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Evidence from GTFS-R that Bus Priority Lanes reduce Marginal Delay

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ABSTRACT: Bus priority measures such as bus lanes have been widely deployed in order to improve bus performance and attract ridership. The validation of these expected benefits has usually been done at the aggregate level with tolerances for acceptable delay. Newer data sources allow us to track micro delays and relate them to spatially detailed bus priority data. Because schedules are adjusted to account for the benefit of bus priority measures, we hypothesise that bus lanes will result in small reductions in expected delay relative to the schedule even when assessed to the second and at the bus-stop-to-bus-stop level. We further hypothesise that the benefit of bus lane priority measures can be seen in the reduction in the variability of delay relative to the schedule.

This study aims to use the GTFS arrival delay data for Sydney from June 2020 to March 2022 in order to analyse the effect of bus-stop-to-bus-stop route characteristics data on bus stop-to-stop marginal delay. This working paper shows the first result using GTFS arrival delay data from March 2021 (i.e. one month) only. The delays are modelled using panel regression with marginal delay and standard deviation of marginal delay as the dependent variables. The independent variables include the presence of priority measures, the traffic volumes, the number of traffic signals and the scheduled travel time.

We find that the bus-taxi lanes and bus-HOV lanes are effective in reducing variation in the stop-to-stop marginal delay. The impact on marginal delay itself is mixed due to the interaction of demand, schedule adjustments and the priority measure. These findings quantify the benefits of bus priority measures at a microscale.

KEY WORDS: ***GTFS-R, Marginal Delay, Bus Lanes, HOV Lanes, Bus Priority***

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1. INTRODUCTION

High quality public transport is a cornerstone strategy for managing urban congestion. Appropriate infrastructure investment can improve the on-time performance of public transport, thus improving its attractiveness when compared to private vehicles. Bus lanes can achieve over five times higher passenger capacity compared with mixed traffic lanes with a relatively lower vehicle frequency [1]. On congested urban corridors, bus priority schemes have been deployed worldwide to ease traffic pressure by enhancing bus service attractiveness [2].

Common bus priority schemes included reserved bus-HOV lanes, bus-taxi lanes, bus-only and dedicated rights of way (busways), as well as traffic signal priority [3]. Bus lanes, as well as other bus priority treatments, claim intuitive benefits in improving bus performance such as delay and reliability [4].

Delay reflects the performance relative to the schedule with important implications for riders undertaking their journeys and operators managing fleet and personnel. The variability of delay represents the reliability, which is needed for riders to estimate buffer times in their journey plans.

Quantifying the benefit of bus priority treatment relies on detailed data usually not available to the public. The emergence of the General Transit Feed Specification (GTFS) Realtime data makes this information available for validation of the expected benefits, such as micro-delay reduction from bus lanes. Notably, this data supports the analysis of micro delays measured by combining on-board GPS equipment with geofenced stops [5].

Previous reporting would have relied on temporal aggregations and accepted margins for on-time arrival. With real-time delays measured to the second, this study aims to quantify the effect of bus priority lanes on bus stop-to-stop marginal delays using one month of GTFS data from the Sydney bus network as a case study. The stop-to-stop marginal route characteristics data, such as type of bus lane, traffic signals and traffic flow, will be spatial correlated with the stop-to-stop marginal delay. Panel regression will be used to relate the performance to marginal determinants.

This study aims to find the general effects and effectiveness of each marginal determinants on bus performance and aims to derive benefits for improving the bus network in Sydney and also enhancing the bus performance globally.

2. LITERATURE CONTEXT

A. Stop-to-stop Marginal Delay

The term marginal delay is useful to measure the bus performance between pairs of successive stops at a microscopic level. Both Yan et al. and Kaddoura et al. defined the marginal delay as 'the difference in schedule delays for a bus trip between pairs of successive stops' [6, 7]. This measure isolates the contribution to the delay that can be attributed to stop-to-stop attributes such as bus lanes and traffic lights. This study will use the bus marginal delay to define microscopic bus performance indicators and model the effect of the independent variables.

Aemmer et al. studied marginal delay using GTFS Realtime data retrieved from the King County Metro bus network in Seattle. The study categorised the delay into systematic delays which is predictable and stochastic delay which is due to the randomness at the stop-to-stop links. The study stated that the proactive infrastructure changes, including bus lanes and public transport signal priority, may be effective at improving bus efficiency and reliability, but the effects are not quantified. This study aims to demonstrate that GTFS Realtime data is suitable to measure the stop-to-stop marginal delay [8].

B. Bus Priority Lanes

B.1. Bus Lanes

With proper enforcement, bus lanes can successfully provide priority to buses by reducing travel time and increasing travel reliability at a relatively low cost and short implementation time [9]. Data limitations have meant that the effectiveness of the bus lanes has not been comprehensively measured using real-time data. Many studies suggest that the reliability measurements are more critical than other bus measurements such as speed, comfort and frequency [8, 10]. As a result, most prior studies for bus lane efficiency are measured by bus travel reliability.

