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The role of right turn in bus operation

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1. Introduction

Traffic congestion has become a widespread problem for cities worldwide as the population density continues to increase. Due to the limited space within cities, transport planners prioritise passenger movement over vehicle movement to improve road corridor efficiency (Waterson et al. 2003). This has raised the importance of improving public transport operation speed and reliability to ease traffic congestion. When traffic becomes congested, the traffic speed reduces, which can significantly affect bus operations since buses commonly share the road space with general traffic.

In our previous studies (Xian et al. 2022, Xian et al. 2023), we found that bus lanes and HOV (high-occupancy vehicle) lanes (known as Transit Lanes in Australia) were effective priority measures for improving bus reliability. When controlling for the presence of bus lanes, higher values for traffic volume, the number of traffic lights, and right turns (cross-traffic turns, left turns for right-hand drive) all significantly contribute to bus unreliability during bus operation (Xian et al. 2022, Xian et al. 2023). This highlights the importance of implementing additional bus priority measures that address reliability at intersections.

Utilising the GTFS-Realtime Trip Updates and Vehicle Positions data, this study conducts a microscopic analysis of the effect of right turns on bus operation. First, we establish the statistical significance of right turns in increasing mean delay and standard deviation of delay using Sydney as a case study. Then we present an analysis of the vehicle speeds and trajectories in the right turn's local environment to understand the cause of delay. Finally, two cases in Sydney where relevant intersection-focused bus right turn priority measures can be implemented are examined. A queue jump lane is implemented for the first intersection with three right turn lanes. For the other intersection with limited space, a novel bus right turn priority measurement, the bus right turn priority box, is implemented, which is an in-lane right turn queue jump lane. This study anticipates recommendations for considering micro-scale factors affecting bus operations and the proposed intersection-focused priority measures can improve bus reliability on bus routes with right turns.

2. Literature content

2.1. Right turn

Kim highlights that buses could face significant challenges when executing right turns on multi-lane arterial streets (Kim 2003). Their findings reveal that such right turning buses not only slow down bus operations but also reduce the overall traffic flow. Researches by Zhao & Zhou and Shu et al. suggest for greater priority for buses undertaking right turns at intersections (Zhao & Zhou 2018, Shu et al. 2019). Their research demonstrates a reduction in delay for both

through and right turn buses, while the performance of private vehicles at the intersection remained stable, thereby reducing total passenger delay at the intersection. Furthermore, Dunne & McArdle indicate the significant negative impacts of right turns on average speed, which is more than double of the effect of left turns (small turns, right turns in right-hand driving scenarios) (Dunne & McArdle 2022). While numerous studies have acknowledged right turns as a concern for bus operations, quantitative evaluations of right turn effects are not commonly conducted, and design alternatives mitigating these negative impacts are infrequently mentioned.

2.2. Queue jump lanes

The queue jump lane is a bus priority treatment that allows buses to bypass waiting queues at signalised intersections, often used in conjunction with Transit Signal Priority. Queue jump lanes have proven effective in reducing bus travel time and enhancing reliability (Transportation Research Board & National Academies of Sciences, Engineering, and Medicine 2013, Zhou & Gan 2009). Similar to other bus priority measures, efficiency can be reduced when significant traffic queues delay buses from entering the queue jump lane (Truong et al. 2015, Nowlin & Fitzpatrick 1997).

2.3. Pre-signal

Wu & Hounsell refer the bus pre-signal as traffic signals installed at or near the end of a with-flow bus lane, providing bus priority to the downstream junction. Bus pre-signals have been installed in Europe since the 1990s (Wu & Hounsell 1998). The bus pre-signal reduces bus delay at signalised intersections by avoiding traffic queues and allowing easy access to the right turn lane (inside lane) (Wu & Hounsell 1998). However, the pre-signal might not provide enough benefit when the intersection becomes congested which results in reduced reservoir capacities between the pre-signal and the main signal (Wu & Hounsell 1998). The analytic approach conducted in Wu & Hounsell's study indicates that bus pre-signal provides benefits for buses while having minor impacts on general traffic.

