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Route Segment Level Analysis of Bus Safety Incidents

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Route Segment Level Analysis of Bus Safety Incidents

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ROUTE SEGMENT LEVEL ANALYSIS OF BUS SAFETY INCIDENTS

Final Report

OTREC-RR-462

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16. Abstract

This paper analyzes collision and non-collision incidents that occurred on TriMet's bus system over a near two-year period. The bus route network was decomposed into stop and line haul segments, and a typology of models was estimated from segment level incident, risk exposure, and roadway feature data. The frequency of non-collision incidents – mainly slips, trips and falls – was estimated to be primarily related to associated risk exposure variables. The frequency of collision incidents was also estimated to be related to risk exposure variables, as well as a number of roadway design variables. The findings serve as an initial step in informing the safety planning process.

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ABSTRACT

This paper analyzes collision and non-collision incidents that occurred on TriMet's bus system over a near two-year period. The bus route network was decomposed into stop and line haul segments, and a typology of models was estimated from segment level incident, risk exposure, and roadway feature data. The frequency of non-collision incidents – mainly slips, trips and falls – was estimated to be primarily related to associated risk exposure variables. The frequency of collision incidents was also estimated to be related to risk exposure variables, as well as a number of roadway design variables. The findings serve as an initial step in informing the safety planning process.

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INTRODUCTION

The U.S. transit industry's safety performance record compares very favorably to other surface travel modes (*APTA, 2012*). Building on this record, MAP-21 (*PL 112-141*) includes provisions that call for the development of a more comprehensive approach to monitoring transit safety performance, analyzing the factors that contribute to safety risk, and identifying opportunities for mitigating risk. As implemented by the Federal Transit Administration (FTA), this new approach will embrace a safety management system (SMS) framework (*Ahmed, 2010; FTA, 2013a*).

One of the cornerstone objectives of the SMS framework relates to enhancing the capacity of transit agencies to use data to identify risk factors in order to address the hazards that contribute to various types of operational safety incidents. Such safety risk factors encompass human (e.g., operator training and behavior), design (e.g., vehicles), and environmental (e.g., service planning and delivery) dimensions.

From a general standpoint, empirical analysis of safety risk factors in bus operations can be characterized by an orientation toward either operators or the operating environment. For example, research focused on operators has been concerned with the effects of stress, fatigue, demographics, experience, and training (*Greiner et al., 1998; Moffat et al., 2001; Sando et al., 2011; Strathman et al., 2010*). Alternatively, research focused on the operating environment has concentrated on the effects of safety hazards represented in route design, roadway engineering features, and traffic conditions (*Cheung et al., 2008; Chimba et al., 2010; Shahla et al., 2009*).

The present study adopts the latter orientation in analyzing bus collision and non-collision incidents. TriMet, the transit service provider for the Portland, OR region, is the subject of the analysis. TriMet's bus system consists of 79 routes and 6,800 stops, which serve a 524-square-mile service area with 1.5 million residents. In 2011 the agency's fleet of 520 buses logged over 19 million revenue service miles and carried over 58 million unlinked passenger trips.

The focus on TriMet's bus system offers several advantages. First, the agency has reviewed and geocoded all of its bus collision and non-collision incidents since December 2010, which allows analysis of incidents in relation to the site-specific characteristics of its route network. Second, TriMet maintains an extensive warehouse of transit ITS and other operational data that facilitates documentation of risk exposure, especially as it relates to bus passengers involved in non-collision incidents (e.g., slips, trips and falls).

The remainder of this paper is organized as follows: The next section describes the study design and methodology. This is followed by a discussion of incident patterns and a presentation of the results of statistical analyses of collision and non-collision incidents. The concluding section then discusses the principal findings and their implications.

STUDY DESIGN AND METHODOLOGY

The first step in designing an empirical study of safety incidents that occurred on the bus system involves defining the unit of analysis. From a geographic standpoint, this definition essentially relates to delineating a segmentation scheme for logically decomposing the bus route network into its constituent units. These route segments, in turn, provide a structure for populating a dataset containing incidents, route and roadway design, operations, and other information.

