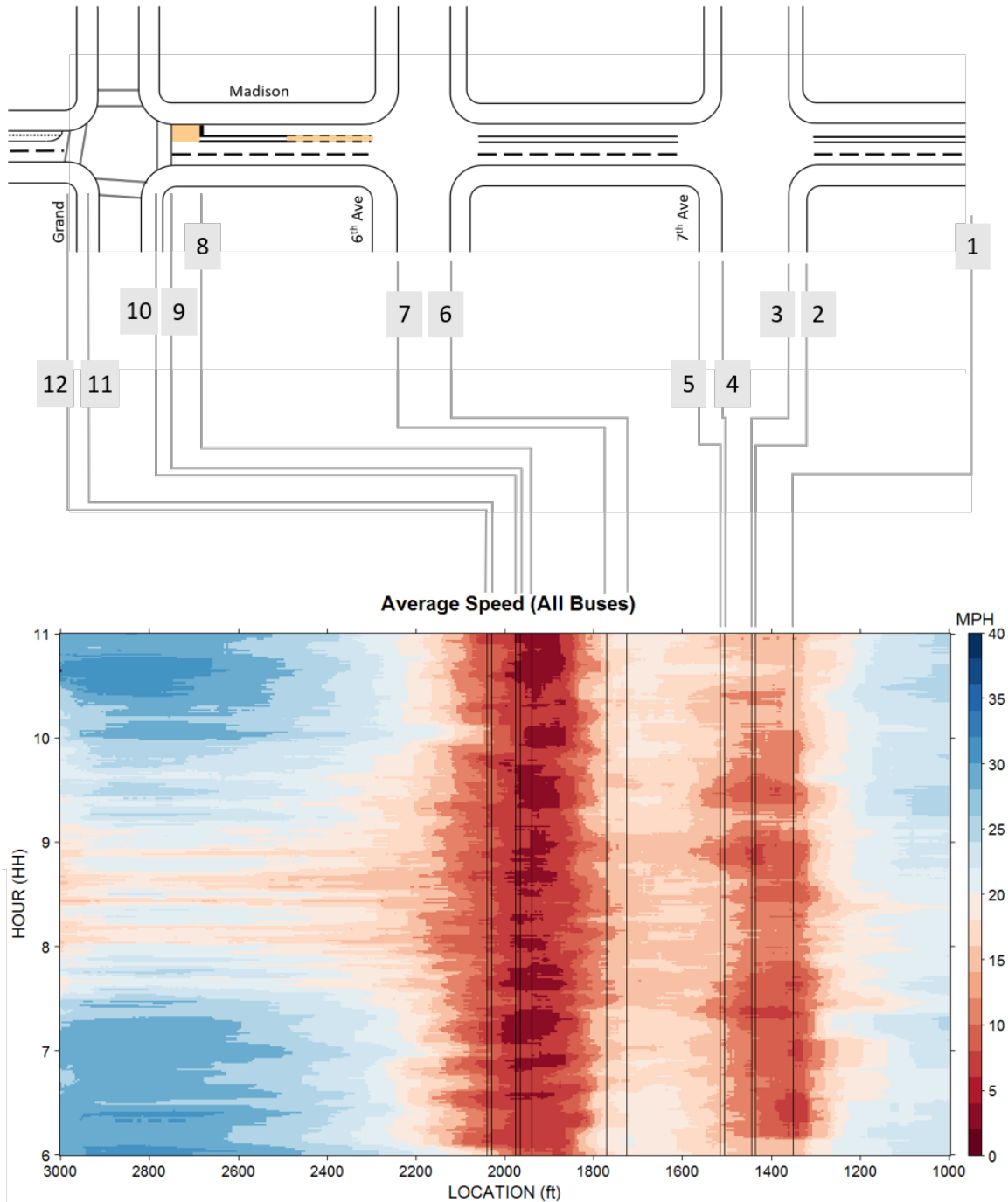


Figure 5.10: Speed heat map using all buses for Madison for morning commute

Figure 5.11 shows the same stretch during the same time, but excludes buses that stopped to serve passengers. Previous research shows that such a heat map represents the general behavior of traffic as the stopping behavior of buses is removed (Figliozzi and Stoll, 2018). The slowest speeds are between 8 and 9 a.m., and there is little evidence that the bike box caused delays separate from passenger boardings and alightings.

