

UNDERSTANDING THE ROAD SAFETY IMPLICATIONS OF BUS PRIORITY MEASURES IN MELBOURNE

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ABSTRACT

This paper summarises findings on the road safety performance and bus incidents in Melbourne along roads where bus priority measures had been applied. Results from an Empirical Bayes safety evaluation showed a 14% reduction in accidents (significant at 90% level). An empirical analysis of the incident types revealed significant changes in the proportion of incidents involving buses hitting stationary objects and vehicles, which suggest the effect of bus priority addressing manoeuvrability issues for buses. A mixed-effects Negative Binomial regression modelling of bus incidents considering wider influences on incident rates at a route section level also showed significant safety benefits when bus priority is provided. A major implication of this research is that bus priority in this context acts to improve road safety and should be a major consideration for road management agencies when implementing bus priority and road schemes.

Keywords: Road safety performance, Empirical Bayes, Regression modelling, Bus incidents

INTRODUCTION

Various types of bus priority initiatives exist internationally, each differing essentially by the amount of road space or time (or combination of both) that has been allocated for transit vehicles. Regardless of its form, there has been overwhelming evidence that bus priority brings about improved travel time, reliability and attractiveness of public transport. However, very little in-depth research has been undertaken to measure the road safety implications of these schemes. A literature review also has revealed that evidence from previous studies on the safety implications of bus priority has been mixed. None of the previous studies had discussed why associations between accident occurrence and bus priority exist or explained the specific road safety effects of bus priority measures.

This paper explores the road safety impacts of bus priority through an analysis of accident and bus incident data in Metropolitan Melbourne, Australia. The focus of this research is on

understanding the effects of bus priority that had been implemented in the ‘SmartBus’ BRT system in Melbourne since 2004¹. SmartBus is an entirely on-road BRT system with similar features to the LA Metro Rapid and has had impressive ridership and cost effectiveness performance compared to busway based BRT systems (Currie & Delbosc, 2010).

This paper is structured as follows. The next section reviews previous research and findings concerning bus safety. The research aim and proposed framework follows. The research context is then presented to provide background to bus priority in Melbourne before an outline of the research methodology and summary of the results is presented. It concludes with a summary and discussion of key findings.

RESEARCH BACKGROUND

Bus priority is typically provided with the aim of improving travel time and reliability of bus operations, passengers at stops and interchanges and altering the traffic balance in favour of public transport. Achieving all these objectives at the same time often involves compromises between improving the bus operation and needs of private vehicles and other road users (Slinn et al., 2005). The types of bus priority initiatives used vary from city to city (Gardner et al., 2009; Hounsell et al., 2004). However, their differences lie essentially in the amount of road space or time allocated for transit vehicles. Bus priority, in terms of space allocation, generally involves giving the right of way to the bus along its route of travel. Various forms of priority treatments fall under this category. The most common are bus lanes, where road space is allocated for buses use only. Priority in terms of time reallocation typically involves the application of transit signal priority, which is currently growing in use internationally (Smith et al., 2005). Typically, this involves the use of bus-only phase, green extension or red truncation, where the traffic phasing is adjusted at intersections to favour buses (Table 1).

Table 1 – Summary of Transit Priority Measures

Bus Priority Strategy	Form of Priority	Traffic Management Strategies
Right of Way (Space Allocation)	Transit-way, Queue jump Prohibited parking Stop consolidation	Full-time, Part-time, intermittent, with-flow, contra-flow, etc.
Signal Priority (Time Allocation)	Transit-only phase Green extension Red truncation Phase insertion / rotation	Active / Passive Conditional / Unconditional Differential

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Studies on Bus Safety

Previous studies on bus accidents and incidents have focused on understanding crash characteristics and identifying accident causation factors. Whalberg developed a taxonomy of buses as a means to study the causes of accidents in terms of driver behaviour and environmental factors (af Wåhlberg, 2002). Based on pre-defined categories, he found that the numbers of bus-to-bus and side-swipe accidents are high, which led to the belief that drivers aim to stop just shy of the bus ahead and that bus stops do not offer enough space for buses to move into. Walberg followed up with an in-depth analysis of bus accidents based on exploring associations between chosen explanatory variables (af Wåhlberg, 2004a). One interesting observation was that in only a third of accidents did the drivers report that the state of the road had contributed to the crash. Half of all single accidents also happened at bus stops. In concluding, Wåhlberg argued that accident data only requires basic tabulation and that the use of more advanced statistical techniques might yield misleading results. Walberg followed up with another study that focused on the effect of acceleration behaviour on bus accidents (af Wåhlberg, 2004b). Although he found number of working hours and to a lesser extent age, are significantly associated with crashes, there was not enough evidence to support the hypothesis that driver acceleration behaviour is a predictor of bus accidents.