Sterman and Schofer's study, as well as Abkowitz and Engelstein's study, both found that many factors, including route length, intersection control, traffic volumes and passenger loads, could significantly degrade the bus travel reliability [11, 12]. Strategy techniques such as decreasing the route length and improving intersection control by prioritising buses can improve bus travel reliability.

B.2. HOV Lanes

HOV lanes are proven to reduce some travel time for high occupancy vehicles, which include buses and significantly increase the person capacity of the road corridor by encouraging carpooling. Increasing the person capacity of a road corridor within a limited space can significantly improve the overall corridor performance [13]. HOV lanes are widely used in the United States and less commonly used in Australia. In the US, the HOV lanes are mainly placed in the middle of the highway and designed to serve the general traffic, whereas the HOV lanes are typically placed on the curbside lane and are heavily used by buses in Australia. Although buses are one of the major user categories for HOV lanes in Australia, the bus benefits from HOV lanes have not been measured before. This study will be one of the first to evaluate bus-HOV lanes.

B.3. Taxi Prohibition

Shalaby's simulation study concluded that the prohibition of taxis on the bus priority lane had caused more performance deterioration to adjacent traffic than the performance improvements to the buses on the bus lane [2]. As the bus density increases, it is expected that the presence of taxis in a bus lane would contribute to more deterioration in bus performance.

C. Traffic Signals

As buses generally travel in a mixed traffic scenario, traffic signals are required at intersections where significant conflicts among traffic occur. Wang et al. studied the effects of public transport signal priority on bus reliability at stop-to-stop segments. Wang et al. suggest that to study the effects of a stop-to-stop segment between two bus stops, design elements including two bus stops, intersections and road links should be considered [14].

Granting signal priority and implementing bus lanes are two typical strategies to improve the buses' speed and reliability. Even though bus lanes can be effective in improving bus prioritization through the corridor, most of the bottlenecks happen at intersections where public transport signal priority is required. Previous studies have defined the signal priority into three strategies: passive, active and adaptive control [9]. Passive public transport signal priority used the fixed signal timings to optimize based on historical bus data. The passive signal priority neglects the bus arrival patterns as well as real-time performance, which means only the on-schedule bus will benefit from the signal priority [15]. The active public transport signal priority detects the arrival of buses and gives priority to buses based on the real-time arrival of the buses using typical signal priority treatments, including early green and green extensions. Compared with passive signal priority, active signal priority accommodates for early and late arrival buses, which improves bus priority [16]. Adaptive public transport signal priority optimizes the traffic performance of both bus and private vehicles by using real-time data collections [16]. By considering traffic flow for both buses and private vehicles, the adaptive signal priority can optimize for the total delay while giving buses priority.

The adaptive traffic signal is widely used in the Greater Sydney Area. To our best knowledge, the public transport priority engine in SCATS, which is the adaptive traffic signal control system used in Sydney, has been deactivated in most of the road corridors. Therefore, only very limited signal priority has been given to public transport in Sydney. The locations of the activated public transport priority signal are not known. As a result, the traffic lights have not been categorized in this study due to the lack of information.

D. Australian Guidelines

Austroads is the collective of the Australian and New Zealand transport agencies. The Austroads's guidelines provide practical advice on the design, management and operation of road networks for all three levels of government (federal, state and local) [17]. As a practical guideline, the Austroads's guideline is not compulsory for the transport agencies in Australia and New Zealand. As a result, different states in Australia might have different geometric designs that have impacts on bus performance. The Austroads guideline suggests that bus services should provide acceptable ride quality and minimise the delay while travelling. The guideline suggests that the horizontal (kerbside vs floating) and vertical (continues vs set-back) bus lanes, intersection layouts, mid-block curves and gradients have effects on bus performance.

The guideline states that the bus stops on the through traffic lanes may cause delays, hazards and reductions in capacity for other traffic. The traffic volume, number of buses and the location and type of bus stops should be considered while designing the bus stops. This issue is more critical on major urban roads where the full width of the carriageway is generally required for the through traffic. The guideline suggests that the indented bus bay can provide safety for both buses and through traffic. Even though the indented bus bay can improve the efficiency of the carriageway, it could cause difficulties for buses to re-enter the heavy traffic flows. Some of the state road agencies have policies to limit the installation of the indented bus bay, which aims to improve the bus operational performance. The guideline suggests that the indented bus bay may be considered for the bus stop, which can be used as a timing point, a driver change point and a particularly high loading bus stop.