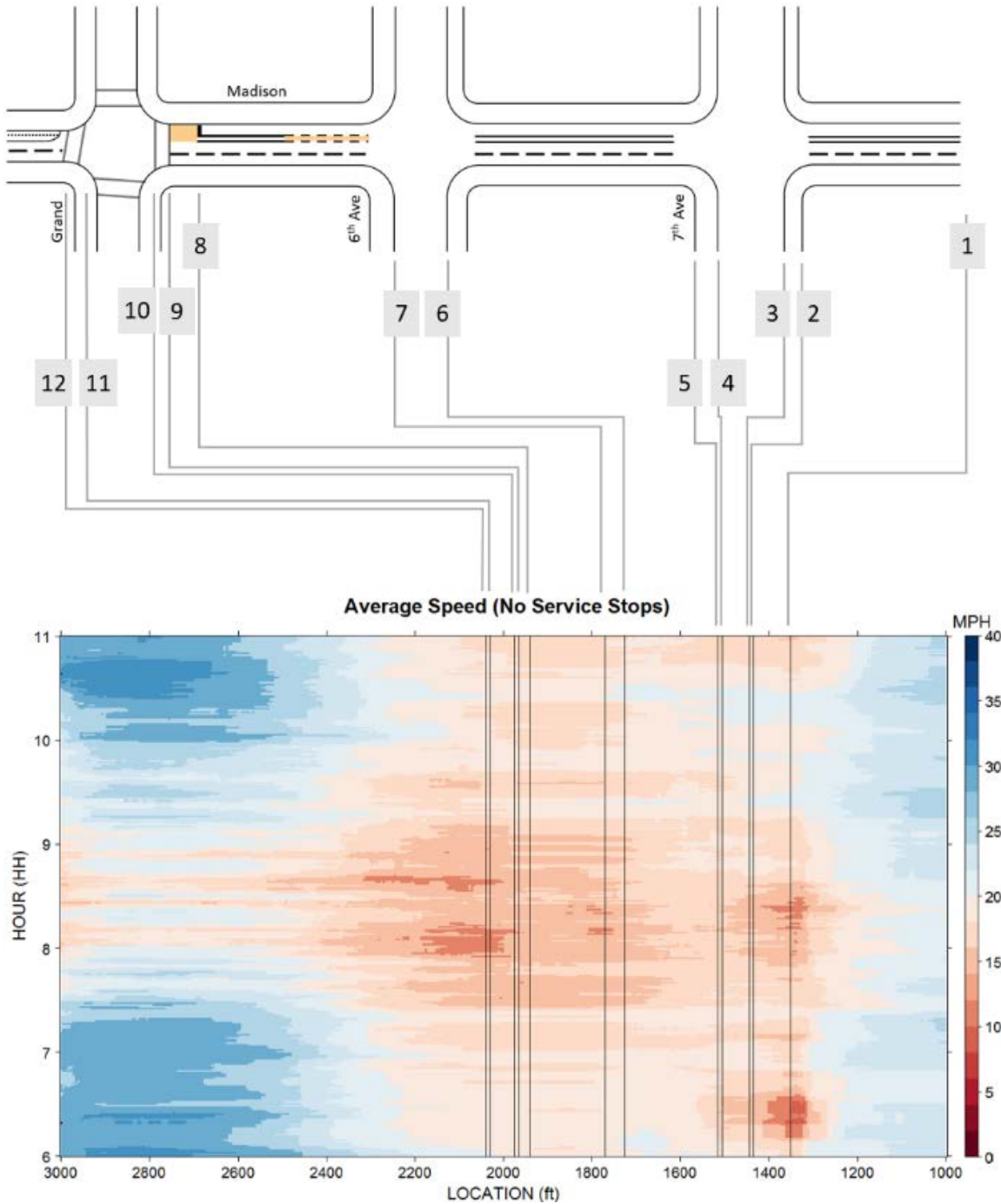


Figure 5.11: Speed heat map using buses that do not stop to serve passengers for Madison during morning commute

Figure 5.9 further restricts the number of buses by only including buses that experienced an unexpected stop separate from passenger movements. This heat maps shows the locations most likely for vehicles to stop just prior to each intersection.