A similar analytical approach was undertaken by Brenac and Clabaux (2005). Through an in-depth examination of police reports, the authors discovered that buses were either directly or indirectly involved in 3.6% of all injury accidents in France. Significantly, the proportion of cases where buses were indirectly involved was higher than those where buses were directly involved. In addition, almost half of cases of indirect involvement of buses related to sight obstruction, with the other half involving pedestrians hurrying across the street to catch the bus. In an attempt to identify factors related to crash frequency of buses and injury severity types, Chimba et al. (2010) used an accident prediction approach by developing negative binomial and multinomial logit models. The results showed that the presence of on-street shoulder parking, lane in which bus was travelling in, posted speed limit, lane width, number of lanes and traffic volume were significant in increasing the accident and injury severity risks. In one of the rare studies that examined bus drivers' at-fault accident risks, Tseng (2012) found that age and educational level were not significant. However, driving experience, yearly driving distance and use of AVL system were associated with tour bus drivers' at-fault accident risk.

In Jovanis' work (1991), accident and incident reports in Chicago were examined to identify patterns of bus accidents and shed light on understanding the effect of vehicle, driver's characteristics, environmental and operational factors in accident occurrence. A key observation was that 89% of all accident and incidents were collision events involving hitting another object or person. Zegeer et al. (1993) analysed 8,897 commercial bus crashes across five states in the U.S. and found crashes in winter months, involving older buses to be over-represented in accidents. As for drivers' characteristics, neither gender nor age was found to be associated to accident involvement. Rear-end accidents where one vehicle stopped and sideswipe accidents were also found to be most common. [This was similar to](#)

findings by Yang et al. (2009), who found rear-end collisions to be most common. In another study, Tseng (2012) examined the effect of drivers' age and experience in influencing the at-fault risks of tour bus drivers. Age was found to be insignificant; Experience, on the other hand, was found to be significant. In the study by Strathman et al. (2010), extensive ITS and operations data were used to analyse factors contributing to bus incidents in the Portland Oregon metropolitan region in the US. It was found that age, gender and experience had an effect on bus incidents. In terms of work characteristics, the number of work hours and its variability were found to be positively correlated to both collision and non-collision incidents. Interestingly, the expected non-collision frequencies for low floor buses and those older than 15 years were found to be lower. There were also positive effects of running early on collision frequency. No temporal effects were found but in terms of customer service, customer commendations were found to be positively associated with collision frequencies. The authors attributed this unexpected finding to a possible link between personality traits and accident risks, as earlier results had showed that operators with the fewest accidents tended to be more low-key, even-tempered and conscientious about their work (Jacobs et al., 1996). Based on this, the authors rationalised that operators with such personality, who are likely to have better accident records, are also less likely to draw commendations from customers.

Table 2 –Summary of Studies on Bus Accidents

Author	Key Accident Risk Factors Found																	
	Rear-end collision	Side-swipe collision	Buses with lift operations	Drivers' age	Drivers' experience	Drivers' gender	Drivers' Work Hours	Drivers' temperament	Mileage	Presence of AVL System	On-street parking	Lane bus was travelling in	Posted speed limit	Lane width	Traffic volume	Sight Obstruction	Crossing Pedestrians	Time of Day
Zegeer et al. (1993)	✓	✓																
Yang et al. (2009)	✓			✓														
Tseng (2012)				✓	✓													
Strathman et al. (2010)			✓	✓	✓	✓	✓	✓										
Jovanis et al. (1991)	✓																	
Chimba et al. (2010)					✓				✓	✓								
Wahberg (2009)											✓	✓	✓	✓	✓			
Brenac and Clabaux (2005)																✓	✓	
Wahberg (2004)				✓			✓											✓

