The Influence of Lane Width on Bus Crashes

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ABSTRACT

To accommodate non-motorized transportation and increase safety for all road users, motor vehicle lane width has been reduced from the conventional 12 feet to as narrow as 9–10 feet in many cases. Although it has not been a big issue for passenger car drivers, the narrowed lanes have posed concerns for bus transit operators. This study uses data from Capital Metropolitan Transportation Authority (Capital Metro), the public transit provider in the Austin area, to evaluate the influence of narrow travel lanes on bus crashes. It includes a comprehensive literature review, interviews with cities and transit agencies, an analysis to determine the correlation between lane width and target bus crashes (sideswipe, fixed-object, and mirror-to-mirror), and a study of the impact of a curb or parked cars immediately adjacent to the narrow outside lane on bus crashes. The literature review and interview findings support a standard lane width of 11–12 feet for bus routes. The statistical analysis suggests that more target bus crashes were associated with narrower lane widths. The presence of a curb or parked cars immediately adjacent to the outside lane was problematic regardless of whether the outside lane was less than 12 feet or not. Though narrower lane width could contribute to less catastrophic crashes due to the slower speeds, it increases the likelihood of certain bus crashes. Cities and transit agencies should work together to make decisions about lane width to balance the needs of all road users.

Keywords: transit crashes, transit safety, bus transit, crash analysis, GIS

INTRODUCTION

Over the years, there has been a move to use the complete streets principles in promoting livable communities. The competition is fierce among various modes of transportation for space within a roadway right-of-way. To make space for other modes, one of the multimodal-oriented design options adopted by the City of Austin is to reduce vehicular lane width from the conventional 12 feet to as narrow as 9–10 feet to accommodate people walking and bicycling. The reduction of travel lane width poses concerns for transit operators. The Capital Metropolitan Transportation Authority (Capital Metro), Austin's regional public transportation provider, concerns that narrow lanes may lead to bus operators encroaching into adjacent lanes or driving too close to the roadway edge, potentially resulting in sideswipe, fixed-object, or mirror-to-mirror collisions.

City of Austin and Capital Metro are not the only cities and transportation agencies mired in the lane width debate for balancing safety and level of service. Historically, wider travel lanes have been favored to create a perceived safer buffer for drivers (*1*). Lane widths less than 12 feet have been assumed to decrease traffic flow and capacity. The *Highway Capacity Manual* suggests that the capacity of a 10-foot lane is 93 percent of the capacity of a 12-foot lane (*2*). In addition, a Transit Cooperative Research Program Report concluded that traffic lanes used by buses should be no narrower than 12 feet based on the maximum bus width (including mirrors) (*3*). However, when taking other road users' safety into consideration, the National Association of City Transportation Officials (NACTO) states that "travel lane widths of 10 feet generally provide adequate safety in urban settings while discouraging speeding" (*1*). Studies have shown that narrower streets positively contribute to slower driving speeds which, in turn, reduce the severity of crashes. The Vision Zero Street Design Standard includes narrow vehicle lanes as one of its design elements. It encourages agencies to "reduce road lane width to 10 or 10.5 feet to reduce speeding" (*4*). Additionally, narrowing vehicular lanes creates space to accommodate facilities for other modes like bike lanes. With the mixed information, it is important to understand how lane width impacts different transportation modes to make sound decisions.

To help cities and transit agencies better understand the potential impact of lane width on bus safety, this study implements a multipronged approach of evaluating the relationship between lane width and bus crashes. It includes a literature review of studies about bus operation and lane width; interviews with transportation officials at seven cities and transit agencies in the United States that have dealt or are dealing with narrowing (9- or 10-feet) travel lanes; a description of the data collection of bus crashes and roadway features (e.g., lane width, roadside barriers); an explanation of methodology used to conduct statistical analysis; and an interpretation of the results and implications for Capital Metro and other cities and transit agencies. The statistical analysis studied Capital Metro bus incidents during the period between October 1, 2008, and May 31, 2018, wherein researchers examined the relationship between the Capital Metro bus crashes and lane width based on the roadways with no other major changes (e.g. bike lane installation) during the study period.

LITERATURE REVIEW

Several studies have evaluated the impact of lane width on bus safety. Zeeger et al. analyzed the factors that contributed to bus crashes in five states over a four-year period (*5*). Through the analysis of 8,897 crashes, researchers found that sideswipe collisions between buses and other vehicles due to narrow lanes was a primary crash type. They also identified that along major arterials, lane widths should be 12 feet where possible, and at least 11 feet wide at a minimum.

Chimba et al. developed negative binomial and multinomial logit models using over 4,000 bus crashes from FDOT's Crash Analysis Reporting System to evaluate factors that influence bus crash frequency and injury severities (*6*). The evaluation of crashes on roadways with widths between 9 and 13 feet showed that crash rates were higher on roadways with 9-10 foot lanes than on roadways with 11–12 foot lanes. The results indicated that the wider the lanes, the lower the crash frequency and low probability of incapacitating and non-incapacitating injuries of bus crashes.

