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

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Abstract

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. 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 ft of 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 cross the intersection before the bus, or the presence of right-turning vehicles.

Cities have sought to alleviate traffic congestion and the 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 in which bus routes, bicycle lanes, and motorized vehicles share space.

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 (*1*). In 2008, the city rolled out a new experimental traffic treatment, the right angle bicycle lane extension, that is, 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 (*2*). Many of the city's bicycle boxes have been visually reinforced with green pavement marking, as is preferred by both motorists and cyclists (*2*).

Although the bicycle network has been improving, Portland's public transit provider, TriMet, has been struggling with declining bus ridership and speeds (Figure 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 average about 18.2 mph and the buses average 13.7 mph, for 2015–2017 (*3*). The quest to increase bus speeds—and plausibly, ridership—pushes transit agencies to find ways to reduce bus delays.

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

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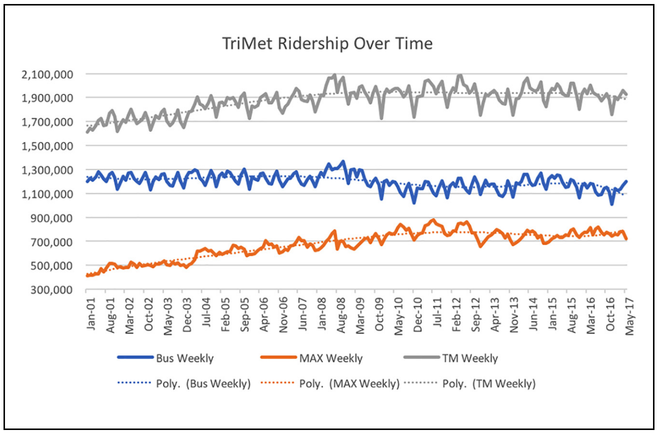

Figure 1. TriMet bus ridership and average bus travel speed.

Figure 2. SE Madison and Grand, satellite image from Google Earth.

addressed bus, bicycle and automobile conflicts in the US. 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.

Literature Review

There is significant opportunity to research bus–bicycle conflicts. In China, models have been proposed to estimate the number of conflicts, but these models are limited to midblock stops and are not applicable for stops close to signalized intersections (*4*, *5*). With regard to bus delay, studies have measured bus mean speeds with respect to particular bus stop designs; however, these studies also focus exclusively on midblock stops (*6*, *7*).

Unfortunately, intersections pose the most challenges for bus–bicycle conflicts. In regard to bicycle safety, an Australian study found that 55% of bus–bicycle accidents take place at intersections (*8*). Another UK study showed that of all the 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 (*9*). This collision primarily occurs 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 (*10*).

Many US studies on bus–bicycle conflicts have evaluated road configurations, including shared bus-bicycle lanes (SBBLs), contraflow bus lanes, and left-side bicycle lanes, and the ability of these designs to mitigate conflict (*11*). From these existing configurations, cities seeking to enhance their multimodal networks can refer to real-world results to inform their design guidelines (*12*).

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

Study Site

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 a 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. The bus and bicycle facilities are shown in Figures 2 and 3.

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,

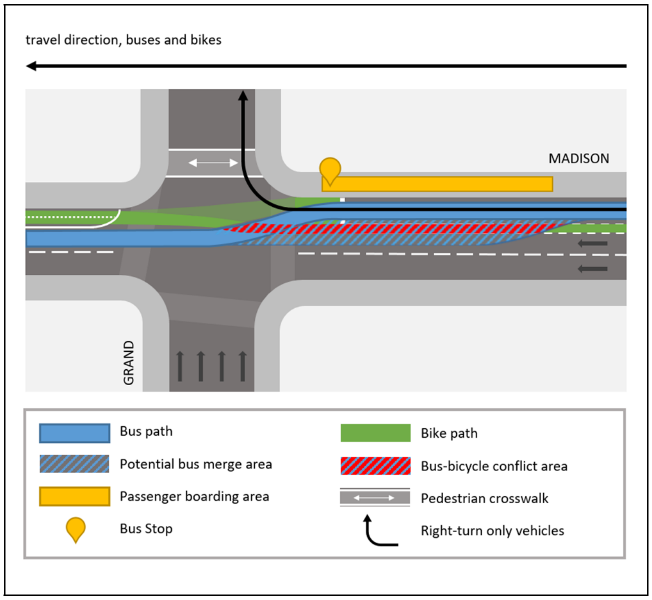

Figure 3. SE Madison and Grand, conflict diagram.