Safety Effects of Bus Priority

When it comes to safety effects of bus priority, most research had focused on Bus Rapid Transit (BRT) systems. Levinson et al. (2003) found that buses using Seattle's bus tunnel (with exclusive rights-of-way for buses only) experienced 40% fewer accidents than in mixed traffic operations while the introduction of the Bogota TransMileneo BRT system saw a 93%

reduction of fatalities among transit users. As for other bus priority measures, Booz Allen Hamilton (2006) found that the introduction of bus lanes in London had resulted in a reduction of 12% of accidents involving buses. Mulley (2010) examined personal injury accidents that occurred over a 3-year period on stretches of roads that are within 50m of a bus priority lane in Tyne and Wear, UK, and found that 5.3% of all personal accidents were due to priority measures along the corridor. However, whether priority measures had actually resulted in more accidents overall is not known. Sarna et al. (1985) studied the accident data on selected roads in New Delhi for a 2-year period before and after dedicated bus lanes were introduced. Results have been unable to provide any definite evidence of safety impacts. LaPlante and Harrington (1984) studied contra-flow bus lanes in Chicago and concluded that they should be retained after determining that bus and pedestrian accidents decreased by 52% and 19% respectively in the “after” period. While results from this study point to transit priority bringing about positive safety effects, there have been other studies that have found otherwise (Cooner & Ranft, 2006; Skowronek et al., 2002).

It is clear from the above studies that evidence of the safety effect of bus priority is mixed. Of the seven studies above, four suggested a positive effect, two pointed to a negative effect while another provided no clear evidence of the safety impacts of bus priority. Clearly, this is an area where further research is needed.

AIMS OF STUDY

This study focuses on estimating the overall safety impact of bus priority and exploring bus incidents that had occurred in Metropolitan Melbourne to understand how bus incident types and frequency differs between routes with and without bus priority.

DATA

Data used in this study was obtained from CrashStats (VicRoads, 2011), which is a crash reporting system developed by VicRoads (the local Road Management Authority) and Victoria Police. The CrashStats database contains traffic accident data on all incidents on roads that involve injury or death. In total, there are 56 locations along the SmartBus routes where bus priority measures were implemented. At each location, 3 years’ worth of “before” data and one or more years of “after” data were extracted for the analysis (depending on when the priority measure was implemented). The exact starting and ending months were used for both periods to account for any seasonality effects. For each case, data from a buffer of period of 3 months were disregarded to account for any disruption of traffic during the construction period and any ramp up in bus operations after implementation.

The second set of data (bus incident records) was obtained from Traffic Incident Management System (TIMS) and human resource database maintained by Grenda Transit (now part of Ventura Group which is Melbourne’s largest bus company). The data from TIMS contained all incidents which occurred between the year 2006 and 2011 that were captured for the purpose of settlement of insurance claims. There were a total of 3,799

incidents along 99 bus service routes that operates in eastern Melbourne during this time period. Of these, 169 records (or 4.4%) had missing information, e.g. location details, and were discarded. The remaining 3,630 records were used for the analyses in this study.

The final set of data comprises estimates of annual average daily traffic (AADT) for intersections and road segments under study as well as those in the reference group. These were obtained from the signal control (or SCATS) system (Lowrie, 1992) maintained by the Traffic Operations Unit and Information Services Department of VicRoads, Australia (VicRoads, 2012) respectively.

METHODOLOGY

The approach involves the use of Empirical Bayes before-after analysis to determine the overall road safety impact of bus priority measures (aggregate level). This is followed by bus incident frequency and type analyses to understand the safety implications of implementing bus priority measures at a bus-route level (disaggregate level).