2.4. Microscopic analysis of real-time bus location data

Pu et al. utilise infrequent automatic vehicle location data from buses to monitor the real-time traffic conditions for both buses and general traffic (Pu et al. 2009). The validation result indicates that automatic vehicle location bus data can be effectively employed to estimate travel speeds and travel times. The automatic vehicle location data used in this study is the GTFS-Realtime Vehicle Positions, which is a bus automatic vehicle location data. Prommaharaj et al. utilise GTFS-Realtime Vehicle Positions data to evaluate various bus operational characteristics at a microscopic level, including speed, flow, density, and headway (Prommaharaj et al. 2020). These studies indicate the feasibility of using GTFS-Realtime Vehicle Positions for conducting microscopic analysis for bus operations.

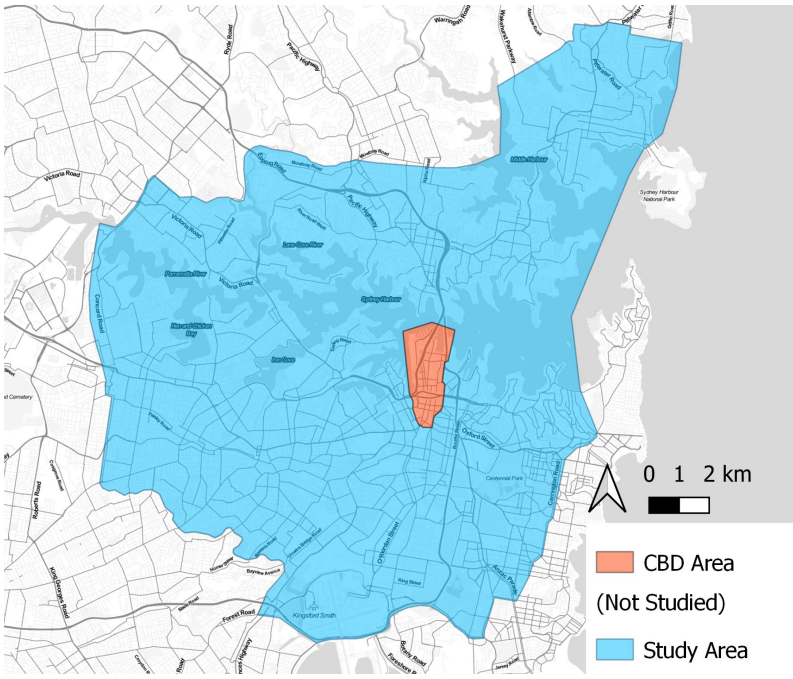
3. Methodology

The GTFS-Realtime dataset includes real-time operational details for public transit systems. It collects real-time updates provided by transit agencies and consists three types of data feeds: Trip Updates, Service Alerts, and Vehicle Positions. This study uses the GTFS-Realtime Trip Updates and Vehicle Positions data feeds. Trip Updates provides estimates of arrival times, whereas Vehicle Positions provides operational status, including GPS location and speed, updated every minute (Google Developers 2022). The GTFS-Realtime data used in this study was developed in our previous study (Chin et al. 2022).

3.1. Statistical significance of right turns

Bus-stop-to-bus-stop marginal delay data is used to test the statistical significance of delay and unreliability caused by right turns. The bus trips within the study area (Figure 1) from November 2020 to June 2022 are used. The GTFS-Realtime Trip Updates, which provide real-time bus schedule delay estimates, are used to calculate the bus-stop-to-bus-stop marginal delay.

Figure 1: Studied Area: Suburbs around Sydney CBD. Tidal flows are significant during peak hours within the studied area. Base map: Stamen



Bus-stop-to-bus-stop Marginal delay is defined as the difference between the arrival delay at the following stop and the departure delay at the previous stop:

$$M = A_{next\ stop} - D_{previous\ stop} \quad (1)$$

M is the stop-to-stop marginal delay ins seconds, $A_{next\ stop}$ is the arrival delay at the next stop and $D_{previous\ stop}$ is the departure delay at the previous stop. The bus-stop-to-bus-stop marginal delay represents the additional delay contributed between two adjacent bus stops caused by bus-stop-to-bus-stop link factors, including right turns.