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. As buses serve passengers at varying distances from the bus stop (owing to traffic queuing), the area of potential bus–bicycle conflict is about 160 ft long (highlighted in red, Figure 3). In effect, the bicycle box addresses the right hook conflicts with right-turn vehicles, but still leaves cyclists vulnerable to bus–bicycle conflicts. The conflict area is the result of overlapping bus and bicycle paths, at and in the intersection.

Site History

The Hawthorne Bridge underwent major improvements in 1999: sidewalks were widened, ramps with conflicting traffic closed, and merging conditions improved (*13*). 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.

Three bus routes, (2, 10, and 14) serve the morning commutes into downtown. The bus stop on site, stop 3633, has been in operation since 1999; in that same year, the first round of cycling improvements were completed. During peak hours of service, stop 3663 often has buses scheduled to arrive concurrently or with only a 1–2 min headway.

A combination of graphic road markings are utilized on the pavement. The graphic layout of the street can have positive effects on a cyclist's perception of safety (*14*). Indeed, a stripe is what demarks and upgrades a bicycle-accessible shoulder to a designated bicycle lane. However, a bicycle lane is not always the preferred type of facility; many cyclists prefer separated paths (*15*). If a bicycle lane is used, studies have shown that the use of bold demarcation is important for the efficacy of a bicycle box (*16*).

The bicycle box on Madison has a 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 (*17*). 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 is does not run the length of the potential conflict area.

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. Therefore, 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 a 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." (*18*)

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 (*19*). At TriMet the buses are also equipped

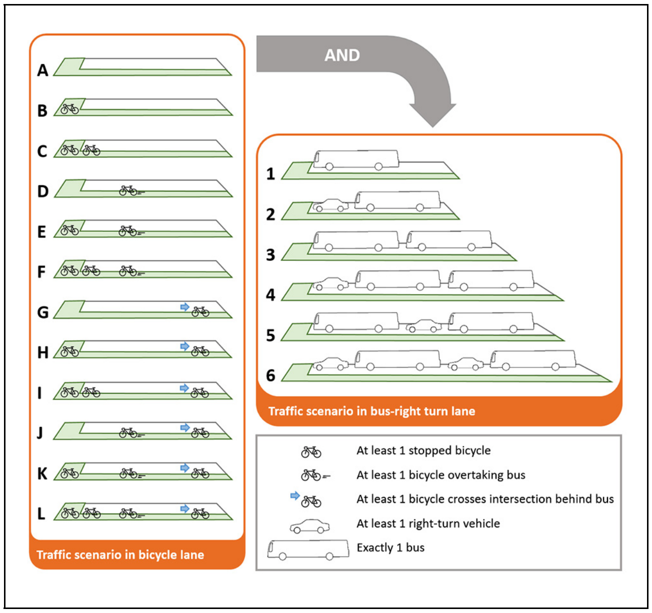

Figure 4. Categorizing traffic scenarios.

with an operator-activated light-up 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.

Methodology

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 with regards to the 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 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 in which a skateboarder, electric scooter user, or motorized board user was using the bicycle lane. In these cases, they were counted as bicycles.

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-turn vehicles. As noted in the key, a car icon in the figure represents one or more right-turn vehicles. When two buses arrive at the intersection, the first bus would be classified by scenario 1 or 2, and the second bus would be classified by scenarios 3–6.

The traffic scenarios A–L and 1–6 were ordered with regards to 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. The "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.

The "G" scenario has a bicycle behind the bus when crossing the intersection. A bicycle less than 60 ft behind the bus was considered to be part of the bus's traffic scenario; 60 ft was chosen because it is 1.5 times the length of a bus. When located within a distance of 60 ft, 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"–"M") 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.

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 application of solid green pavement marking. Figure 5 shows bicycles (i) and (ii) counted as being in the bicycle box, and (iii) as being in the bicycle lane.