Before-After Analysis (Aggregate Level)

Before-and-after studies have also been central to road safety research, where the aim is to determine the estimates of the safety effects brought about by treatments applied to roadway sites. Various before-after methodologies exist, with each having its own strengths and limitations. From the literature, it appears that the Empirical Bayes (EB) methodology is the most commonly adopted approach adopted by researchers. Since the pioneering work by Hauer (1997) and Persaud (2007), the EB methodology is now part of the approach used in highway safety design (Knovel et al., 2011) at the Federal level in the USA. The EB methodology is considered a statistically defensible approach because it not only accounts for secular trend and unrelated effects (that cannot be measured), it also addresses the widely accepted phenomenon of regression-to-the-mean effects as well. It does this by combining observed accident counts with knowledge about the safety of similar entities (Ezra Hauer et al., 2002).

In recent years, there has been much development in the use of Full Bayes (FB) method, which can also account for spatial correlations between treated and comparison sites. Although findings from previous studies have shown that the FB method yields smaller standard errors, they have also indicated that its treatment effect estimates are largely comparable to those computed from the EB method (Lan et al., 2009; Miaou & Lord, 2003; Persaud et al., 2010). Given that the use of full Bayes method requires a high level of statistical training (as its methodology is rather complex), it is likely that the EB and CG methods would remain the mainstay for most practitioners (Persaud & Lyon, 2007). In this study, the EB approach was adopted where safety performance functions were first developed for intersections and roadway segments:

$$\text{Intersections: } E(A) = \alpha_0 \times Q_{\min or}^{\beta_1} \times Q_{\min or}^{\beta_2} \quad (1)$$

$$\text{Roadway segments: } E(A) = \alpha_0 \times Q_0^{\beta_1} \times L^{\beta_2} \quad (2)$$

where

- $E(A)$ = Predicted crash count per year;
- $\alpha_0, \beta_1, \beta_2$ = Model parameters estimated in STATA;
- Q_0 = AADT along the roadway segment;
- Q_{minor} = AADT from the major approach of an intersection;
- Q_{major} = AADT from the minor approach of an intersection; and
- L = Length of roadway segment

The models are assumed to take on a negative binomial (NB) structure, which is a common practice adopted by most researchers to account for crash counts which are non-negative, random, infrequent and thus prone to over-dispersion. The variable coefficients and over-dispersion parameter are estimated using maximum likelihood techniques in the STATA statistical software (STATA, 2005). To assess the model's goodness-of-fit, the R_α^2 proposed by Miaou et al. (1996) is used given that the R^2 value found in OLS regression is not a good measure for negative binomial regression models. The remaining steps were taken in accordance to the procedure outlined in the Highway Safety Manual (2011), with the eventual safety effect of implementing bus priority measures computed as:

$$\text{Safety Effect, } \theta = 100 \times (1 - OR) \quad (3)$$

where OR is the odds ratio that represents the unbiased safety effect of bus priority.

Bus Incident Type and Frequency Analysis (Disaggregate Level)

Taxonomies of traffic accidents have been used widely to by researchers, road management agencies, police and insurance companies to summarize and understand accidents patterns and characteristics (af Wählberg, 2002). In this study, a descriptive analysis was first carried out to identify bus incident characteristics before regression modelling is done to examine the bus incident frequency.

Given that the bus incident records are in the form of a cross-sectional and time series (or panel) structure, heterogeneity and serial correlation issues may exist. The former is due to unobserved location-specific factors while the latter arises from the time series nature of the data. In road safety, random effects negative binomial (RENB) modelling approach have been adopted in previous studies address to address these spatial and temporal effects (Chin & Quddus, 2003; Kumara et al., 2003). This study uses a relatively recent development in computational statistics to model location and time-specific variables as crossed, independent effects. Compared to RENB, a mixed-effects negative binomial (MENB) regression modelling approach offers the following key advantages (Baayen et al., 2008):

1. It allows for random effects to be crossed and not necessarily nested as assumed to be in the traditional random effects modelling;
2. It is more flexible in dealing with missing data issues; and
3. It overcomes deficiencies in statistical power due to repeated observations;

With A_{ij} as a vector representing the observed number of incidents along bus route