The data is aggregated by each bus-stop-to-bus-stop link and hour. Rows with the same bus-stop-to-bus-stop link and hour in time are clustered as one group. Bus-stop-to-bus-stop links with fewer than five readings per studied hour are dropped to reduce randomness. The mean and standard deviation values of marginal delays are calculated for each group and used for comparison.

The marginal delay mean value is used as a marginal delay indicator for each cluster with a unique bus-stop-to-bus-stop link and hour of time. The marginal delays used in this section are measured in seconds. The marginal delay standard deviation value is used as a bus travel reliability indicator for each cluster with a unique bus-stop-to-bus-stop link and hour of time. A higher value in standard deviation indicates higher unreliability. To analyse the effect of the

right turns, the data is divided into two groups: bus-stop-to-bus-stop segments with right turns and bus-stop-to-bus-stop segments without right turns. T-tests are performed to determine the statistical significance of the difference caused by right turns.

3.2. Microscopic analysis

The microscopic analysis is used to have a more detailed understanding of the effects of right turns at the intersection level. Two intersections within the Sydney Metropolitan Area, Australia have been selected for the microscopic study: the intersection of Parramatta Road and Liverpool Road, Ashfield (Figure 2) and the intersection of Parramatta Road and Norton Street, Leichhardt (Figure 3). Both intersections are critical within the region, experience significant traffic congestion and are heavily used by buses and other traffic during both morning and evening peak hours.

The GTFS-Realtime Vehicle Positions data from June 2022 is utilised to conduct the microscopic analysis. This study focuses on the morning peak, which is more critical in the Greater Sydney Area. GTFS-Realtime Vehicle Positions data from 6 a.m. to 10 a.m. is used, which is the morning peak hours definition by Transport for NSW. The Vehicle Positions data is first separated by direction. Speed maps are plotted for the studied directions at both intersections. Lane-level trajectories of the studied directions are estimated by the common trajectory of buses at the intersection. The trajectories are divided into 5-meter lines in each direction. The Vehicle Positions data are spatially joined to the nearest 5-meter lines of the trajectories. The nearest five Vehicle Positions data is used if the trajectories have less than five readings.

Figure 2: GTFS-Realtime Vehicle Positions Data at the Intersection of Parramatta Road and Liverpool Road, Ashfield, Sydney Metropolitan, Australia.

At the intersection of Parramatta Road and Liverpool Road, Ashfield (Figure 2), the critical right turn direction is from southwest (Liverpool Road) to east (Parramatta Road), which is heavily used by city-bound buses during peak hours. The westbound through buses on Parramatta Road have a queue jump lane facility, which is studied to provide estimates for the potential time-saving after implementing a queue jump lane on the southwest-east right turns.

At the intersection of Parramatta Road and Norton Street, Leichhardt (Figure 3) the critical right turn direction is from east (Parramatta Road) to north (Norton Street), which is heavily used by outbound buses during peak hours. The westbound through buses on Parramatta Road are

studied for estimating the potential time saving after implementing the bus right turn priority box as the buses are required to use part of the through lanes to bypass the right turn queue.

Figure 3: GTFS-Realtime Vehicle Positions Data at the Intersection of Parramatta Road and Norton Street, Leichhardt, Sydney Metropolitan, Australia.