Strathem et al. developed a crash model using three years of bus collision data from TriMet's (the transit provider for the Portland, Oregon, region) to determine the characteristics that significantly contribute to collision risk (*7*). The results suggest that lane width was a significant contributor to collision risk. However, the types of collisions that lane width contributed to were characterized as minor incidents: mirror strikes and collisions with parked vehicles and fixed objects. The authors also noted that "for communities considering 'shrinking' their streets to promote traffic calming, it is worth emphasizing that standard buses—at 8.5 feet in width—are already operating with very narrow clearances."

Sando and Moses conducted perhaps the most comprehensive study on the impact of lane width on bus safety by employing mixed methods (*8*). The following provides an overview of each method and the subsequent findings:

- A questionnaire of transit safety and operations officials found that most streets that experienced width-related collisions had a lane width of 11 feet or less.
- An analysis of bus-related crashes from the Florida Statewide Crash Database revealed that a decrease in lane width was likely to increase the frequency of crashes. Additionally, in the comparative analysis of crash rate for 9-, 10-, 11-, and 12-foot lanes in the transit network, the crash rates of sideswipe and mirror collisions were overrepresented on 9–10 foot lanes.
- An evaluation of sideswipe and mirror crashes from three Florida transit agencies' incident reports suggested that the average width of roadways where sideswipe and mirror crashes occurred was 10.55 feet.
- A field observational study by videotaping bus movements on roadways with narrow lanes (11 feet or less) revealed that narrower lanes make it difficult for buses to maintain their lane and pass other buses in opposing directions. It also caused buses to encroach adjacent lanes when performing right turning maneuvers.
- A physical constraints analysis that considered the space requirements of buses and the interaction of buses and other modes of transportation was also conducted. The analysis showed that a minimum of 11.25 feet is required for the outside lane of curbed roadways and 11.75 feet is required for outside lanes without a curb and gutter to (a) adhere to the 3-feet clearance law for bicyclists and (b) ensure that buses (including mirrors) maintain their lane without encroaching into adjacent lanes.

Based on these findings, Sando and Moses recommended that roadway lanes with transit routes be no narrower than 12 feet.

When it comes to federal guidance, the Transit Street Design Guide developed by NACTO recommends that bus lanes may be 10 to 11 feet when the lane is adjacent to a buffer such as a bike lane or parking, and 11 to 12 feet when configured curbside or in a roadway adjacent to an opposing lane of bus traffic. Where space is available, using buffers rather than widened lanes to reduce sideswipes is preferable because it reduces speed (*9*).

PEER AGENCY INTERVIEWS AND FINDINGS

To find potential interviewees, researchers referred to a list of pre-identified peer agencies of Capital Metro (*10*) and asked for recommendations from contacts at NACTO for cities and transit agencies that have dealt with narrowed travel lanes. Based on these two approaches, researchers developed and sent a recruitment email to contacts within 11 cities and agencies to coordinate interviews; of which, 7 accepted.

A discussion guide with five questions was developed and provided to the interviewees prior to the interviews. All interviews were conducted over the phone except for the Regional Transportation District, which responded via email. Note that two groups of cities and agencies from the same geography participated in interviews simultaneously. The findings from interviews are organized by the interview questions below.

Question 1: What Is the Standard Lane Width for Roads That Carry Buses? What Is the Range (Narrow to Wide) for Roads that Carry Buses?

As Table 1 shows, the majority of interviewees indicated that the standard width of travel lanes for buses is between 11 and 12 feet, and depends on whether the travel lane is adjacent to a curb or a buffer (e.g., bicycle lane, parking). While Cambridge, Massachusetts, was the only city with standards below 11 feet, the interviewee indicated strongly that the 10.5-foot standard is too narrow and should be increased to 11 feet. The acceptable range of lane width suggests that most interviewees prefer to build lanes wider than 10 feet when redesigning roadways that carry buses. Despite both the standard and preferred lane widths being 10 feet or greater, the width of travel lanes that buses currently travel on in those municipalities can be as low as 8 feet.

Table 1. Summary of Interview Findings Regarding Standard Lane Width, Acceptable Lane Width, and Maximum/Minimum Lane Widths for Travel Lanes for Buses.

City or Agency	Standard Lane Width	Acceptable Lane-Width Range	Minimum and Maximum Lane Width in City
San Francisco Municipal Transportation Agency, San Francisco, California	12 feet (buffer), 12 feet (curb)	11 feet or wider	8 feet–15 feet
Regional Transportation District (RTD), Denver, Colorado	12 feet (buffer), 12 feet (curb)	N/A*	N/A*
City of Philadelphia, Pennsylvania	11 feet (buffer), 11 feet (curb)	10 feet or wider	9 feet–14 feet
Southeastern Pennsylvania Transportation Authority	11 feet (buffer), 11 feet (curb)	10 feet or wider	9 feet–14 feet
City of Cambridge, Massachusetts	10.5 feet (buffer), 10.5 feet (curb)	10 feet or wider	10 feet (unaware of widest)
City of Vancouver, British Columbia	11 feet (buffer), 11.5 feet (curb)	11 feet–12 feet	9 feet–15 feet
TransLink, Vancouver, British Columbia	11 feet (buffer), 11.5 feet (curb)	11 feet–12 feet	9 feet–15 feet

*N/A represents not available. RTD did not provide this information.