3. METHODOLOGY

A. Study Area

This study analyses the buses in neighbouring suburbs around the Sydney CBD area (see Figure 1). The study area is determined to focus on tidal flow from and towards Sydney CBD. Job centres such as Macquarie Park and Chatswood, which might have effects on the tidal flow, are avoided. Due to the significantly different traffic environment inside Sydney CBD, the CBD is not included in the study area. Several corridors within the studied area have bus priority treatments, including bus-taxi lanes and bus-HOV lanes in some sections. All of the bus stop-to-stop segments within the studied area are analysed.

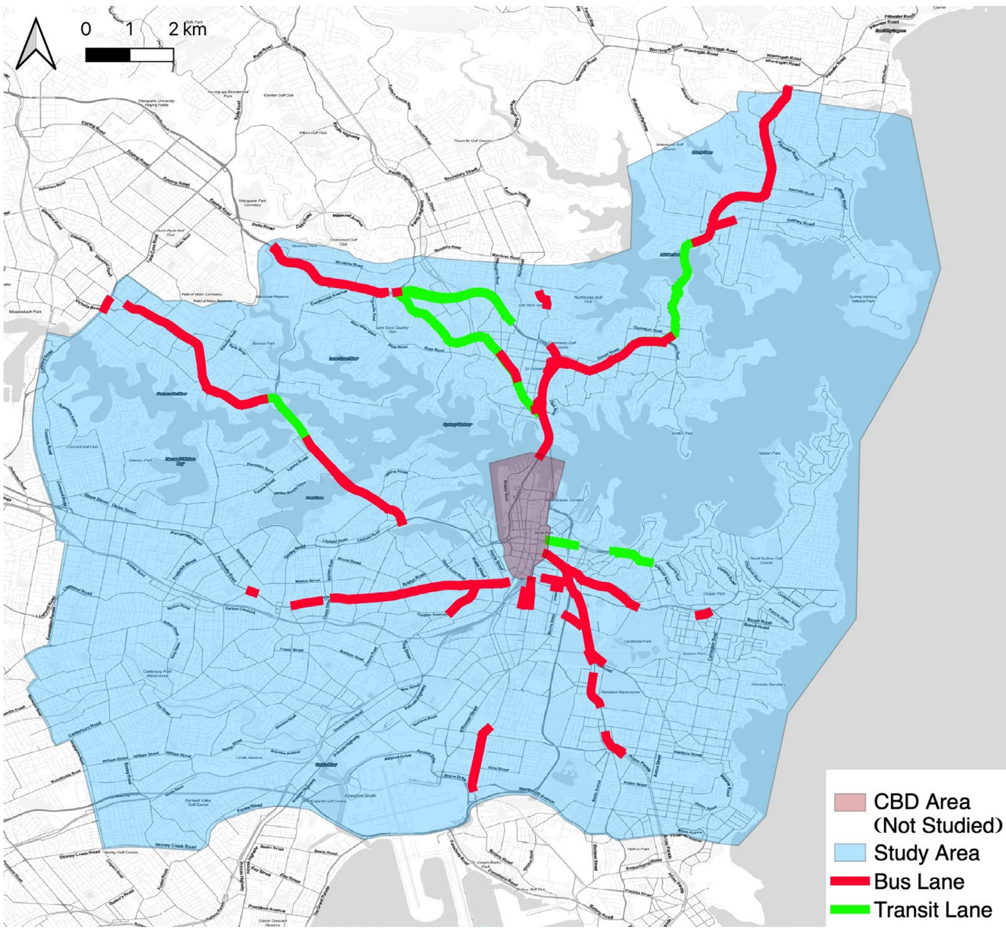

Fig. 1. Studied Area: Suburbs around Sydney CBD

B. Data

This study uses several datasets from New South Wales (NSW) to study the effects of bus priority lanes on marginal delay (Table 1). The GTFS-Realtime dataset has the real-time bus schedule delay estimate as temporal data, which is used to find the stop-to-stop marginal delay. The Clearway data and Signalised Intersections data contain spatial route information, which are used to find the stop-to-stop route characteristics. The GTFS-static dataset has both spatial bus information for trajectory and stop location and temporal bus information for schedule and stop sequence, which is used to correlate the GTFS-Realtime dataset and the stop-to-stop route characteristics.

B.1. GTFS-Static

The General Transit Feed Specification (GTFS), also known as GTFS-static, is the common format for public transport schedules and associated geographic information. The GTFS-static data contains temporal elements, including the bus schedule and bus stop sequence information and spatial elements, including the trajectories for each bus route and bus stop locations [18]. The GTFS-static data was downloaded from the Transport for NSW (TfNSW) Open Data Hub.