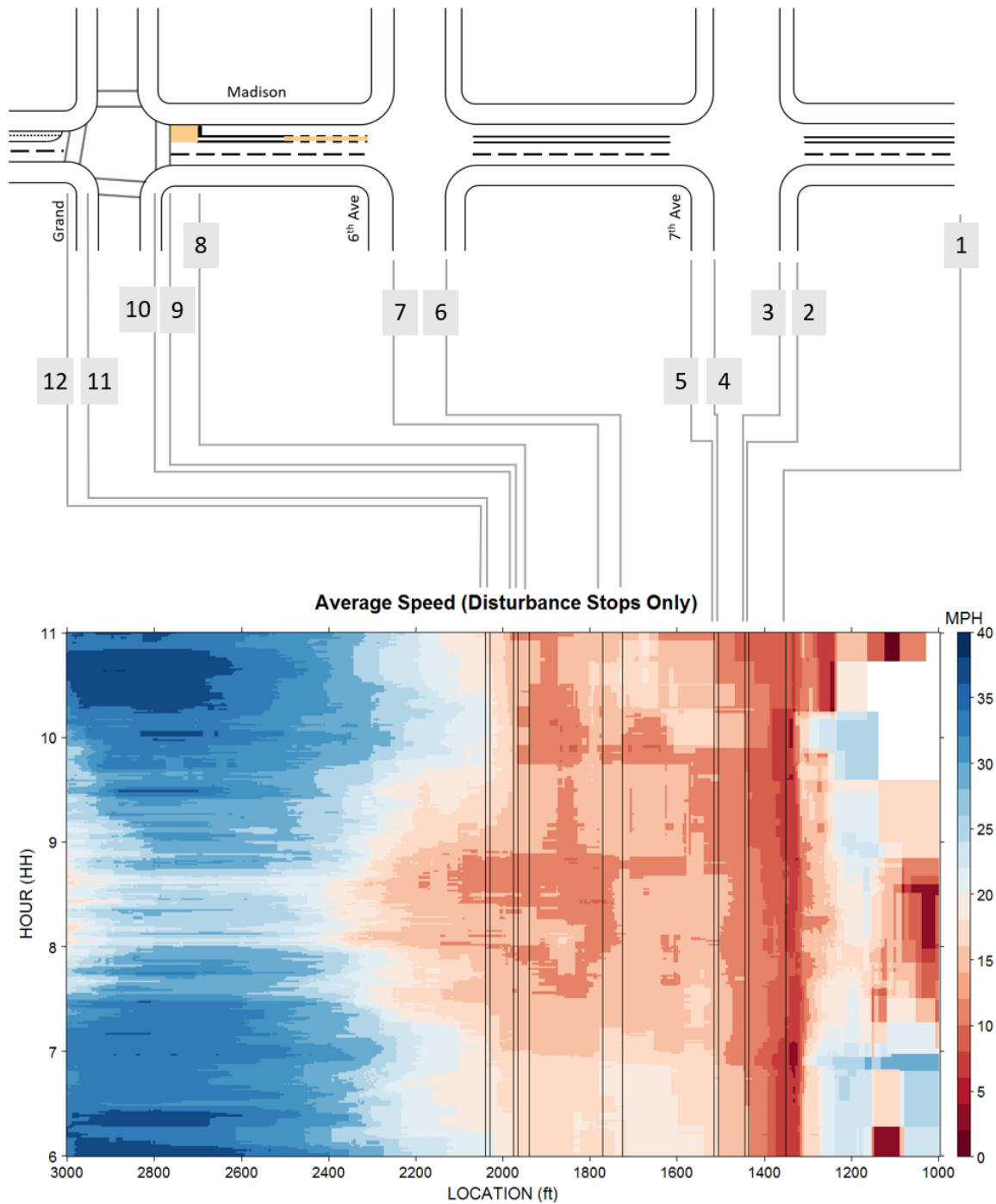


Figure 5.12: Speed heat map using buses that experience a disturbance stop for Madison during morning commute

It is important to mention that the intersections of Madison and 7th Avenue and Grant Avenue have traffic lights. Hence, average speeds are also reflecting red-time durations. These delays can be seen clearly in Figure 5.11 without the effect of bus stops. It should be noted, too, that buses experience delays after passing Grant Avenue between 8 and 9 a.m. In Figure 5.11, it is also possible to see the lower bus speed in the conflict area between 8 and 9 a.m. This is also confirmed by the heat map utilizing disturbance (unexpected stop) data in Figure 5.12.