Question 2: What Are Some of the Factors that Your Agency/City Take into Account when Considering Lane Width?

The most commonly mentioned factors that influence decisions on lane width are bike lanes and parking. Almost all interviewees indicated that the motivation behind redesigning roadways has been to accommodate the addition of bike lanes, but rarely at the expense of parking. Instead, the travel lanes are narrowed to accommodate bike lanes. One notable exception was a project in Cambridge in which a long stretch of parking was replaced by bike lanes. According to the interviewee, this project was extremely contentious from the public's perspective and unlikely be duplicated due to the negative public sentiment. In addition to accommodating bicycle lanes, interviewees also commonly cited reducing vehicular speed as a motivation to narrow travel lanes.

The lane and directional configuration of the roadway was another factor frequently discussed. While the acceptable lane width is as low as 10 feet, some interviewees indicated that it would only be under certain conditions. For instance, acceptable conditions would include a one-way, single-lane roadway with either parking or bicycle lanes that provide a striped buffer that the bus can use when maneuvering. Oftentimes, the lower end of the acceptable range is only implemented on roads that have low traffic counts and have infrequent bus service.

Researchers also probed to understand if, in practice, cities design lane width based on whether a lane was adjacent to a curb or a buffer (e.g., bike lane/parking). As shown in Table 1, Vancouver was the only city that had separate standards for lane widths. In most cases, cities have one standard built on optimal conditions regardless of whether the travel lane is against a curb or buffer.

Question 3: What Are the Lessons that Your Agency/City Has Learned Regarding Bus Safety with Respect to Lane Widths?

The most commonly shared lesson learned was that there is no one-size-fits-all on lane width and safety for all modes; and the range of contexts that is presented with each unique section of roadway must be considered when reconfiguring an existing roadway. Oftentimes, the transit agencies and cities have to negotiate to identify what the ideal configuration is. One commonly cited example is to approach the reconfiguration as a pilot where paint is used as opposed to more permanent features, and to then closely monitor how different modes interact.

Another lesson learned was the increased safety benefit of a 4 to 3 road diet (going from two travel lanes in each direction to one travel lane in each direction and a middle turning lane). Interviewees indicated that this redesign was very effective in slowing traffic yet still provided the standard lane width for buses, bike lanes, and parking. In addition, it has led to a significant decrease in sideswipes. However, interviewees acknowledged that there is not always sufficient room for this configuration, especially in downtown locations.

Some interviewees also indicated that the complete streets approach does not always benefit user safety by trying to accommodate all modes on one street. They stated that it may be safer to have some corridors be designed to move traffic (including buses) efficiently and others to accommodate bicyclists, rather than trying to compress all modes into one corridor.

Question 4: Does Your Agency/City Have a Policy Regarding Lane Width with Respect to Bus Safety?

Interviewees indicated that their cities and agencies have standards that they abide by, but these are considered guidelines more than policies because, as mentioned previously, all roadways are designed on a case-by-case basis, and in some cases, a reconfigured roadway may not be designed to the city's or agency's preferred standard. Interviewees also indicated that they are hesitant to create any official policy because it could present legal problems for the city if they do not always follow the policy.

DATA PREPARATION

A total of 9,576 bus incidents during the period between October 1, 2008, and May 31, 2018, were obtained from Capital Metro for this study. After excluding bus-yard crashes or non-crash incidents (e.g., trips, slips, or falls), 7,082 bus crashes were retained for analysis. Since Capital Metro gathers crash location information by recording the name of the street where the crash occurred and the name of the adjacent cross street, the crashes were located at intersections when they may have actually occurred at a midblock location (Figure 1).