Table 1. Data Source and Information Contained

Data Name	Source	Information Contained
GTFS-Static	Transport for NSW	Route Trajectory Schedule Bus Stop Location and Sequence
GTFS-Realtime	Collected using Transport for NSW's Open API	Arrival Delays
Clearway Data	Transport for NSW	Bus Lane Location Operating Hours
Signalised Intersections Data	Transport for NSW	Location of Traffic Signals
Traffic Volume Viewer	Transport for NSW	Network Hourly Flow

B.2. GTFS-Realtime

The GTFS-Realtime dataset is an extension to the GTFS-static. GTFS-Realtime contains real-time public transport operational information by collecting real-time updates provided by the transit agencies. The GTFS-Realtime has three types of data feeds: Trip Updates, Service Alerts and Vehicle Positions. This study will use the GTFS-Realtime Trip Updates, which provides real-time delay estimates for buses [19]. Hence, the comparison of real-time transport performance data from GTFS real-time against the schedule data of GTFS static enables the user to assess bus service performance both in real-time and in a historical context. The GTFS real-time data was collected using TfNSW's GTFS API. The data was cleaned and processed into daily csv files.

B.3. Clearway Data

In NSW, a clearway is a road section where stopping and parking are prohibited with the intention of improving traffic flow during peak hours [20]. The clearway data set provided by TfNSW's Open Data Hub contains bus lane information. The bus lanes data, which is categorised as bus-only lanes, bus-taxi lanes and bus-HOV lanes, was filtered and cleaned from the clearway dataset. The bus-only lanes only permit buses and emergency vehicles to use the lanes. Bus-taxi lanes permit buses, taxis and emergency vehicles to use the lane. Bus-HOV lanes permit all vehicles that have high occupancy to use the lane, which are categorised as T2 (HOV lanes for vehicles with two and more passengers) and T3 (HOV lanes for vehicles with three and more passengers) lanes in NSW (these are shown as Transitways on Figure 1). Even though the HOV lanes are primarily for high occupancy vehicles, buses benefit from HOV lanes.

Due to significant errors in the clearway data set, it was first cleaned by dropping duplicates. When duplicates are found, the more accurate result is kept. The clearway dataset will be further checked against Google Maps Street View during corridor analysis. Multiple formatting had been found for the bus lane operation time of the day, which cannot be directly used for time of the day analysis. Four study time periods are set for weekday analysis: Morning Peak, Between Peak, Evening Peak and Off Peak. Two study time periods are set for the weekend analysis. The bus lane operation time for each of the studied time periods is recorded.

B.4. Signalised Intersections Data

The signalised intersections data provided by the TfNSW Open Data Hub contains the locations and the installation time of the signalized intersections within NSW. This data set is used to spatial join with the stop-to-stop trajectories to calculate the number of traffic lights at each stop-to-stop link which is one of the route characteristics.

B.5. Traffic Volume Viewer

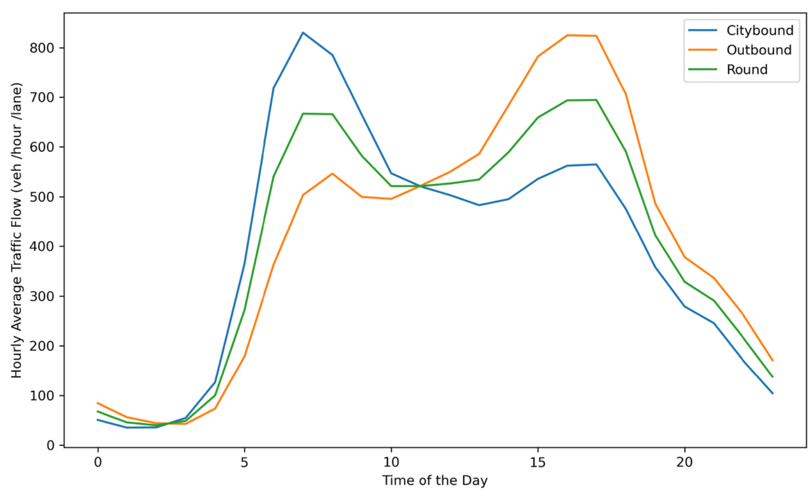

Fig. 2. Traffic Volume Data

The TfNSW's Traffic Volume Viewer provides the archived real-time traffic volume counts at a number of sites within NSW. The average hourly flows per lane among eight sites within or near the studied area in Sydney are calculated and used as a traffic flow indicator. The traffic volume data provides traffic counts in both citybound and outbound directions. For the buses going neither citybound nor outbound, the average traffic volume between citybound and outbound is used, which is the line 'Round' shown in Figure 2. The average hourly flows are tabularly joined by time and direction with the stop-to-stop marginal delay.

C. Spatial Correlation

The datasets with road characteristics information mentioned above are spatially joined with the stop-to-stop trajectory generated from GTFS-static. With the road characteristics data spatial correlated with the marginal delay, the effects of bus lanes on bus marginal delay can be found.