- where
- X_{ij} = Matrix representing factor contrasts and covariates
 - β = Vector of pooled coefficients (fixed effect)
 - L_i = Matrix to account for location-specific effect
 - l_i = Vector representing location-specific effects
 - T_j = Matrix to account for time-specific effect
 - t_j = Vector representing time-specific effects
 - ε_{ij} = Vector of residual errors

segment i at time j , the structure of the MENB model is given as:

$$A_{ij} = X_{ij}\beta + L_i l_i + T_j t_j + \varepsilon_{ij} \quad (4)$$

Following the combination of the matrix L and T to a single matrix Z , and random effects

where $\varepsilon \sim N(0, a)$, $\alpha \sim N(0, b)$

vector l and t into a single vector b , the formulation can be re-written as:

$$A = X\beta + Z\alpha + \varepsilon \quad (5)$$

The residual error (ε) and random effects (α) terms are assumed to take on the normal (Gaussian) distribution with means 0 and variances a and b respectively. Table 3 provides a brief description and summary statistics of the covariates used in the MENB model. Similar to the aggregate analysis, the R_α^2 as proposed by Miaou et al. (1996) is used to assess the model's goodness-of-fit:

$$R_\alpha^2 = 1 - \frac{\alpha}{1 + \alpha_{\max}} \quad (6)$$

- where α = Over-dispersion parameter for final RENB model; and
 α_{\max} = Over-dispersion parameter for base model with only a constant term

Table 3 – Summary Statistics of Variables Used in NB Model

Variable	Min	Min	Mean	S.D.
Incident Frequency (Incidents/year)	0	29	3.68	4.89
Length of bus route segment (km)	2.5	55.0	15.94	10.11
Average Annual Daily Traffic (AADT) of segment	1,495	78,433	7,335	6,286
Number of bus services per week	6	314	111.43	87.63
Number of bus stops (per km)	0.53	7.33	2.50	0.941
Presence of bus priority (With = 1; otherwise = 0)	0	1	0.15	0.36
Total Observations, n = 297				

RESULTS AND DISCUSSION

Empirical Bayes Before-After Analysis

Results of the NB models for the reference group of road intersections and segments, which form as inputs to the EB methodology, have been reported in Goh et. al (In Press). The final EB results are presented in Table 4, which shows the breakdown of the safety effect estimates of bus priority at intersections and road corridors where bus priority was applied. When all locations were considered, the safety effect was found to be 14% (with a standard error of 8%). This effect was found to be statistically significant at the 90% level when the t-test was applied. Assuming all other causal effects had been accounted for, this implies that introduction of bus priority measures had resulted in an overall reduction of about 14% in accident counts in Metropolitan Melbourne.

Table 4 – Results of EB Analysis of Bus Priority Effect

Parameter	Bus Priority at		
	Intersections	Road Segments	Overall
Number of Locations	31	25	56
Total observed crash counts in “after” period	94	66	160
Expected crash counts in “after” period	105.38	80.29	185.7
OR'	0.892	0.822	0.862
OR	0.889	0.818	0.860
SE(OR)	0.11	0.12	0.08
Safety Effect, θ	11.1%	18.2%	14.0%*

* Significant at 90% level

Bus Incident Type Analysis

Figure 1 presents the incident frequency (per bus-km) along routes with bus priority and those without. For this study, only on-road incidents were analysed, i.e. those involving acts of vandalism or objects thrown at buses were disregarded.

The most common incidents involve buses hitting vehicles (or vice versa) and buses hitting stationary objects. In general, these findings mirror those in Wahlberg’s work (2002), where buses hitting objects were found to be most common while those involving pedestrian were very rare occurrences.

When comparing between routes with and without bus priority, the most noticeable difference was in the proportion of incidents involving buses hitting stationary objects and vehicles. For the former, a two-third reduction was recorded, and this was found to be significant at the 95% level. The latter registered a bigger drop (about 80%), which was also significant at the 95% level. These percentage changes are likely due to the effect of bus priority in facilitating bus movements. Given that buses need not pull in and out of bus bays as frequently as before, manoeuvrability becomes less of an issue. Consequently, the risk of hitting roadside objects and colliding with stationary vehicles reduces. Although bus lanes provide exclusive

right of way to buses, the downside is that buses have to contend with increased weaving movements due to private vehicles entering from and exiting side streets. The relatively smaller reduction in proportion of incidents involving other vehicles hitting buses appears to support this case (noting that such incidents are likely to be classified under the “vehicle hit bus” category with them taking place in bus lanes).