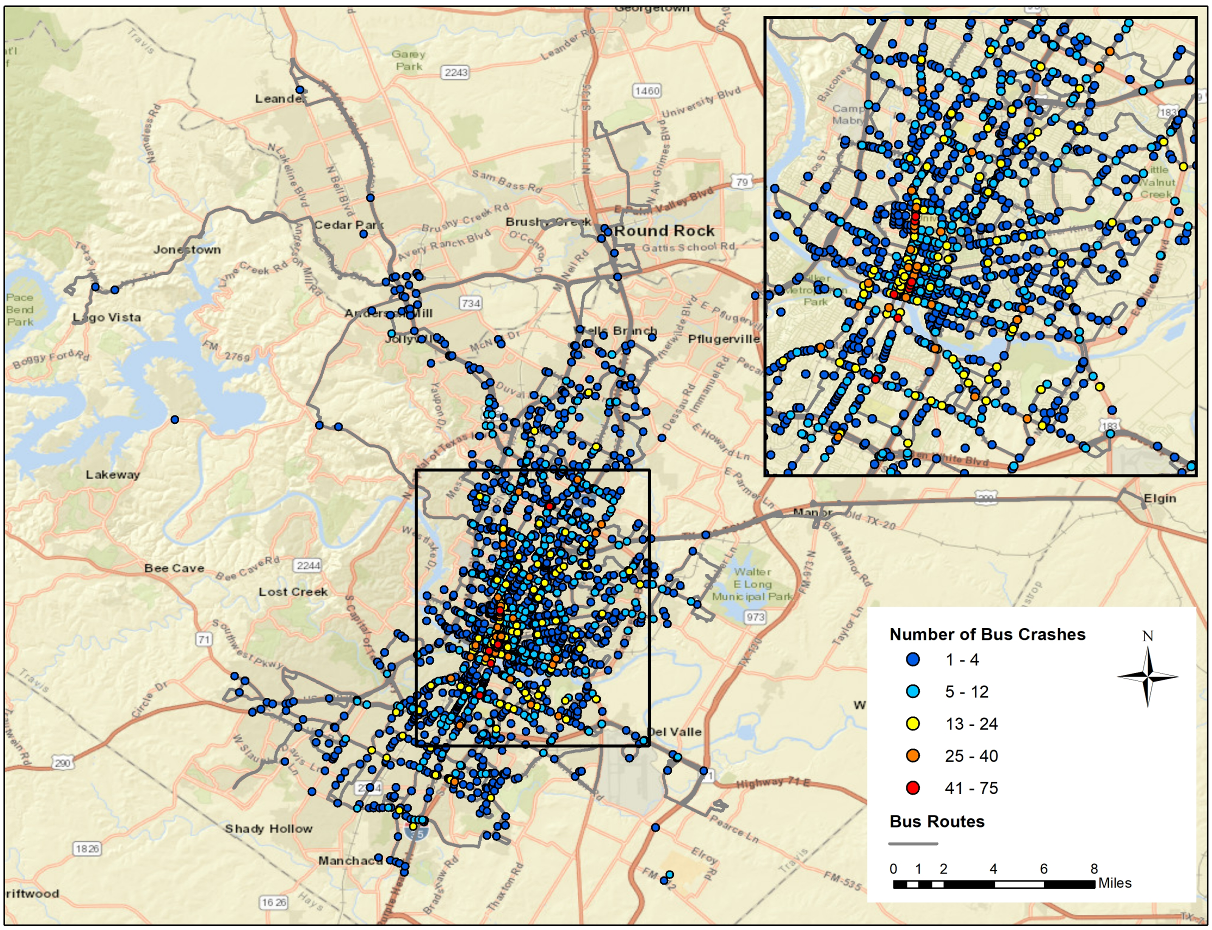

Figure 1. Number of Non-yard Bus Crash Clusters.

Capital Metro bus route data from the State of Texas Open Data Portal were merged into one file to create a complete network that included bus routes traced back as far as August 2015. The complete bus network file was then used to clip the Texas Department of Transportation's Roadway-Highway Inventory Network (RHINO) to only keep roadway segments along bus routes. This provided abundant roadway feature data for the bus network. Meanwhile, researchers collected additional roadway features using Google Earth satellites that include the total number of lanes, outside lane width (Figure 2), total lane width, roadside barriers (Figure 3), designated bus lane width, and existence of bike lanes or shoulders (≥ 2 feet). Among the lane width data, outside lane width was the most relevant variable of interest associated with bus crashes since buses mostly operate in the rightmost lane. Roadside barriers refer to the curbs, street parking, and guard rail/fence/concrete wall that are immediately adjacent to outside lanes.