C.1. Stop-to-Stop Trajectory

The bus stop locations and bus trajectories are used to generate the trajectories for each stop-to-stop link. The stop-to-stop trajectory was generated from shape files from the GTFS static files, which records the bus travel path. The shape files show the full travel path of each bus trip, which is from the origin to the destination. To analyse the bus operational performance stop-to-stop, which is the link between two stations, the shape files are cut by stop locations. Thus, each shape file which is the origin to the destination of the bus trip are cut into many sections, which are the path between adjacent stop pairs. The stop-to-stop trajectory is correlated with the marginal delay measurement from GTFS-Realtime, which is used for spatial correlation with the other road link characteristics. The length of each stop-to-stop link is also calculated based on the shapefile length, which is used as of the dependent variables in the regression model.

C.2. Stop-to-Stop Bus Lane Information

The stop-to-stop bus lane information is generated by merging the priority lane data and the stop-to-stop trajectory. The directions (bearing degree) are calculated for each bus lane shape file as well as for the stop-to-stop trajectory. The direction is used to prevent errors in spatial joins, such as the westbound trip merging with the eastbound bus lane. The operational hours for each bus lane are considered while merging. The effective length and type of the bus lane are recorded for each of the stop-to-stop trajectories while merging.

C.3. Stop-to-Stop traffic lights

The number of traffic lights at each stop-to-stop link is calculated by spatially joining the location of the traffic lights from signalised intersections data with the stop-to-stop trajectories.

D. Marginal Delay

The definition of marginal delay used in this study is the difference between stop-to-stop travel time and the free flow travel time, which is the additional travel time due to the effects of factors including added traffic volume and traffic lights. The marginal delay is an indicator of marginal delay compared with the free flow scenario measured in seconds.

E. Regression Analysis

Panel regression is used because there are repeated measures of the same stop-to-stop links leading to correlation in the errors [21]. The model specification describes the stop-to-stop marginal delay as a function of the route's attributes. The panel data were clustered by location (stop-to-stop links) and time (hours). The model specification is given in the Equation below and the variables are explained in Table 2.

$$\Delta_{it} = \alpha_i + \beta_B B_i + \beta_H H_i + \beta_S S_i + \beta_D D_t + \beta_V V_{it} + \epsilon_{it}$$

Table 2. Variables used in Panel Regression Model

Symbol	Name	Units
Δit	Marginal Delay Change at link i time t	Seconds
α_i	Link-specific effects	
β	Fitted coefficients	
B_i	Bus-taxi lane proportion on link i	%
H_i	Bus-HOV lane proportion on link i	%
S_i	Number of traffic signals on link i	
D_t	Traffic flow at time t	10^3 veh/(hour× lane)
V_{it}	Scheduled speed at link i time t	kph
ϵ_{it}	Error term	

4. RESULTS

A. Peak Hour Effects Regression

The bus priority lane operation time and traffic conditions are significantly different during different time periods in Sydney, which lead to changes in variable effects. For example, the traffic lights cause more delays during the peak period than the non-peak period. To overcome this issue, the peak hour effects regression model splits the full dataset into four different time groups and models each of the individual time group separately (Table 3). The four time groups are: AM Peak (6-10 AM), Between Peak (10 AM - 3 PM), PM Peak (3-7 PM) and Off Peak (7 PM 6 AM), which is based on TfNSW's peak period definition. Due to the low number of Bus-HOV lanes active during non-peak hours, Bus-HOV lanes are not considered in the Between Peak and Off Peak models.

Among all four models, the Bus-taxi lanes are generally effective in reducing marginal delay. Each of the traffic light increases the marginal delay by about 2-11s during the day. As traffic volume increases, which means the congestion level increases on the network, the marginal delay reduces. As the scheduled travel time increases, which means a longer stop-to-stop segment, the marginal delay decreases. Both of the negative coefficients in traffic flow and scheduled travel time could possibly be due to the schedule padding from the transit agency. The schedules are set up before the COVID pandemic. As the traffic volume decreased with the onset of the pandemic, the buses are expected to run faster. The previous schedule padding might be too high for post-COVID traffic conditions.

Table 3. Marginal Delay Time Segment Regression Model

Time Period	Variable	Coefficient	Std. Err.	P-value	R^2
AM Peak	Bus-taxi lane proportion	-10.942	0.3897	0.0000	0.0958
	Bus-HOV lane proportion	-2.1398	0.7560	0.0046	
	Number of Traffic signals	7.8770	0.0975	0.0000	
	Traffic Flow	-34.962	0.2352	0.0000	
	Scheduled Travel Time	-0.4029	0.0019	0.0000	
Between Peak	Bus-taxi lane proportion	-1.8068	0.7746	0.0197	0.0934
	Number of Traffic signals	2.4070	0.0853	0.0000	
	Traffic Flow	-66.178	0.2748	0.0000	
	Scheduled Travel Time	-0.1743	0.0013	0.0000	
PM Peak	Bus-taxi lane proportion	-12.493	0.4529	0.0000	0.0745
	Bus-HOV lane proportion	2.0678	0.8673	0.0171	
	Number of Traffic signals	10.747	0.0992	0.0000	
	Traffic Flow	-36.004	0.2375	0.0000	
	Scheduled Travel Time	-0.3946	0.0020	0.0000	
Off Peak	Bus-taxi lane proportion	-7.4276	0.9154	0.0000	0.0100
	Number of Traffic signals	-5.1945	0.0910	0.0000	
	Traffic Flow	-20.485	0.4933	0.0000	
	Scheduled Travel Time	-0.0028	0.0001	0.0000	