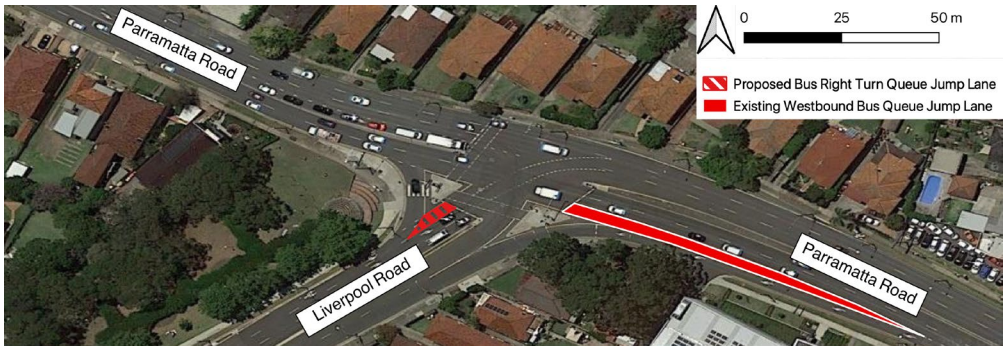
3.3. Priority measures

To reduce the bus operation speed reduction and unreliability caused by right turns at intersections, two proposed priority measures are considered: queue jump lanes and bus right turn priority box, which is an in-lane right turn queue jump lane.

3.3.1. Queue jump lanes

The proposed right turn queue jump lane is located on the southwest segment of the intersection of Parramatta Road and Liverpool Road (Figure 4). It is proposed to convert the outer right turn lane into a bus-only lane, allowing only left turn vehicles and buses to use the outer lane, which has a similar condition as the existing queue jump lane for the westbound through buses. The new proposed bus queue jump lane is expected to have similar time saving as the existing queue jump lane. The travel time with the right turn queue jump lane is estimated based on the time saved from the existing westbound queue jump lane while maintaining the delay at the intersection for the right turn movements, which is about 40 seconds assuming buses can go through the intersection within one cycle.

Figure 4: Proposed Queue Jump Lane at the Intersection of Parramatta Road and Liverpool Road, Ashfield, Sydney Metropolitan, Australia.

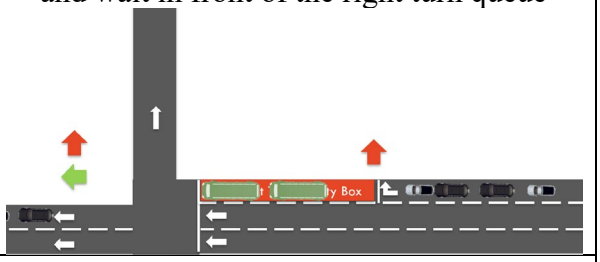
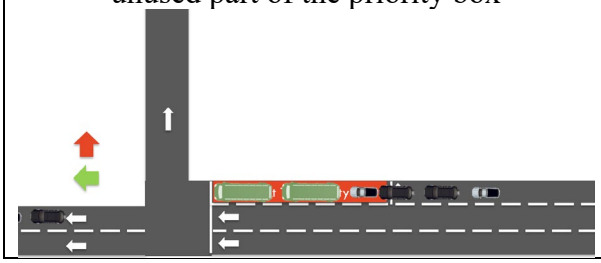
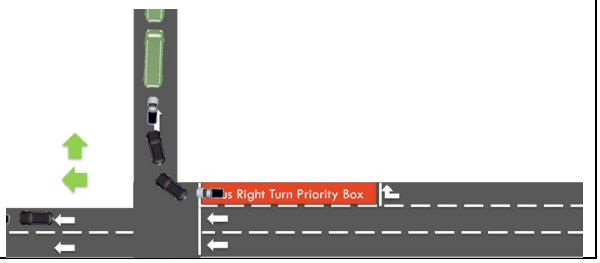


3.3.2. Bus right turn priority box: In-lane right turn queue jump lane

The commonly used existing bus right turn priority measurements are queue jump lane, pre-signal and signal priority. Both queue jump lane and pre-signal require a bus lane near the signal (Wu & Hounsell 1998), which is unsuitable for many intersections within the urban

environment where the road space is relatively limited. Bus right turn priority box (Table 1) is a novel priority measurement designed for right turn buses, which only requires the right turn traffic to offset away from the intersection to accommodate the bus right turn priority box. The length of the bus right turn priority box is designed to vary based on the demand, service rate and road geometry at different intersections.

Table 1: Bus Right Turn Priority Box Step-by-Step Guide: Example at the Intersection of Parramatta Road and Norton Street, Leichhardt, Sydney Metropolitan, Australia.