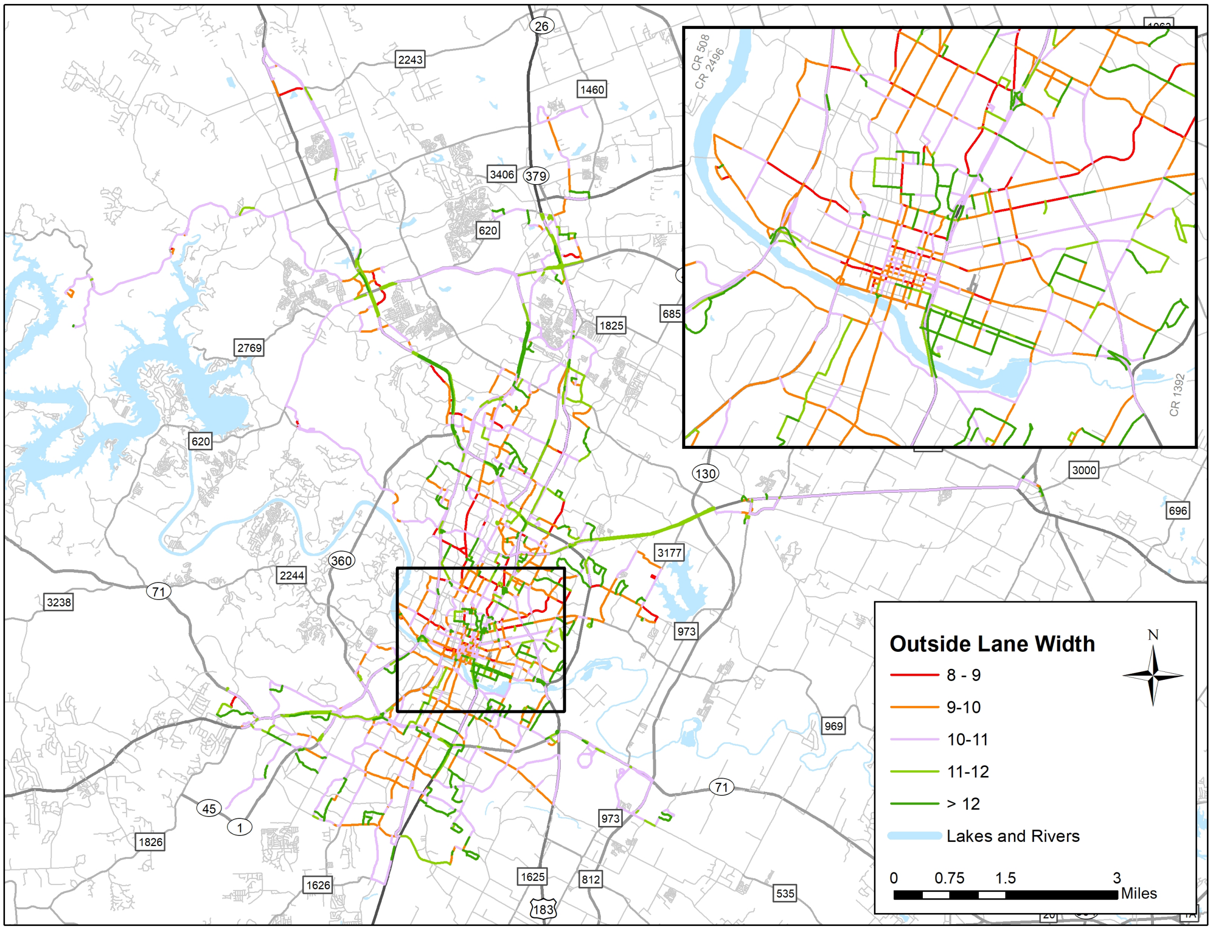

Figure 2. Outside Lane-Width Measurement (Based on Google Earth).

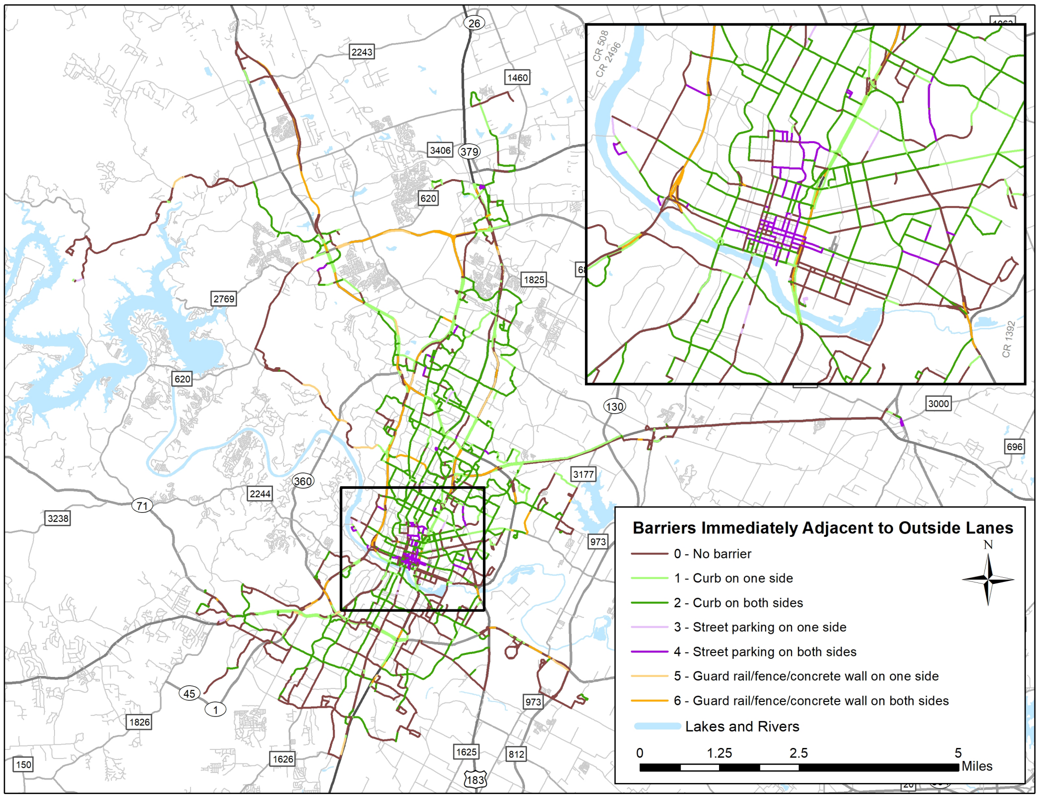

Figure 3. Roadside Barriers.

In order to minimize confounding introduced by roadway changes during the study period in the cross-sectional analysis, researchers further excluded the roadway segments that had changed lane width, added/removed bike lanes, changed or added shoulders, and the like from the bus route data file. To do so, researchers requested and obtained a list of roadway construction projects from the City of Austin.