A logical route segmentation scheme that follows from the transit safety literature is to distinguish stop zones from the remainder of the route network. This scheme corresponds to specific hazards and differential safety risks that have been observed at or in the vicinity of stops (*Hess et al., 2004; Pecheaux et al., 2008; Truong et al., 2011; Wahlberg, 2004*). These risks are related to the boarding and alighting of passengers; the closer proximity of passengers, pedestrians, fixed objects, parked cars, and other moving vehicles to buses pulling into and out of stops; and the location of most stops at roadway intersections, where turning actions and cross traffic pose greater risks to buses and their passengers. Thus, the route segmentation process for this study began by using a geographic information system (GIS) to delineate a 75-foot radius buffer around each stop in the bus route system, creating what will subsequently be referred to as *stop segments*. Given the creation of stop segments, a GIS was then used to delineate each of the remaining route portions that connect the stop segments. These latter links will be referred to as *line haul segments*. Application of this segmentation scheme to TriMet's bus route network produced 6,800 stop and 7,320 line haul segments.

With stop and line haul segments delineated, the next step entailed the creation of segment data records for subsequent analysis. This process began with the assignment of 1,664 geocoded collision and non-collision incidents that occurred on the bus system between December 1, 2010 and September 1, 2012. Selected risk exposure data for this period were retrieved from TriMet's enterprise data warehouse. These data are recovered daily by TriMet's computer-aided dispatch/automated vehicle location (CAD/AVL) system and are referenced to stop locations. Line haul segment exposure values were interpolated from the nearest stop location. CAD/AVL exposure data included the number of bus trips traversing a segment over the study period, the number of routes serving a segment, the number of lift operations, total boardings and alightings, and the average passenger load per trip. Passenger movement data are recovered by automatic passenger counters (APCs), which have been deployed fleet-wide. Segment lengths were derived by a GIS for the line haul segments. The final exposure variable was a segment level estimate of average daily PM peak traffic volume, produced by a travel demand model maintained by the Portland region's metropolitan planning organization.

Segment-level route and roadway design data included counts of total, signalized, and signalized with transit priority intersections; the number and width of directional travel lanes; the presence of center turning lanes; posted speed; the number of route turns; the presence of striped bike lanes; the presence of on-street parking; the presence of a bus-only travel lane; the presence of a bus pullout lane at stops; stop location (i.e., mid-block, intersection near-side, and intersection far-side); and the existence of a transfer point at stops (i.e., to other bus routes, light and commuter rail, and street car). Given that no cyclist volume data were available, the presence of a striped bike lane in a segment thus served as a crude cyclist risk exposure proxy.

With respect to methodology, the objective of the study's empirical analysis is to estimate the effects of the exposure, route, and roadway design factors on the frequency of collision and non-collision incidents for both stop and line haul segments. One frequently observed characteristic of segment-level incident data is that it is not normally distributed. In this study, a substantial majority of stop and line haul segments experienced no incidents during the study period, which produced incident frequency distributions with a strong left skew and over-dispersion. As in other instances where such frequency distributions have been encountered (e.g., *Cheung et al., 2008; Chimba et al., 2010; Shahla et al., 2009; Strathman et al., 2010; Washington et al., 2003*), this study employs negative binomial estimation in relating incident counts to their underlying contributing factors.

There is also an interest in addressing more specific types of safety incidents. For example, in 2011, collisions with pedestrians accounted for over 40% of all bus-involved fatalities in the U.S. transit industry (*FTA, 2013b*), and gaining a better understanding of contributing risk factors would potentially have very beneficial consequences. However, the actual frequency of collisions with pedestrians is quite small. Data for the present study include just 17 such incidents, or about 2% of all collisions. Furthermore, no study route segment experienced more than one pedestrian collision. In such circumstances, logit is preferable to a negative binomial estimation. Nevertheless, given that the nominal odds in this study of observing a pedestrian-involved collision in any given study segment are about one-in-830, the prospect that even an appropriate estimator will identify significant contributors to safety risk is fairly limited. A similar assessment pertains to collisions involving cyclists, which totaled 14 during the study period.

In the present study, pedestrian and cyclist-involved incidents represent the most limiting estimation cases. More common are mirror strikes and collisions with fixed objects or parked cars, which are typically associated with bus maneuvers in tight spaces. For modeling purposes these incidents were combined to form *clearance* collisions. In other instances, such as collisions involving other vehicles, the incident frequencies are large enough to allow negative binomial estimation of a specific incident type.