Bus-taxi lanes are found to be more effective during peak hours compared with non-peak periods, which means bus lanes provide more benefits for buses under high traffic volume. Bus-HOV lanes coefficients are significantly different between AM and PM peaks, which is possibly due to the small sample size as well as the lack of priority enforcement on Bus-HOV lanes in Sydney. The variety in Bus-HOV lane location and tidal traffic flow patterns also contribute to the unrobustness of Bus-HOV lane coefficients. The traffic signal increases the marginal delay during the day, whereas during the night, the traffic signal reduces marginal delay, which could possibly be due to the over schedule padding as well as the SCATS traffic control system (where it is operational) providing more priority to the main roads during low traffic volumes.

B. Marginal Delay Between-Effects Panel Regression

The Between-Effects panel regression model is an OLS model using the mean value of each cluster. It is an effective measure to study the correlation among clusters but loses the variety within the clusters. The Between-Effects panel regression model (Table 4) shows the effects of the variables but ignores the variety in time within each cluster. Both the Bus-taxi lanes and Bus-HOV lanes reduce the marginal delay. Similar to the other models, the P-value for the Bus-HOV lane is higher than the other, which represents an increased uncertainty for the Bus-HOV lane effectiveness. Each traffic light increases the marginal delay by about 3s. Every thousand vehicles added to each lane each hour reduces the marginal delay by 38s. A thousand vehicles added to each lane each hour is typically more than the variety between midnight and peak hour in most places. The result indicates that, on average, around 30s of scheduled travel time padding is added onto each stop-to-stop segment during peak periods, and every 1s of scheduled travel time contains 0.08s of schedule padding time.

Table 4. Marginal Delay Between-Effects Panel Regression Model

Variable	Coefficient	Std. Err.	P-value
Bus-taxi lane proportion	-19.304	4.8017	0.0001
Bus-HOV lane proportion	-6.9203	10.012	0.4895
Number of Traffic signals	2.5349	0.5211	0.0000
Traffic Flow	-38.054	1.3226	0.0000
Scheduled Travel Time	-0.0758	0.0086	0.0000
Number of clusters	6158		
R^2	0.2708		

C. Stop-to-stop links Within-Effects Regression Models

The stop-to-stop links within-effects regression model split the full dataset into 6158 clusters where each cluster is a stop-to-stop link and models each of the clusters separately. Only stop-to stop links with bus lanes are used to study the effects of bus lanes to produce the Within-Effects model. Two different models are presented in this section.

C.1. Three Independent Variable Model: With Bus-taxi Lane, Traffic Flow and Schedule Travel Time

For each of the stop-to-stop clusters, this model considers three variables: Bus-taxi Lane, Traffic Flow and Schedule Travel Time. Due to the constant value in the number of traffic lights in each stop-to-stop segment and the small number of Bus-HOV lanes, the number of traffic lights and the Bus-HOV lanes cannot be used as a variable for the Within-Effects model. Even though the Between-Effects model shows robust results with mostly low P-value, the parameters for regression models built using each of the stop-to-stop clusters, which means the stop-to-stop segment condition could be significantly different in Sydney.

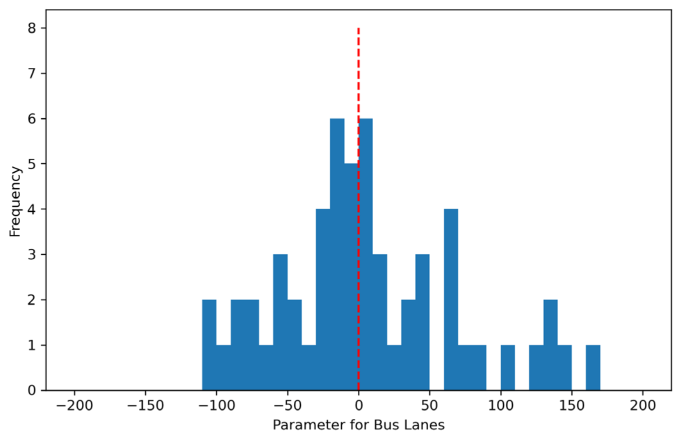

Fig. 3. Bus-taxi Lane Proportion Parameters Distribution by Marginal Delay between Stops with Stop-to-stop Link Three Independent Variable Within-effects Panel Regression

Figure 3 shows the distribution of Bus-taxi lane proportion parameters. Most of the parameters are skewed towards 0. Overall, the data is slightly more skewed towards negative, which leads to the negative coefficient in the Between-Effects model (Table 5), but the bus lanes in different stop-to-stop links could have significantly different effects.