1: Offset turning traffic to accommodate bus right turn priority box 	2: Buses use through traffic lanes to overpass and wait in front of the right turn queue 
3: Eliminate the offset right turn signal to allow other vehicles to use the unused part of the priority box 	4: Buses turn right first during the right turn phase 

At the intersection of Parramatta Road and Norton Street, the bus right turn priority box is set as 40 meters, which can serve two buses per signal cycle which has a service rate of about one bus per minute. Based on the bus demand and cycle length at this intersection, a 40-meter bus right turn priority box is sufficient to serve approaching buses. While designing the bus right turn priority box length is critical, insufficient length could result in bus queue spilling back onto the through traffic lanes, which could significantly reduce the intersection efficiency particularly during peak hours.

The travel time for the right turn buses with priority box is estimated based on the time saved using through lanes to skip the right turn queue. The through-lane bus travel speed is used for estimating the right turn with priority box trajectory speed before the bus enters the bus right turn priority box. The bus delay per cycle at the intersection for the right turn movements remains, which is about 50 seconds, assuming buses can go through the intersection within one cycle with the bus right turn priority box.

4. Result

4.1. Statistical significance of right turns

The T-test conducted on the mean values of bus-stop-to-bus-stop marginal delays between segments with right turns and those without right turns within the studied area (Figure 5) yielded a T-statistic value of 315.30 and a P-value of 0.00. Similarly, the T-test conducted on the

standard deviation values of bus-stop-to-bus-stop marginal delays (Figure 6) returned a T-statistic value of 435.97 and a P-value of 0.00. A P-value smaller than 0.05 in a T-test indicates that the result is statistically significant. These results confirm that significant differences exist in the distribution between segments with and without right turns. This evidence supports the claim that performing right turns reduces both bus operation speed and reliability.

Figure 5: Bus-stop-to-bus-stop Marginal Delay Mean Value Comparison.

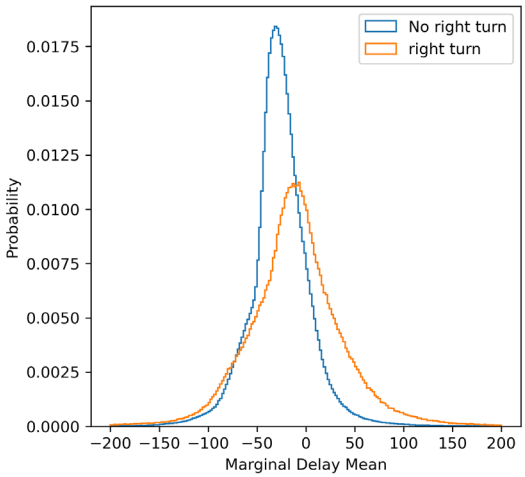
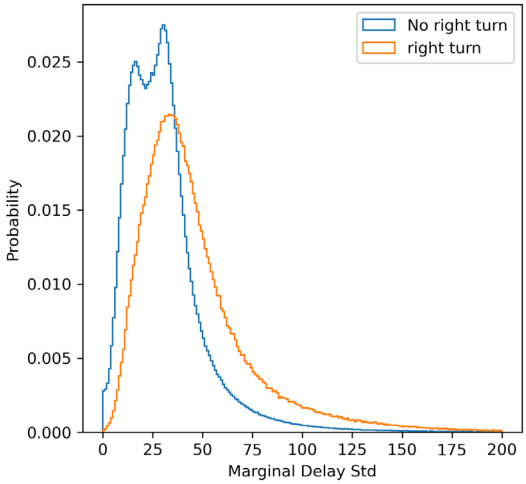