RESULTS

The presentation of results begins with a description of the data by incident and route segment type. The description also covers associated risk exposure measures and corresponding incident rates. The discussion then proceeds to a presentation of negative binomial and logit parameter estimates for various collision and non-collision models.

Table 1 provides a breakdown of the 1,664 collision and non-collision incidents that occurred during the study period, along with information on risk exposure and incident rates. Overall, about 65% of the collision incidents and 80% of the non-collision incidents occurred within the stop segments of the bus route network. It is also apparent that the composition of collision and non-collision incident types differs between stop and line haul segments. For example, mirror strikes and collisions with parked vehicles account for a relatively greater share of all collisions in stop segments, reflecting the limited clearances that buses often encounter as they move out of and into the traffic stream to service stops. The share of collisions with pedestrians is also greater in stop segments, in part reflecting greater risk exposure associated with the access and egress movements of passengers. In contrast, collisions with other vehicles make up a relatively greater share of collisions in line haul segments, as does the share of other collisions (which oftentimes involved animal strikes). Lastly, the shares of collisions with cyclists within the stop and line haul segments are equivalent.

Non-collision incidents almost always involve passengers, and thus tend to occur more frequently at locations where there is passenger movement. Nearly half of the non-collision incidents in stop segments were directly associated with the boarding and alighting process. It is also likely that a number of the other on-bus incidents in stop segments were related to slips, trips and falls that occurred as passengers intending to alight were moving toward the bus exits. About 10% of the non-collision incidents in stop segments involved a slip, trip or fall of a passenger who was running to catch the bus.

A great majority of the non-collision incidents that occurred in the line haul segments involved onboard passengers. In limited circumstances, TriMet will drop off or pick up bus passengers at locations other than designated stops, and the relatively small share of boarding and alighting incidents that occurred in the line haul segments reflects this practice.

Table 1 also presents information on four measures of risk exposure: (bus) vehicle miles, passenger miles, boardings and alightings, and lift operations. Each of these metrics is relevant to particular circumstances. For example, bus vehicle miles provides a good measure of risk exposure for collision incidents, while lift operations provides a good measure of risk exposure for incidents involving the boarding and alighting of passengers using wheelchairs or other mobility devices. The geographic resolution of the boarding and alighting metrics is somewhat constrained in that APC and lift event data records are written to the nearest stop location. Thus the vehicle mile and passenger mile risk exposure metrics can be determined for both line haul and stop segments, while the validity of the boarding/alighting and lift metrics is limited to the combination of stop and line haul segments.

The vehicle and passenger mile information in Table 1 clearly indicate the greater collision risk that exists in stop segments. For example, while bus movements within stop segments accounted for 16% of total vehicle miles during the study period, collisions in stop zones accounted for 64% of all collision incidents. In other words, accounting for vehicle miles, collisions in stop zones were overrepresented by a factor of four.

Table 1 Breakdown of Bus Safety Incidents, December 2010-September 2012

	Line Haul Segments		Stop Segments		All Segments	
Characteristics	**Number**	**%**	**Number**	**%**	**Number**	**%**
A. Collision Incidents						
1. Fixed Object	25	7.8	36	6.4	61	6.9
2. Mirror Strike	65	20.2	194	34.3	259	29.2
3. Parked Vehicle	24	7.4	55	9.7	79	8.9
4. Vehicle in Traffic	187	58.1	250	44.2	437	49.3
5. Pedestrian	3	0.9	14	2.5	17	1.9
6. Cyclist	5	1.6	9	1.6	14	1.6
7. Other	13	4.0	7	1.2	20	2.2
8. Total Collisions	322	100.0	565	100.0	887	100.0
B. Non-Collision Incidents						
9. On-Bus	160	100.0	556	90.1	716	92.1
- Regular Boarding/Alighting	14	8.8	239	38.7	253	32.6
- Lift Boarding/Alighting	5	3.1	58	9.4	63	8.1
- Other On-Bus	141	88.1	259	42.0	400	51.5
10. Off-Bus	0	0.0	61	9.9	61	7.8
11. Total Non-Collision	160	100.0	617	100.0	777	100.0
C. Collision & Non-Collision						
12. Total Incidents	482	--	1,182	--	1,664	--
D. Risk Exposure						
13. Boardings + Alightings (in 000s)	--	--	--	--	205,503	--
14. Lift Operations (in 000s)	--	--	--	--	1,110	--
15. Vehicle Miles (in 000s)	26,711	--	5,015	--	31,816	--
16. Passenger Miles (in 000s)	248,059	--	56,168	--	304,227	--
E. Incident Rates						
17. Collisions Per Million Vehicle Miles	12.1	--	112.7	--	27.9	--
18. Collisions Per Million Passenger Miles	1.3	--	10.1	--	2.9	--
19. N-Cs: Reg. B/A Per Million B/As	--	--	--	--	1.2	--
20. N-Cs: Lift B/A Per Million Lift Ops.	--	--	--	--	56.8	--
21. N-Cs: Other On-Bus/Mil. B/As	--	--	--	--	1.9	--
22. N-Cs: Off-Bus Per Million B/As	--	--	--	--	0.3	--