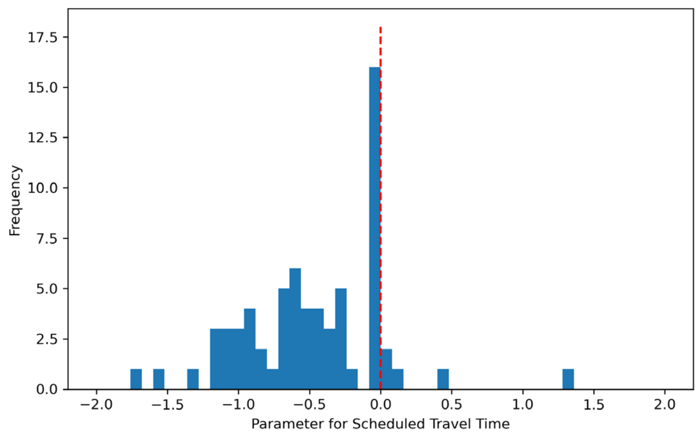

Fig. 4. Scheduled Travel Time Parameters Distribution by Marginal Delay between Stops with Stop-to-stop Link Three Independent Variable Within-effects Panel Regression

Figure 4 shows the distribution of scheduled travel time parameters. The distribution is skewed to the negative region, which shows that in most of the stop-to-stop clusters as scheduled travel time increases, the marginal decreases, indicating that schedule padding in the studied time is slightly over.

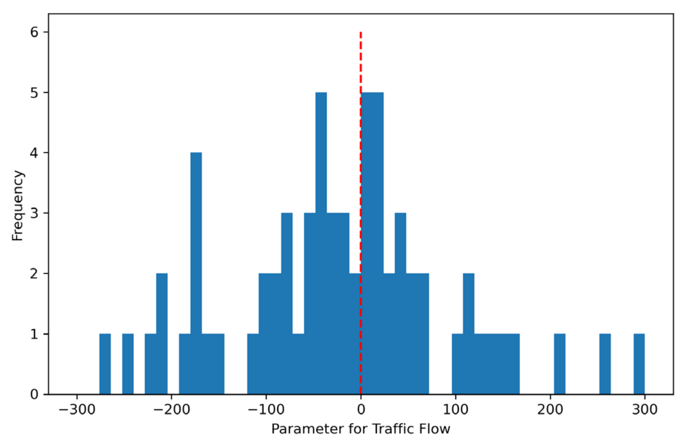

Fig. 5. Traffic Flow Parameters Distribution by Marginal Delay between Stops with Stop-to-stop Link Three Independent Variable Within-effects Panel Regression

Figure 5 shows the distribution of traffic flow parameters. A large variety could be seen, meaning traffic flow effects vary based on location. The schedule padding is high in the stop-to-stop links with low traffic flow parameter values and low in the stop-to-stop links with high traffic flow parameter values.

C.2. One Independent Variable Model: Bus-taxi Lane Only

This model only considers one independent variable: The bus-taxi lane proportion parameter (Figure 6). This model is designed to show the correlation between Bus-taxi lane proportion and marginal delay. By removing significant outliers, the One-tailed T-test results show a 72.76% confidence that the Bus-taxi lane proportion parameter is negative, which means most of the Bus-taxi lane reduces marginal delay.

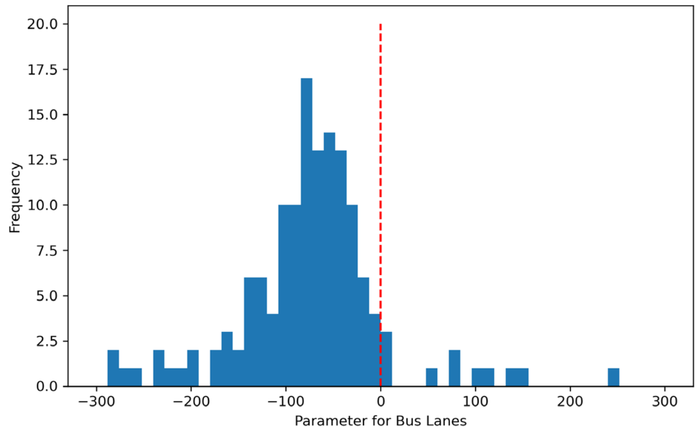

Fig. 6. Bus-taxi lane proportion parameters distribution by Marginal delay between stops with stop-to-stop link within-effects panel regression.