6.0 CONCLUSIONS AND FINAL DISCUSSION

This research presents a novel approach to study bus, bicycle, and automobile conflicts in the U.S. Conflicts are categorized as a function of traffic scenarios, and main sources of delay are identified and quantified.

The results show that the overlapping of bus facilities and bicycle facilities does result in numerous bus-bicycle conflicts, most frequently during rush hours. However, complex bus-bicycle conflicts do happen, albeit less frequently, during off-peak hours. The results of the analysis suggest that the bicycle box onsite does not significantly contribute to bus delay, nor do stopped bicycles that do not fit in the bicycle box but stop in the bicycle lane. Bicycle boxes have been studied with regards to their effects on cyclist and motorist comfort and perception of safety, and it is a welcome finding that they do not burden bus flow. However, each bicycle crossing the intersection behind a bus adds a delay of more than half a second per bicycle.

The traffic scenarios categorized as highly complex (Gx-Lx) are equivalent to the scenarios with bicycles that cause delay. The frequency of high-complexity scenarios will increase as bus and bicycle traffic increase. At current bus and bicycle volumes, we expect over 11,000 annual conflicts, a volume which supports concern for cyclist safety. These quantitative findings can be used to justify funding for intersection upgrades or for an education/enforcement campaign.

6.1 DISCUSSION OF POTENTIAL COUNTERMEASURES

6.1.1 Bicycles Behind Bus

As shown in Figure 6.1, configuring the bicycle lanes behind bus stops completely eliminates all bus-bicycle conflicts. The Portland Bureau of Transportation has included “Bicycles Behind Bus” as an operational strategy in its Enhanced Transit Corridors Plan (City of Portland, 2017). Unfortunately, this configuration—colloquially called “bus stop islands”—is best for wide roadways, as it requires a significant amount of right-of-way and is relatively expensive (City of Portland, 2017). Bicycles may be redirected onto the sidewalk, but the study location only has a 10-foot sidewalk; therefore, this solution would create new bicycle-pedestrian conflicts but would increase bicyclists’ comfort levels (Blanc and Figliozzi, 2016). For any transit treatment, questions of costs and benefits rely on available data. The conflicts and delays observed on Madison and Grand offer insight as to what can be expected without a bus island treatment.



Figure 6.1: Bus stop islands (TriMet conceptual design–Division Transit Project)

6.1.2 Bus Stop Relocation and Consolidation

Another treatment option is bus stop relocation and consolidation. Routes 10 and 14 have a stop two blocks east of the study site at 7th Avenue and Madison. If both stops at Grand and 7th were eliminated in favor of a single stop at 6th and Madison (Figure 6.2), there would not be a bus stop at a signalized intersection. Though there would still be bus-bicycle conflicts, the proposed location would allow bus operators to focus on the merge without having to simultaneously navigate the traffic signal or to merge right after serving the current bus stop. A secondary benefit is that cars using the right-turn-only lane at Grand would not have to wait behind buses serving the station and vice versa. However, the increased walking distance to reach a stop on Grand may have a negative effect on ridership; bus users would have to walk farther to connect with the streetcar and other bus lines running on Grand Avenue. Although bus stop consolidation is a strategy included in Portland’s Enhanced Transit Corridors Plan, it is not a preferred treatment for our study site specifically.