Quantification of Delays

For every bus that traveled through the study site, the bus delay was calculated in two different ways. The first

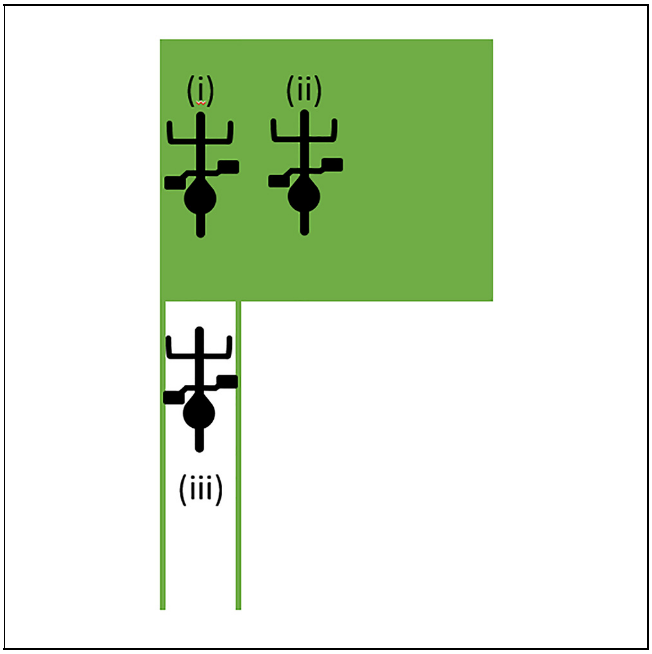

Figure 5. Distinction of bicycle box, in solid green: Bicycles (i) and (ii) are in the bicycle box, and bicycle (iii) is in the bicycle lane.

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.

$$D_G = t_l - t_e$$

in which: D_G is the gross delay; t_l is the time a bus leaves the intersection; and t_e is the time a bus enters the area of study.

$$D_T = D_G - t_s - t_w$$

in which: D_T is the travel delay; t_s is the time interval spent serving the bus stop; and t_w is the time interval spent waiting for a green light.

The confines of the study area are shown in Figure 6. 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 7) offered four observable proxies: turn signal, bus kneeling/rising, doors opening/closing, and time buffers after stopping/starting.