While there were a small percentage of incidents involving buses failing to give way along all other routes, no such incidents occurred along routes with bus priority. In percentage terms, there were also slight reductions in lane-changing collisions and incidents involving buses hitting other vehicles. These difference, however, were not found to be statistically significant.

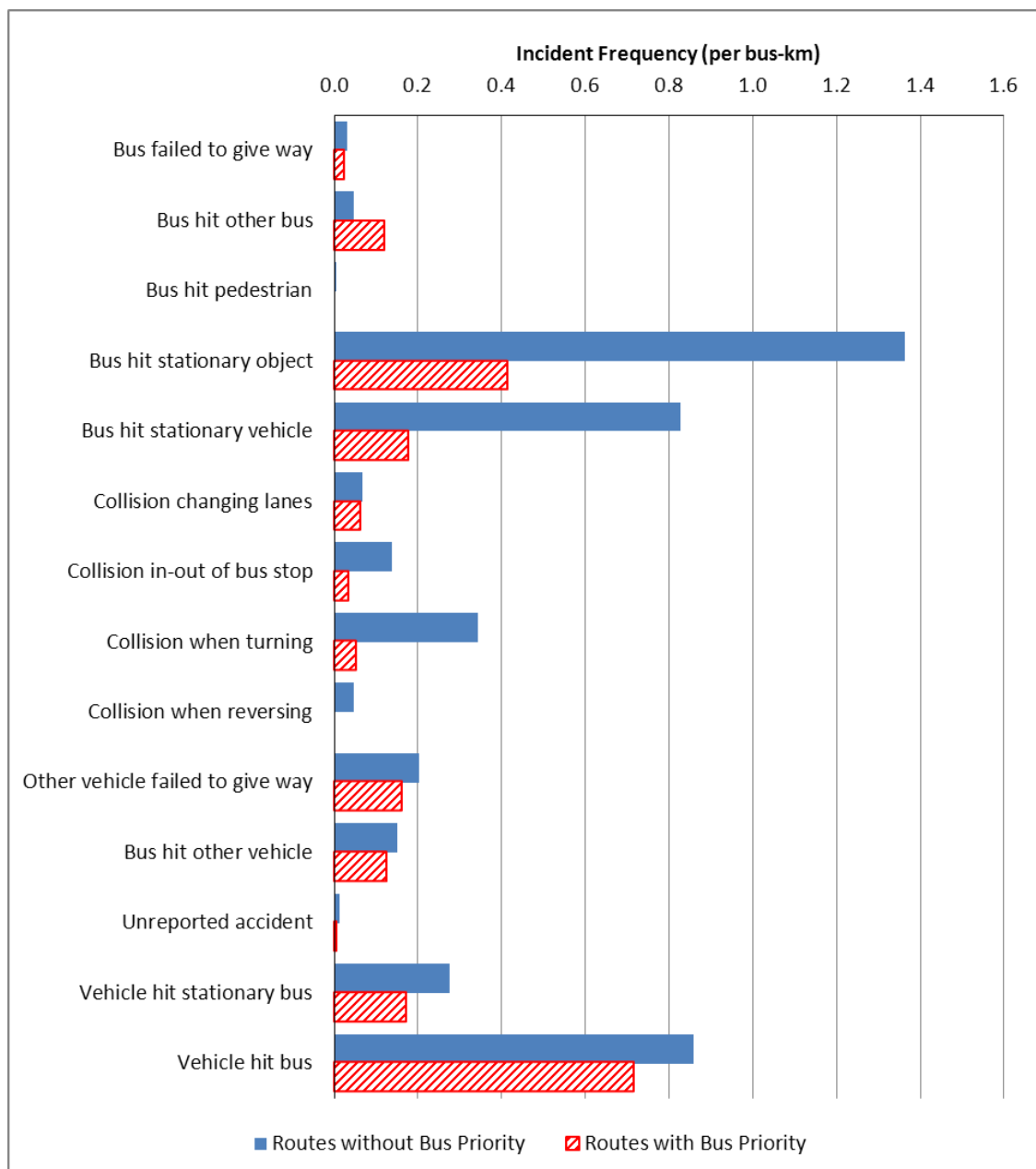


Figure 1 –Breakdown of Incident Type (Locations with and without Bus Priority)