D. Between-Effects Std Regression Model

Between-Effects std regression uses the std value of marginal delay from each stop-to-stop segment as the dependent variable. In Table 5 the negative signs for the Bus-taxi and Bus-HOV lane proportion indicate a reduction in marginal delay variety. Even though the P-values for Bus-taxi lane and Bus-HOV lane proportions are a bit high, due to the variety in Bus-taxi lane and BusHOV lane effects in different locations, it can be found that both Bus-taxi lane and Bus-HOV lane are effective in reduction marginal delay variety. The bus priority lanes in this study improve bus travel reliability.

The positive signs for the number of traffic signal, traffic flow and scheduled travel time indicates an increase in marginal delay variety, which adds uncertainties to schedule adherence. On average, every additional 24 vehicles per lane per hour in traffic flow or additional 200s has the same negative effects on travel reliability as one traffic light.

Table 5. Marginal travel time increase from free flow travel time per kilometre with Between-Effects panel regression.

Variable	Coefficient	Std. Err.	P-value
Bus-taxi lane proportion	-10.156	6.9603	0.1446
Bus-HOV lane proportion	-7.6652	14.064	0.5857
Number of Traffic signals	5.2479	0.7546	0.0000
Traffic Flow	217.24	1.9172	0.0000
Scheduled Travel Time	0.0263	0.0124	0.0346
Number of clusters	6158		
R^2	0.8161		

5. DISCUSSION

This study pilots the use of GTFS-Realtime to assess the micro-level performance of bus priority lanes based on detailed infrastructure measurements. With a month of data across the Sydney metropolitan area, the results in this study show that both bus-taxi lanes and bus-HOV lanes improve performance. While there is an impact on the overall marginal delay, the main benefit is seen in the variation of marginal delay due to the interaction between the priority measures, the schedule adjustment and the traffic volumes. The results further suggest suitable bus priority treatments related to signalised intersections could be effective in achieving schedule adherence.

Overall, most of the parameters for Bus-taxi and Bus-HOV lanes are negative in the models, indicating that both Bus-taxi and Bus-HOV lanes are effective in the studied area. The data is taken from the COVID-19 period, where the reduced traffic volumes resulted in many buses arriving ahead of schedule. The study shows that only a limited number of bus lanes are implemented in Sydney. As bus lanes effectively improve bus travel reliability, there is a case for further development of the bus priority network.

It is found that Bus-HOV lanes generally have a higher P-value than Bus-taxi lanes. The results indicate that the benefits of Bus-HOV lanes are not as reliable as bus-taxi lanes. This could possibly be due to the lack of lane painting and law enforcement in Sydney. Based on casual observations, it is hard to distinguish the Bus-HOV lanes from the regular traffic lanes due to the lack of surface painting. It is expected that with a larger dataset with a longer time span, the difference in effects between bus-taxi lanes and bus-HOV lanes can be more significant, which will be beneficial in deciding on the use of different types of bus lanes.

Due to the small size of the dedicated busways in the studied area, the dedicated busways are categorised as bus-taxi lanes. With the dedicated right of way, it is expected that the dedicated busways improve the bus reliability compared with the bus-taxi lanes. With an expanded studied area, it is expected to model the effects of dedicated busways.

Traffic lights are found to have increased effects on marginal delay. This indicates the lack of bus signal priority in the studied area. To enhance bus travel reliability, transit signal priorities are essential to be considered.

The reduction in delay between stops could result in early running bus. Early running buses impact the passenger experience because the early running buses can result in more waiting time for passengers than late buses. The standard deviation regression model can be used to model the variety in order to consider the negative value in marginal delay.

The scheduling principle might have a significant impact on marginal delay. The results indicate that most of the stop-to-stop links are over in schedule padding, possibly due to the reduction in bus travel time as the traffic volume reduced during the COVID pandemic. Due to the lack of information on TfNSW's schedule padding principle, this study cannot quantify the schedule padding. It is suggested that the transit agency update the public transport schedule to adopt post-COVID travel patterns.

6. CONCLUSION

This working paper shows the effectiveness of using GTFS-Realtime to calculate the stop-to-stop marginal delay for buses. With a month of GTFS-Realtime data, the results indicate that both Bus-taxi lanes are effective in reducing marginal delay and more effective in improving travel reliability. The results are expected to be more generalized and robust with the complete GTFS data from June 2020 to March 2022. The Bus-HOV lanes appeared to be less effective than Bus-taxi lanes, which is possibly due to the lack of surface paint and priority enforcement in Sydney. It is found that the traffic signal increases bus stop-to-stop marginal delay, which is an indication of the lack of public transport signal priority within the studied area. Transit signal priorities are suggested to enhance bus performance. Over schedule padding patterns can be seen in the data, which is possible due to the reduction in bus travel time as the traffic volume reduced after the start of the COVID pandemic. Transit agencies should consider updating the schedule to adopt post-COVID travel behaviours.

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