The bottom panel of Table 1 draws on the exposure metrics to derive incident rates. For the vehicle and passenger mile metrics, this provides another means of documenting collision risk and distinguishing risk levels between stop and line haul segments. Thus, we see that the vehicle mile-based collision risk for stop segments (112.7 collisions per million vehicle miles) is about nine times greater than the corresponding risk for line haul segments, while the passenger mile-based collision risk (10.1 collisions per million passenger miles) is about eight times greater.

TriMet is one of the few (if not the only) metropolitan transit provider with fleet-wide deployment of APCs. This ensures that the passenger boarding/alighting exposure metric is not subject to sampling error. In addition, there appears to be no reference in the transit literature to the use of lift operation event data to represent risk exposure for wheelchair or other mobility impaired passengers in fixed route bus service. Thus, a fairly rigorous documentation of boarding/alighting safety risk in these two contexts can be obtained. With respect to the boarding and alighting process, the risk differences are fairly considerable. The incident risk for lift-using passengers (56.8 incidents per million lift operations) is 47 times greater than it is for passengers using the stairs. More generally, the National Highway Traffic Safety Administration (NHTSA) found that lift malfunctions and falls from ramps accounted for 25% of fatalities and injuries to wheelchair users in incidents involving all motor vehicles (*NHTSA*, *1997*), while Frost et al (*2007*) found that 43% of all wheelchair-involved incidents on Louisville's fixed route bus system occurred during the boarding/alighting process. Lastly, although the boarding and alighting process is considered to represent a relatively greater source of safety risk (e.g., *Hundenski*, *1992*), the study period data indicate that on-board risk (1.9 non-collision incidents per million boardings and alightings) is about 60% greater than the boarding and alighting risk of stair-using passengers.

Parameter estimates (with standard errors in parentheses) for the models addressing various types of collision and non-collision incidents are presented in Tables 2 and 3, respectively. Given that the parameters themselves are not directly interpretable, the discussion will first focus on the general direction and pattern of the estimated effects of the specified variables across incident types. Following this discussion, the derived elasticities (from the negative binomial parameters) or odds ratios (from the logit parameters) for statistically significant parameters will be presented. The odds ratios and elasticity values more clearly portray the magnitude of the effects of given model variables on incident occurrences.

Table 2 presents results for models covering bus collisions in line haul and stop segments. Results are presented for models of total collisions, as well as sub-models covering clearance collisions and collisions with other vehicles (in line haul segments), and clearance collisions, collisions with other vehicles, and collisions with pedestrians (in stop segments). The pedestrian collision model's parameters are logit estimates, while the remaining models' parameters are negative binomial estimates.

Among the exposure variables in the collision models, the volume of bus trips in the line haul and stop segments has the most consistent and significant effect across the various types of collisions. A polynomial transformation of the bus trip variable provided the best statistical fit, and the resulting estimates indicate that the expected collision frequencies increase at a decreasing rate with bus trip volumes. In contrast, the effects of afternoon peak traffic volumes are more selective, having positive effects on bus clearance collisions in line haul segments and on vehicle and clearance collisions in stop segments.