Finally, researchers matched every bus crash with the corresponding roadway segment in the bus route data file. This enabled the calculation of the number of bus crashes on each roadway segment and an analysis of the relationship between the roadway features and crash frequencies. Crashes were also marked as either target crashes (sideswipe, fixed-object, and mirror-to-mirror crashes that are most likely to be affected by lane-width variance) or comparison crashes (all other crashes).

METHODS

Researchers assessed the effects of the lane width on bus crashes based on the 7,082 Capital Metro bus crashes that occurred on the 833 RHINO segments that make up the Capital Metro bus service routes—roughly corresponding to 323.3 miles of roadways. The following crash types were the most relevant target crashes: sideswipe, fixed-object, and mirror-to-mirror. Comparison crashes consisted of the remaining bus crash types. Researchers were interested in answering the following questions:

Q1. Are road segments with narrow lanes associated with more crashes?

Q2. Is the presence of a curb or parked cars immediately adjacent to the narrow outside lane more problematic than being immediately adjacent to a lane that is not narrow?

Table 2 provides the descriptive statistics for the roadway variables from the compiled data and new variables recoded or categorized from the original variables to answer the above questions. Because there is no obvious cutoff value for defining a narrow lane, researchers considered each of 12 feet, 11 feet, and 10 feet as a cutoff value. The variable Narrow_lt_12 is a categorized variable of outside lane width that is defined to be 1 if the outside lane width < 12 and 0 otherwise. Likewise, so are the variables Narrow_lt_11 and Narrow_lt_10. The variable Barrier_recoded is also a recoded variable of Barrier (original variable has 9 categories) for identifying roadway segments with curb or street parking.

Table 2. Descriptive Statistics for Roadway Segments.

Segment Variable Name	**Variable Description**	**Variable Types**	**Number of Segments (miles): 833 Segments (323.3 mi)**		
			Minimum	**Maximum**	**Average**
Outside_Ln_W	Outside lane width	Numerical	8	32	12.23
Total_Ln_W	Total lane width	Numerical	10	120	42.69
Avg_Ln_W	Average lane width	Numerical	9	32	12.40
Num_Ln	Number of lanes	Numerical	1	10	3.62
ADT_2016	2016 ADT	Numerical	0	201,699	21,932.2
Seg_Len_mi	Segment length in miles	Numerical	0.002	4.58	0.39
Barrier	Barriers on the side of road	Categorical	0: No barrier 1: Curb on one side 2: Curb on both sides 3: Street parking on one side 4: Street parking on both sides 5: Guard rail/fence/concrete wall on one side 6: Guard rail/fence/concrete wall on both sides 7: Other barriers on one side 8: Other barriers on both sides		
Bike_Shoulder	Existence of bike lane or shoulder	Categorical	0: No bike lane or shoulder 1: Bike lane or shoulder exists on one side 2: Bike lane or shoulder exists on both sides		
Variables Recoded					
Barrier_recoded	Barriers recoded	Categorical	None: Barrier = 0 Curb_StreetParking: Barrier = 1, 2, 3, or 4 Other: Barrier = 5, 6, 7, or 8		
Narrow_lt_12	Indicator variable for outside lane width that is less than 12	Categorical	1: Outside lane width < 12 ft 0: Outside lane width >= 12 ft		
Narrow_lt_11	Indicator variable for outside lane width that is less than 11	Categorical	1: Outside lane width < 11 ft 0: Outside lane width >= 11 ft		
Narrow_lt_10	Indicator variable for outside lane width that is less than 10	Categorical	1: Outside lane width < 10 ft 0: Outside lane width >= 10 ft		

The generalized linear models, specifically negative binomial regression models, were applied to assess the effects of outside lane width and barriers on relevant bus crashes. The general form of the expected number of crashes in a negative binomial regression model can be given as follows:

$$\mu_i = \exp\left(\beta_0 + \beta_c C_i + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki}\right)$$

where μ_i is the expected number of relevant bus crashes at Segment i, C_i is the number of comparison crashes at Segment i, $X_{1i}, \ldots, X_{ki}$ are the covariates/predictors corresponding to roadway characteristics of Segment i, and β_0, β_1, β_2,…, β_k are the regression coefficients. Note that inclusion of comparison crashes greatly helps with controlling for the effects of any extraneous factors that are not included explicitly as covariates/predictors in the above model.

After exploring various negative binomial regression model forms with different predictors and interaction terms, the model that included outside lane width (or a categorized version of it), Barrier_recoded, existence of bike lane or shoulder (Bike_Shoulder), log of segment length, and log of annual average daily traffic (AADT) as predictors seemed to be most appropriate for these data.

Temporal correlations in the crash counts obtained from the same road segment over 11 years were originally handled by employing two different approaches: (a) negative binomial regression analysis on the crash frequencies aggregated over 11 years, and (b) analysis on yearly crash frequencies using the negative binomial regression models with yearly trend and accounting for temporal correlations in the parameter estimation using the generalized estimating equations procedure. Similar conclusions were reached from both approaches. Only the results from the first approach are presented below.