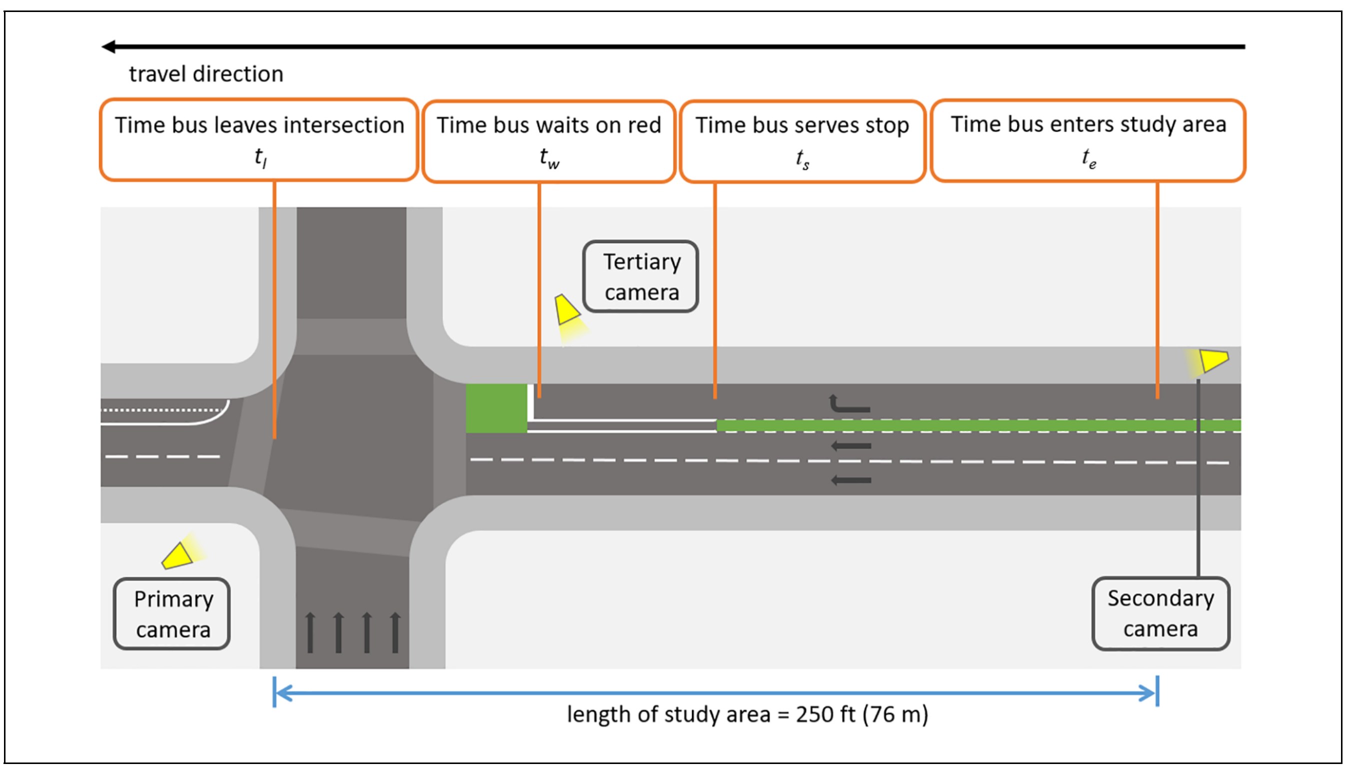

Figure 6. Times used to calculate delay.

Figure 7. Primary camera view of study area.

Buses will signal right when serving the stop, and signal left to indicate when they intend to pull away from 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 2 s after the bus stops at the bus stop, and the end of service as 2 s 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 8) to provide consistency across data collections. For all 219 bus events, the time of service was calculable before the hierarchy was exhausted.

To validate the estimation of the service time, TriMet bus stop level (BSL) dwell was determined, 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.

Results

The data was collected during a weekday in June, August, and September, when cycle activity is high owing to sunny and dry weather. The first two hours, 6:30–8:30 a.m., reflect peak (bus service) conditions, while 6:00–6:30 a.m. and 8:30–11:00 a.m. reflect off-peak bus service conditions. Specifically, for peak conditions, the bus stop on site is scheduled to host a bus every 2.8 min. For off-peak conditions: a bus every 4.8 min. The grade at the site is slight (+ 2%) and the impact on bus acceleration is negligible at grades less than 3% (*20*).

The aggregate traffic conditions from our data collections are shown in Table 1. Our analysis included 219 bus events. Although the peak/off-peak distinction was determined by the 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 off-peak conditions.

The bicycle arrivals were counted in 15 min intervals. Assuming a bicycle speed of 10 mph and a conflict zone of 160 ft, a bicycle is expected to be in the conflict area for 10.9 s. Assuming Poisson arrivals, the probability of a bus encoutering a bicycle increases from 6:00–8:45 a.m.,