Bus Incident Frequency Analysis

A preliminary data analysis revealed that incident frequencies between the period of 2006-2008 and 2009-2011 were significantly different. To address possible concerns that there could be unobserved effects in the data, the year 2006-2008 records were discarded, leaving 1,099 records for the RENB modelling. Table 5 presents the parameter estimates obtained from maximum likelihood algorithms in the *glmmADMB* package in the statistical software *R*, an open-source language and environment for statistical computing that is freely available at <http://cran.r-project.org> (R Development Core Team, 2012). The dispersion parameter estimate was found to be significantly different from zero, which indicated that NB error structure was more suitable than the Poisson structure. The implications of the modelling results for each of the explanatory variables are discussed below.

Table 5 – RENB Model Results for Bus Incident Frequency

Variable	Estimate	P-value
Intercept	-6.640	0.000
Services per week	0.006	0.000
Ln(AADT)	0.431	0.001
Ln(Route Section Length)	0.773	0.000
Stops Interval	0.389	0.000
Bus Priority = Yes	-0.766	0.002
Bus Priority = No	0 (Reference)	
Random Effect:	Variance	Standard Deviation
Year	0.357	0.598
Location	0.195	0.441
Dispersion parameter, α	0.242	
95% CI for α	[0.169,0.429]	
Log likelihood	-607.205	
AIC	1232.4	
R_α	0.807	

Route Length and Services

The results show that bus incident occurrence is largely influenced by the route section length ($p=0.000$) and number of services per week ($p=0.000$). These findings were as expected given that increased services and route length will lead to more incidents because of greater exposure. Route length, in particular, has been shown to be a reliable predictor of crash frequencies in numerous studies (Abdel-Aty & Radwan, 2000; Milton, 1998; Vogt & Bared, 1998).

Stop Intervals and Bus Priority

The models also indicate that having more stops per route km increases incident risks ($p=0.000$), while the presence of bus priority reduces incident risks ($p=0.002$). The former

could be attributed to the fact that having more stops would mean buses have to brake and accelerate at bus stop locations more often. A similar finding was also recorded in other studies, where bus stop density was found to be positively correlated to accident occurrence (Cheung, 2008; Chin & Quddus, 2003). Of interest in this study was the effect of bus priority given that this had rarely been examined in previous research. The results suggest that the incident rate along routes with bus priority is approximately $\exp(-0.766)$ or 0.46 times the incident rate for routes without bus priority assuming all other variables are held constant. In other words, the presence of bus priority is associated with a 53.5% reduction in bus incident occurrence. A similar albeit much smaller positive effect was also found in another study (Booz Allen Hamilton, 2006), which revealed a 12% reduction in bus related accidents following the implementation of bus lanes in London.

CONCLUSION

An analysis of the accident and bus incident data was carried out to assess the safety impact of introducing bus priority measures in Metropolitan Melbourne, Australia. The findings can be summarized as follows:

1. Results from the Empirical Bayes before-after safety evaluation revealed bus priority brought about an overall safety effect of 14.0%. This was found to be statistically significant at the 90% level;
2. An analysis of the incident types showed that the proportion of incidents involving buses hitting stationary objects and vehicles along routes with bus priority was two-third and 80% lesser respectively when compared to routes without bus priority. These differences are statistically significant at 95% level and could be attributed to the effect of bus priority facilitating bus movements;
3. The relatively smaller reduction in proportion of incidents involving other vehicles hitting buses appears to reflect the downside of bus lanes - in that buses have to contend with increased weaving movements due to private vehicles entering from and exiting side streets; and
4. Results from negative binomial regression modelling indicated that the presence of bus priority led to a 53.5% reduction in bus incident occurrence.

In concluding, findings from this study point to bus priority measures bringing about significant positive safety effects to road intersections and corridors on which they are implemented. At a bus route section level, it had shed new light on the effect of bus priority on bus safety. One major implication of this study is that bus priority could be a major consideration for road management agencies when implementing road schemes. Current practice in bus priority and road design has generally ignored these effects.

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