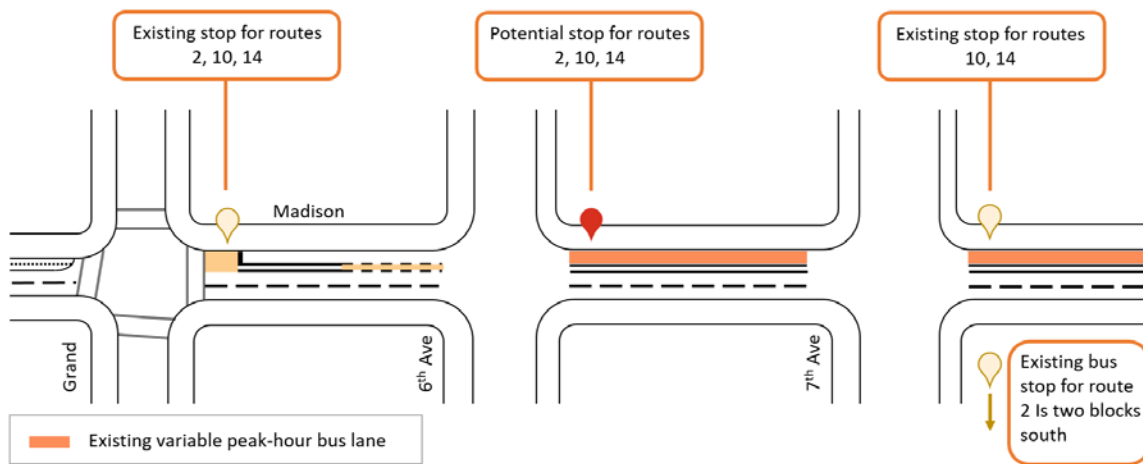


Figure 6.2: Potential bus relocation and consolidation

6.1.3 Pavement Markings

Another treatment option is to adjust the green pavement marking such that an elongated break in the green color better aligns with the actual area of conflict (Figure 6.3). This may help cue cyclists to pay attention for conflicts earlier.

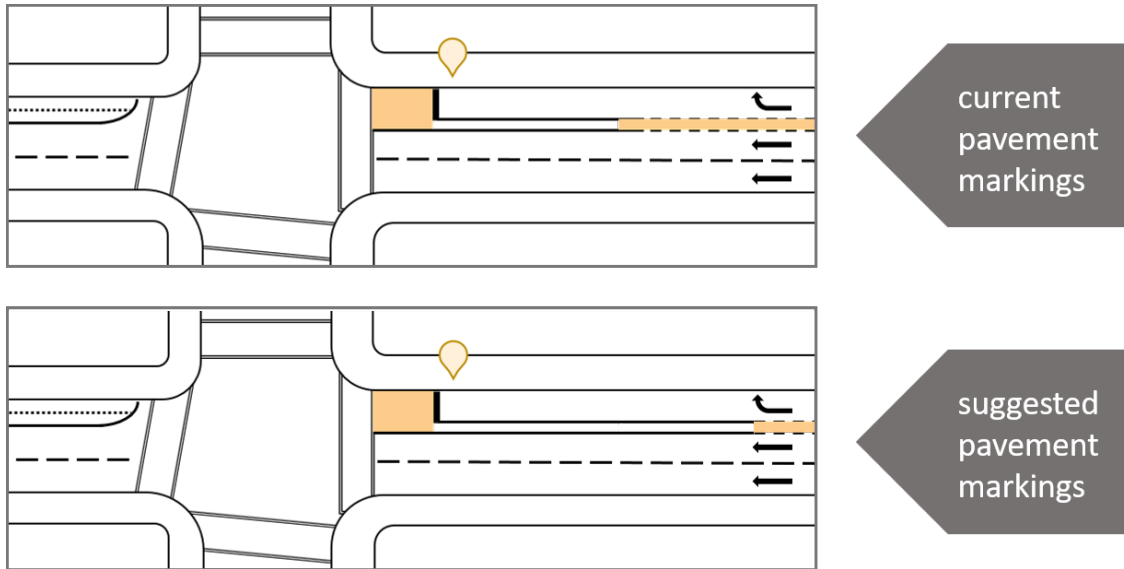


Figure 6.3: Suggested larger break in green pavement marking

6.1.4 Reducing Bus Delay

Finally, buses incur long delays when they leave the stop only to find the end of the green indication or the start of the red indication at the traffic signal. Delays caused by bicyclists and traffic signals can be alleviated by a combination of floating island bus stops, jump queue signal for the buses, and transit priority. Unfortunately, this configuration requires a significant amount of right-of-way, resources, and is incompatible with right-turning traffic. Future research efforts should evaluate cost tradeoffs that result from the redesign of bus stop facilities at intersections with high volumes of conflicts and delays.

6.2 CONCLUDING REMARKS

Better design and engineering solutions can reduce conflicts and bus delays. In addition, education and/or enforcement strategies can be used to improve cyclist and driver awareness of bus priority and to improve transit operations citywide.

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