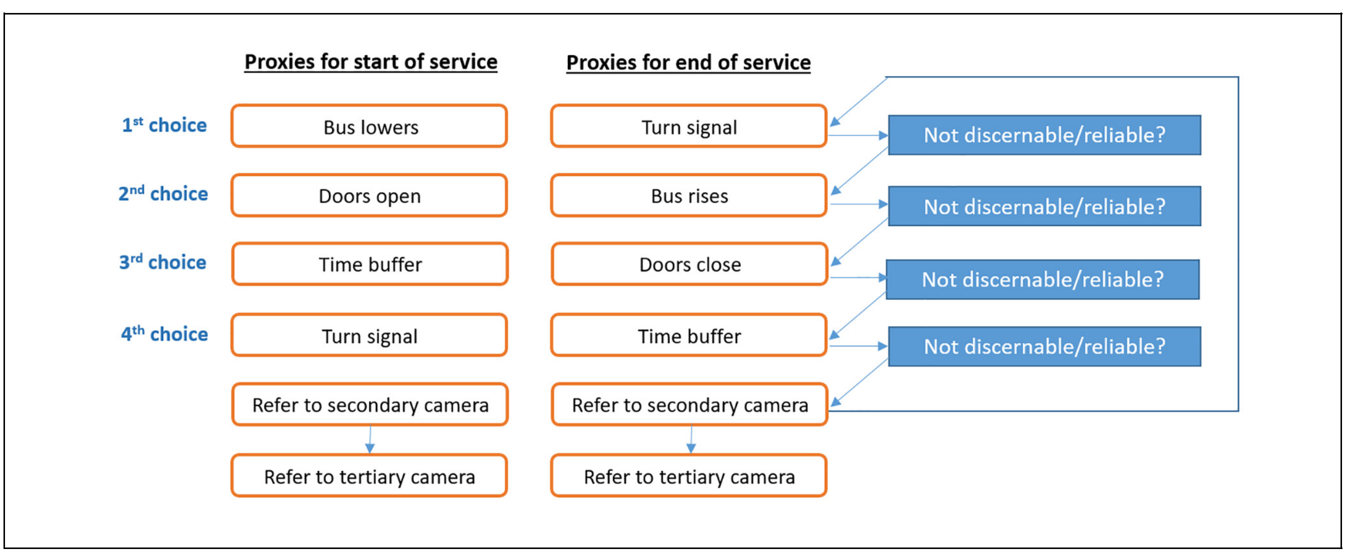

Figure 8. Hierarchy of utilizing service time proxies.

Table 1. Overall Study Traffic Conditions

	Bicycle flow (bicycle/hr)	Bus flow (bus/hr)	Right-turning cars (veh/hr)
Peak traffic	333	21	92
Off-peak traffic	199	12	148

Note: veh = vehicles.

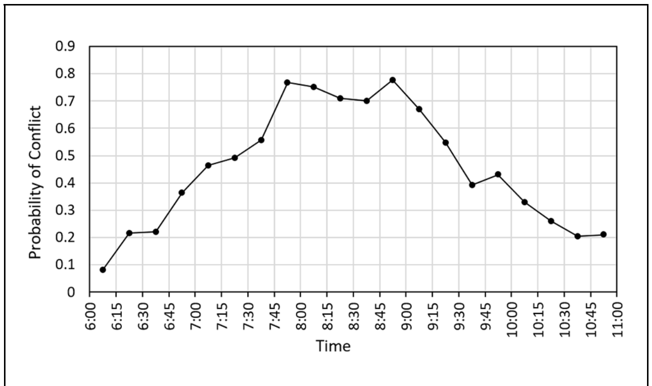

Figure 9. Probability that a bus encounters a bicycle in the conflict area.

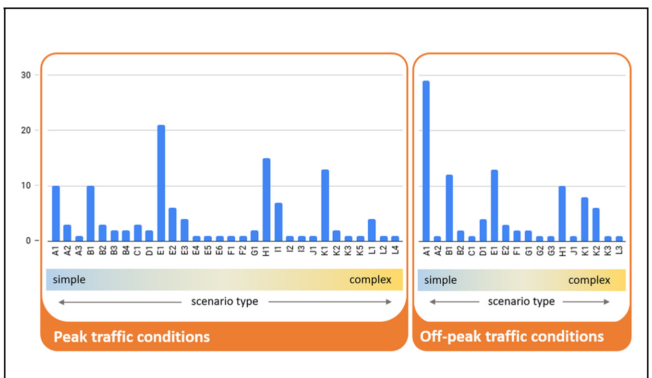

Figure 10. Traffic scenario distribution.

and declines from 8:45–11:00 a.m. (Figure 9). The highest probability for bus–bicycle conflicts occurs in the 15 min interval before 8:00 a.m. and the 15 min interval before 9:00 a.m.

During the 14 h of data collected, 33 of the possible 72 traffic scenarios occurred. As shown in Figure 10, 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-turn vehicles or bicycles. However, highly complex scenarios occurred in both peak and off-peak hours.

Table 2 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 when the bus was ready to leave the stop (categories Ax–Cx). A medium rating was assigned when all bicycles cross the intersection in front of the bus (categories Dx–Fx), and a high label was assigned to any scenario that includes at least one bicycle crossing the intersection behind the bus (Gx–Lx). 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.

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, therefore the westbound counter data can be referenced in this analysis. The bus traffic is relatively constant year round, therefore the variation in 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 conflicts is over 11,000. Figure 11 shows a link to a video example of a J1 type scenario, a high complexity traffic occurrence.

Table 2. Summary Statistics of the Five Most Common Traffic Scenario Types

Rank of frequency of occurrences	Traffic scenario	Mean travel delay (s)	Sample standard 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

Figure 11. QR link to high complexity traffic scenario example.

Regression Analysis

Multiple regression analyses were conducted to identify variables that have a significant impact on dwell times. Table 3 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 a bus;
- Route 2: Binary equal to 1 if the bus belonged to Route 2. 0 if the bus belonged to routes 10 or 14.

Many other variables were tested, but were disregarded owing 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-turn 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.