RESULTS

For the first research question, the results suggest that there is a negative safety effect of the narrower outside lane width. Table 3 shows the estimates of the negative binomial regression model coefficients. The regression coefficient for outside lane width (Outside_Ln_W) was negative and statistically significant at $\alpha = 0.05$, which indicates a positive safety effect of the wider outside lane width (i.e., a smaller number of crashes is associated with wider outside lane width), or equivalently, a negative safety effect of the narrower outside lane width.

Table 3. Estimates of Regression Coefficients with Outside_Ln_W

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	−1.1439	0.5129	−2.1492	−0.1387	4.97	0.0257
Outside_Ln_W		1	−0.0945	0.0159	−0.1257	−0.0633	35.20	<.0001
Barrier_recoded	**Curb_StreetParking**	1	0.4914	0.1719	0.1545	0.8283	8.17	0.0042
Barrier_recoded	**None**	1	0.2289	0.1988	−0.1608	0.6185	1.33	0.2496
Barrier_recoded	**Other**	0	0.0000	0.0000	0.0000	0.0000	.	.
Bike_Shoulder	**0**	1	0.4870	0.1102	0.2710	0.7030	19.52	<.0001
Bike_Shoulder	**1**	1	−0.2250	0.2363	−0.6881	0.2381	0.91	0.3410
Bike_Shoulder	**2**	0	0.0000	0.0000	0.0000	0.0000	.	.
Log_Seg_Len		1	0.1720	0.0461	0.0816	0.2625	13.90	0.0002
Log_AADT		1	0.0625	0.0351	−0.0063	0.1313	3.17	0.0750
Dispersion		1	1.0093	0.0641	0.8912	1.1431		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

LR Statistics for Type 3 Analysis

Source	DF	Chi-Square	Pr > ChiSq
Outside_Ln_W	1	33.79	<.0001
Barrier_recoded	2	11.34	0.0034
Bike_Shoulder	2	25.43	<.0001
Log_Seg_Len	1	13.56	0.0002
Log_AADT	1	3.12	0.0773

Table 4 shows the estimates of the negative binomial regression model coefficients with a categorized outside lane-width variable Narrow_lt_11. The regression coefficient for Narrow_lt_11 (0.6396) was positive and statistically significant at $\alpha = 0.05$, which indicates that roadways with an outside lane width of less than 11 feet are associated with more crashes. The estimate for the percent crash increase (PCI) for roadways with an outside lane width of less than 11 feet (compared to roadways where the outside lane width is at least 11 feet) can be computed by $\{\mathrm{Exp}(\beta_{LW}) - 1\} \times 100$ where β_{LW} represents the estimated coefficient of Narrow_lt_11. Using the coefficient for Narrow_lt_11 in Table 4, the PCI can be computed as:

$$\mathrm{PCI}_{LW<11} = \{\mathrm{Exp}(0.6396) - 1\} \times 100 = 89.6 \text{ percent.}$$

Table 4. Estimates of Regression Coefficients with Narrow_lt_11.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.8786	0.4026	−3.6677	−2.0894	51.11	<.0001
Narrow_lt_11		1	0.6396	0.0871	0.4689	0.8103	53.93	<.0001
Barrier_recoded	**Curb_StreetParking**	1	0.3724	0.1713	0.0367	0.7081	4.73	0.0297
Barrier_recoded	**None**	1	−0.0370	0.1938	−0.4169	0.3430	0.04	0.8487
Barrier_recoded	**Other**	0	0.0000	0.0000	0.0000	0.0000	.	.
Bike_Shoulder	**0**	1	0.4671	0.1068	0.2578	0.6764	19.14	<.0001
Bike_Shoulder	**1**	1	−0.1771	0.2371	−0.6418	0.2877	0.56	0.4552
Bike_Shoulder	**2**	0	0.0000	0.0000	0.0000	0.0000	.	.
Log_Seg_Len		1	0.1734	0.0453	0.0846	0.2622	14.63	0.0001
Log_AADT		1	0.1181	0.0316	0.0562	0.1800	13.98	0.0002
Dispersion		1	0.9779	0.0627	0.8624	1.1090		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

LR Statistics for Type 3 Analysis

Source	DF	Chi-Square	Pr > ChiSq
Narrow_lt_11	1	53.97	<.0001
Barrier_recoded	2	16.38	0.0003
Bike_Shoulder	2	24.18	<.0001
Log_Seg_Len	1	14.28	0.0002
Log_AADT	1	13.57	0.0002