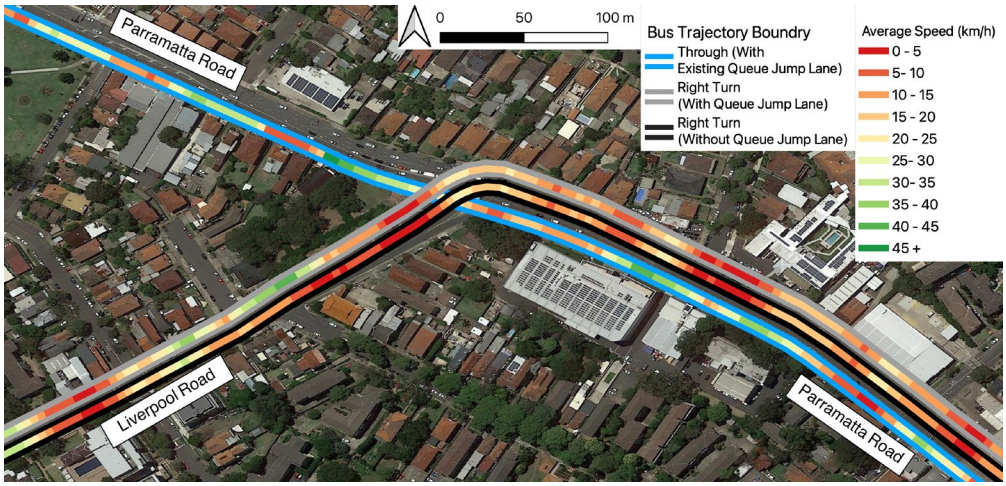
Figure 6: Bus-stop-to-bus-stop Marginal Delay Standard Deviation Value Comparison.



4.2. Microscopic analysis: Queue jump lanes

Figure 7 shows the estimated speed map at the intersection of Parramatta Road and Liverpool Road using GTFS-Realtime Vehicle Positions data. The inner right turn trajectory indicates the original speed estimate, whereas The outer right turn trajectory indicates the speed estimate with queue jump lanes. Speed improvements occur as the buses approach the intersection after the outer right turn lane is converted into a bus only lane (Figure 4), which reduces the bus right turn queuing time at this intersection.

Figure 7: Microscopic Speed Map at the Intersection of Parramatta Road and Liverpool Road, Ashfield, Sydney Metropolitan, Australia.



The quantified results are shown in Table 2 indicating a 42-second time saving with the proposed bus queue jump lane. Even though the right turn delay is still higher than the through traffic, the improvement is relatively significant because the through traffic is prioritised.

Transit agencies should consider implementing right turn queue jump lanes where bus right turn demand is significant. The major challenge within the urban environment is the space required for implementing right turn queue jump lanes. Delay increases to other vehicles are worth consideration while implementing queue jump lanes, and will be explored later in this study.

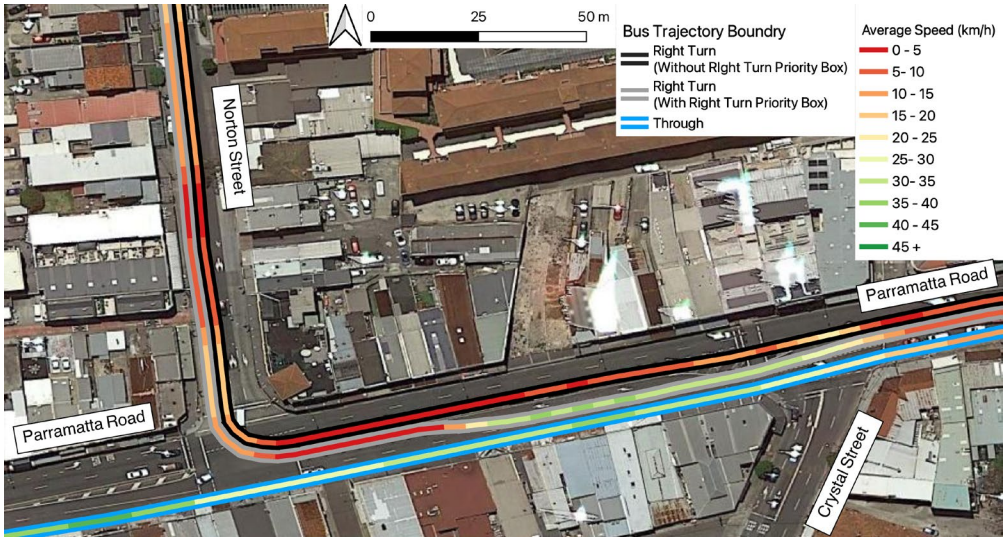
Table 2: Time Savings with Priority at the Intersection of Parramatta Road and Liverpool Road, Ashfield, Sydney Metropolitan, Australia.