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 s 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 bus or peripheral) or condition (stopped or moving). These regression results should be considered with caution owing to the low number of observations. Future studies are necessary to solidify or reject these preliminary findings.

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, and 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 BSL data was available, it could be compared to the video analysis estimates.

In Figure 12, the scatter plot comparing BSL data and the video analysis show a strong correlation, with a median offset of 12 s. This is an indication of the quality of the data collection efforts. The 12 s offset is likely the result of how the BSL data records the arrive times and leave times. The resolution of BSL data is a 45 ft diameter around the bus stop (Figure 13) (*21*). If, for example, a bus starts serving passengers while 20 ft behind the stop bar, when it is finished, it may pull up closer to the intersection by 20 ft. However, TriMet's BSL data would record the time spent waiting for a green light dwell time. In these scenarios, $t_s \neq$ BSL dwell.

Table 3. Regression Analysis Results

Variable	Coefficient	Standard error	*t*-Value	Relative contribution
Intercept	0.907	1.896	0.478	na
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
Number of bicycles behind bus	0.516*	0.278	2.127	0.0127
Route 2	–2.198*	1.032	–2.130	0.0069

Note: na = not applicable. Adjusted R-square = 0.4365.
$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.001$.

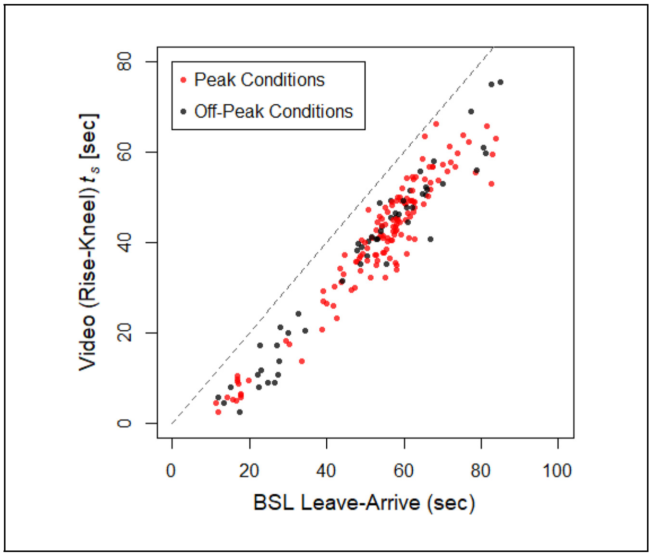

Figure 12. Correlation between video time of service and the BSL leave–arrive time .

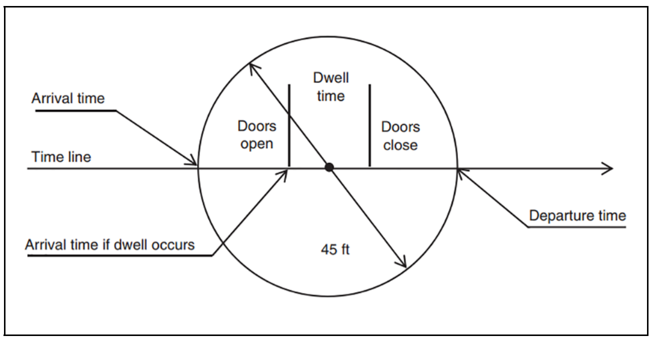

Figure 13. Resolution of bus stop level location data.

Conclusions and Final Discussion

This research presents a novel approach to study bus, bicycle, and automobile conflicts in the US. Conflicts are categorized as a function of traffic scenarios and the 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 peak hours. However, complex bus–bicycle conflicts do occur, albeit less frequently, during off-peak hours. The results of the analysis suggest that the bicycle box on site does not significantly contribute to bus delay, nor do stopped bicycles that do not fit in the bicycle box and stop in the bicycle lane. Bicycle boxes have been studied with regards to their effects on cyclist and motorist comfort and the 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.

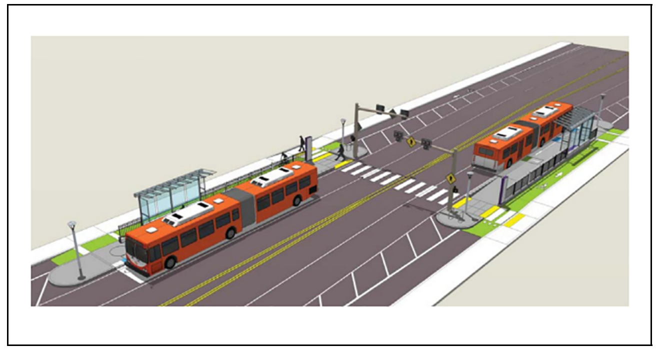

Figure 14. Bus stop islands (TriMet conceptual design—Division Transit Project).