Table 5 shows the estimates of the negative binomial regression model coefficients with a categorized outside lane-width variable Narrow_lt_12. The regression coefficient for Narrow_lt_12 (0.6200) was again positive and statistically significant at $\alpha = 0.05$, which indicates that the roadways with an outside lane width of less than 12 feet are associated with more crashes. Using the coefficient for Narrow_lt_12 in Table 5, the percent crash increase for roadways with an outside lane width of less than 12 feet (compared to roadways where the outside lane width is at least 12 feet) can be computed as:

$$PCI_{LW<12} = \{ \text{Exp}(0.6200) - 1\} \times 100 = 85.9 \text{ percent.}$$

Table 5. Estimates of Regression Coefficients of with Narrow_lt_12.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.9256	0.4062	−3.7217	−2.1295	51.87	<.0001
Narrow_lt_12		1	0.6200	0.0872	0.4490	0.7910	50.50	<.0001
Barrier_recoded	Curb_StreetParking	1	0.4647	0.1721	0.1274	0.8020	7.29	0.0069
Barrier_recoded	None	1	0.1262	0.1952	−0.2564	0.5088	0.42	0.5180
Barrier_recoded	Other	0	0.0000	0.0000	0.0000	0.0000	.	.
Bike_Shoulder	0	1	0.4956	0.1084	0.2831	0.7081	20.90	<.0001
Bike_Shoulder	1	1	−0.1351	0.2375	−0.6005	0.3303	0.32	0.5694
Bike_Shoulder	2	0	0.0000	0.0000	0.0000	0.0000	.	.
Log_Seg_Len		1	0.1379	0.0456	0.0486	0.2272	9.16	0.0025
Log_AADT		1	0.0913	0.0324	0.0278	0.1548	7.94	0.0048
Dispersion		1	0.9867	0.0631	0.8705	1.1185		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

LR Statistics for Type 3 Analysis

Source	DF	Chi-Square	Pr > ChiSq
Narrow_lt_12	1	48.54	<.0001
Barrier_recoded	2	14.22	0.0008
Bike_Shoulder	2	25.49	<.0001
Log_Seg_Len	1	8.98	0.0027
Log_AADT	1	7.77	0.0053

To answer the second research question (on the interaction effect between outside lane width and the presence of a curb or parked cars immediately adjacent to the outside lane), an interaction term between Barrier_recoded and one of the categorized outside lane-width variable was also added to the negative binomial regression model. However, the interaction term is not statistically significant, which indicates that the effect of the presence of a curb or parked cars does not significantly change with the outside lane width. The coefficient for "Barrier_recoded = Curb_StreetParking" is consistently larger than the coefficient for "Barrier_recoded = None" throughout the tables above, which suggests that the presence of a curb or parked cars immediately adjacent to the outside lane is problematic whether the outside lane is narrow or not. This finding is statistically significant.

CONCLUSIONS

This study included a multifaceted approach to identify how lane widths influence bus crashes. Both the literature review and interview findings support a standard lane width of 11 to 12 feet for travel lanes that carry buses. Travel lanes narrower than 12 feet increase the likelihood of crashes due to the standard width of buses (including mirrors) and increase occurrence of lane departures. Only one city interviewed reported a standard less than 11 feet, but the interviewee added that their existing standard of 10.5 was too narrow and advocated for 11 feet as a minimum. Though NACTO Transit Street Design Guide states that travel lanes may be as narrow as 10 to 11 feet when adjacent to a bike lane or parking, it recommends travel lanes be at least 11 to 12 feet when adjacent to a curb or on a two-lane road with an opposing lane of bus traffic.

While the literature review and interviews show consistency on the minimum lane width for buses, the interviews provided context on how the standards for lane widths are actually designed and implemented in cities in North America. Though the design standard is between 11 and 12 feet, there is not always enough room for travel lanes to be designed at that width. Every interviewee reported that their city had travel lanes where buses operate that are narrower than that standard, in some cases as narrow as 9 feet. Interviewees indicated that while the 11- to 12-foot range is preferred, each roadway is unique, and the process of designing roadways happens on a case-by-case basis. In addition, both the literature review and interviews revealed that narrower lane widths result in slower speeds and therefore less catastrophic crashes. However, narrower lanes increase the likelihood of mirror strikes and sideswipes. And in the case of narrow travel lanes adjacent to bicycle lanes, narrower lanes increase the potential for interactions with bicyclists.

Results from the extensive bus crash analysis for the entire Capital Metro network are in line with the findings from the literature review and interviews. The evaluation suggests that more crashes occurred on outside lanes narrower than 12 feet; the PCI for roadways with an outside lane width less than 12 feet is 85.9 percent; the PCI for roadways with an outside lane width of less than 11 feet is 89.6 percent; and a barrier such as a curb or parked cars immediately adjacent to the outside lane is problematic in a 12-foot lane and an 11-foot lane. These are statistically significant findings.

As discussed earlier, each situation is unique and requires careful consideration when making decisions about lane width design. To say that all outside lane widths should be at least 12 feet to minimize sideswipe, fixed-object, and mirror-to-mirror bus crashes would miss the point of designing for all users. Transit agencies, such as Capital Metro, have a responsibility to address safety in their community and for their customers who likely walked or bicycled to the transit stop. As such, taking a holistic approach to balance the possible increase in minor crashes with an increase in safety for people driving, walking, or bicycling is recommended. The process of deciding the ideal lane width is a negotiation among cities and transit agencies, and the bottom line is that there is a balancing act wherein decision makers must consider safety, the comfort of all users, and providing facilities for numerous modes.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: BD, BE, EP, JH; literature review: BE; interviews: BE and JH; data collection and preparation: BD; analysis and interpretation of results: EP; and draft manuscript preparation: BD, BE, EP, JH. All authors reviewed the results and approved the final version of the manuscript.

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