	Through traffic	Right turn	Right turn with priority
Travel Time (s)	194.69	311.37	268.60
Difference with right turn	-116.68	-	-42.77

4.3. Microscopic analysis: Bus right turn priority box

Figure 8 shows the estimated speed map at the Intersection of Parramatta Road and Liverpool Road using GTFS-Realtime Vehicle Positions data. The inner right turn trajectory indicates the original speed estimate, whereas the outer right turn trajectory indicates the speed estimate with the right turn priority box. Speed improvements occur before the buses enter the priority box.

Figure 8: Microscopic Speed Map at the Intersection of Parramatta Road and Norton Street, Leichhardt, Sydney Metropolitan, Australia.



The quantified results are shown in Table 3 indicating a 53-second time saving with the proposed bus right turn priority box. With priority measures, the bus right turn travel time is similar to the through traffic travel time as buses mostly use the through lanes before the intersection. The bus right priority box is able to reduce the bus right turn travel time while not reducing lanes for other traffic within limited road space. The effect of the bus right turn priority box on other vehicles is expected to be minor, except for causing the right turn queue to spill back further away from the intersection. While implementing the right turn bus priority box, the right turn lanes might need to be extended to overcome the queue spillback effects. This study plans to use microscopic simulation to further examine the performance of the bus right turn priority box which includes time bus travel time saving, bus reliability improvements and effects on other traffic.

Table 3: Time Savings with Priority at the Intersection of Parramatta Road and Norton Street, Leichhardt, Sydney Metropolitan, Australia.

	Through traffic	Right turn	Right turn with priority
Travel Time (s)	306.69	389.74	336.87
Difference with right turn	-83.05	-	-52.87

5. Discussion and conclusion

With the high T-statistic and low P-values, this study demonstrates the statistical significance of the mean and standard deviation of stop-to-stop marginal delays caused by right turns. In our previous study using panel regression, we found that each right turn results in 26 s of stop-to-stop marginal delay and has the same unreliability effects as about 13 traffic lights and 900 vehicles added on each lane and each hour (Xian et al. 2023). The findings in this study further proves that right turns during bus operation not only lead to schedule delays but also to service unreliability. Hence, buses making right turns is a significant concern for bus operations. To maintain quality bus service, transit agencies should consider various strategies such as minimising right turns, avoiding such turns at congested intersections, performing early or late right turns to avoid congestion, and reducing lane changes required for right turns during route planning.

For mitigating bus right turn delays, especially at intersections with significant bus right turn demand and traffic congestion, bus priority measures such as queue jump lanes, transit signal priority, and bus right turn priority box should be considered. The bus queue jump lane requires large road surface and is not typically used for bus right turns. The bus queue jump lane is a viable solution for reducing bus right turn delays where lateral space is not relatively limited. Where lateral space is limited, the innovative bus right turn priority measure, the bus right turn priority box, which is an in-lane right turn queue jump lane, is recommended. The real-data estimates prove that both the bus queue jump lane and the bus right turn priority box can reduce bus right turn delay effectively. The studies by Saberi et al. and Chang et al. prove that bus delay is a source of bus unreliability. This suggests that reducing travel time at intersections where bus delays occur should improve reliability (Saberi et al. 2013, Chang et al. 2003).

Even though the benefits of the bus right turn priority measures introduced in this study are estimated based on real-time data, the results seem reasonable. The claims regarding the benefits of the bus right turn priority measures could be strengthened with validation from traditional measuring methods such as analytical techniques and simulations. The negative effects of the bus right turn priority measures on general traffic have not been examined. A future step in this study is to conduct microscopic traffic modelling to further assess the effects of the proposed priority measures on both buses and other vehicles by considering various bus and general traffic demand scenarios.

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