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 increases. At the 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.

As shown in Figure 14, 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 their Enhanced Transit Corridors Plan (*22*). 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 (*22*). Bicycles may be redirected onto the sidewalk but the study location only has a 10 ft sidewalk; therefore, this solution would create new bicycle–pedestrian conflicts but would increase the comfort levels of bicyclists (*23*). 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.

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 Ave and Madison. If both stops at Grand and 7th were eliminated in favor of a single stop at 6th and Madison (Figure 15), there would not be a bus stop at a signalized intersection. Although 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

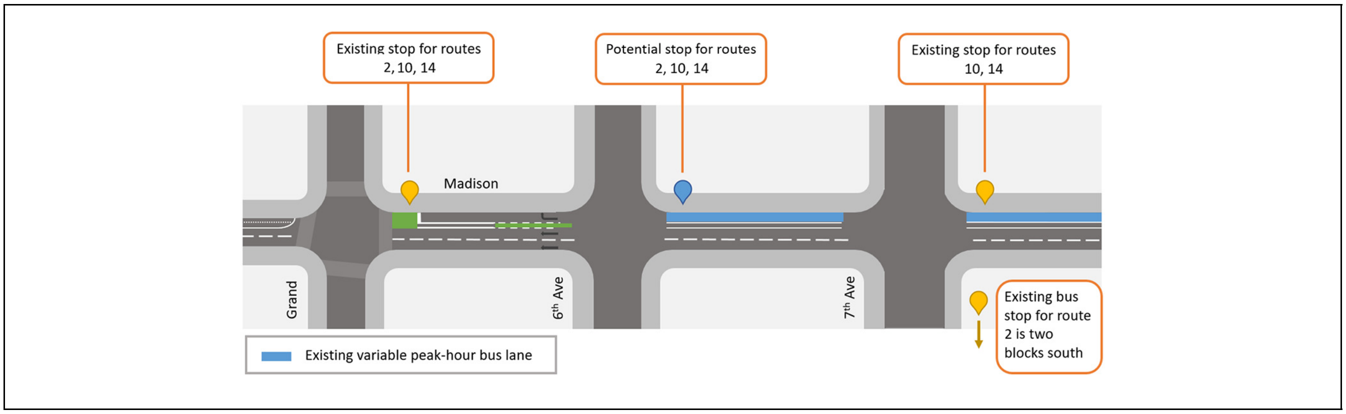

Figure 15. Potential bus relocation or consolidation.

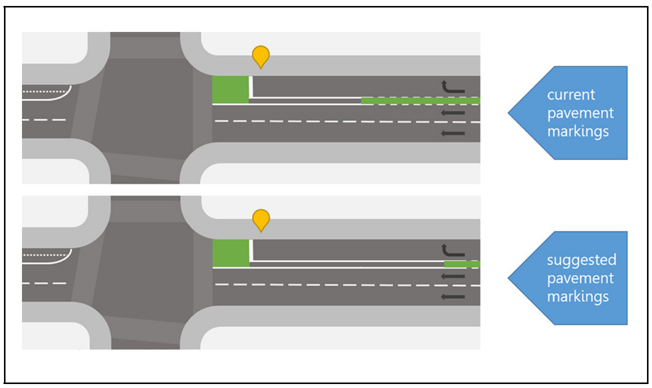

Figure 16. Suggested break in green pavement marking.

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.

Another treatment option is to adjust the green pavement marking so that an elongated break in the green color better aligns with the actual area of conflict (Figure 16). This may help cue cyclists to pay attention for conflicts earlier.

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 stop, queue signal jumping for the buses, and transit priority (see Figure 14 for a conceptual idea of the geometric design). Unfortunately, this configuration requires a significant amount of right-of-way, resources, and is incompatible with right-turn 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.

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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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: MAF, MC; data collection: TBG, KLK, MC; analysis and interpretation of results: KLK, TBG, MC, MAF' draft manuscript preparation: KLK, TBG, MAF, MC. All authors reviewed the results and approved the final version of the manuscript.

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