The volume of boardings and alightings was hypothesized to have a positive effect on collisions with pedestrians in stop zones, but the estimated parameter for this variable was not significant. Also, while expected collision frequencies in other traffic safety studies (*Hadi et al., 1995; Strathman et al., 2003*) were found to increase with segment length, the reverse is estimated to be the case for bus collisions with other vehicles in the line haul segments. In the present study, the longest line haul segments occur on express routes (often traversing freeways), and the longer segment lengths in this case may thus be confounded with design features that were not accounted for in the models (e.g., limited access, medians, shoulders).

Turning to roadway design features, the expected frequency of clearance and vehicle collisions on line haul segments is estimated to be inversely related to the width of travel lanes, while the reverse is estimated to be the case for collisions with vehicles in stop zones. The latter was not expected, and one speculation for this finding is that other motorists may be more inclined to pass a bus serving a stop when travel lanes are wider. Although Oregon law requires other vehicles to yield to buses pulling out of stops, operators indicate that failure to yield in such circumstances is nevertheless fairly common (*Strathman et al., 2013*). Expected collisions with other vehicles in line haul segments are also estimated to be greater on one-way streets. Here again, operators indicated that motorists attempting to make a right turn from the left lane on one-way streets represented a common "close call" safety problem (*Strathman et al., 2013*).

The existence of center turning lanes was estimated to have the expected positive effect on bus collisions with other vehicles in line haul segments. However, it was also estimated to have a negative effect on clearance collisions in both line haul and stop segments. The expected frequency of clearance collisions was estimated to be lower in stop zones located along exclusive bus lanes, likely reflecting the simpler pull-in/pull-out maneuver required.

In other traffic safety studies, expected collision frequencies have been found to be inversely related to posted speeds, reflecting the greater safety margins designed into higher speed roadways (*Hadi et al., 1995; Shankar et al., 1997; Strathman et al., 2003*). In the present study, it was hypothesized that a positive relationship might occur in stop zones, given that the pull-in and pull-out processes would seem to be riskier when the traffic stream is moving at higher speeds. However, posted speeds were found to be unrelated to all bus collision types in both stop and line haul segments.

Table 2 Estimation Results for the Collision Models

Variable	Line Haul Segments			Stop Segments			
	All Collisions	**With Vehicles**	**Clearance Collisions**	**All Collisions**	**With Vehicles**	**Clearance Collisions**	**With Pedestrians**
Bus Trips (0000s)	0.4777* (.0858)	0.4953* (.1092)	0.4831* (.1501)	0.3164* (.0610)	0.3384* (.0694)	0.2661* (.0820)	1.3626* (.5178)
Bus Trips $(000s)^2$	-0.0239* (.0068)	-0.0223* (.0083)	-0.0338* (.0137)	-0.0087* (.0034)	-0.0090* (.0042)	-0.0067 (.0044)	-0.0877* (.0411)
Traffic Volume (000s)	0.0502 (.0344)	0.0400 (.0497)	0.0831** (.0428)	0.1185* (.0471)	0.0979* (.0471)	0.1569* (.0715)	0.1989 (.2051)
Traffic Volume $(000s)^2$	-0.0015 (.0013)	-0.0019 (.0020)	-0.0013 (.0013)	-0.0048* (.0020)	-0.0031** (.0019)	-0.0074* (.0034)	-0.0129 (.0100)
Boardings+Alightings (000s)	--	--	--	0.0006 (.0009)	0.0008 (.0011)	0.0003 (.0012)	.00325 (.00349)
Segment Length (ft.)	-0.0002* (.0001)	-0.0002* (.0001)	-0.0001 (.0001)	--	--	--	--
No. of Directional Travel Lanes	0.0165 (.1430)	0.0617 (.1793)	-0.0808 (.2348)	0.0334 (.0191)	-0.0435 (.1795)	0.0859 (.2400)	0.9181 (.5624)
Lane Width (ft.)	-0.0912* (.0393)	-0.0815** (.0484)	-0.1453* (.0669)	0.0274 (.0261)	0.0530* (.0250)	0.0077 (.0395)	0.0016 (.1135)
One-way Street	0.4852** (.2586)	0.8808* (.3294)	0.1478 (.4109)	-0.0996 (.2847)	-0.4428 (.3286)	0.2008 (.3848)	-0.2150 (1.0003)
Center Turning Lane(s) in Segment	0.1203 (.1818)	0.5334* (.2355)	-0.6711* (.3411)	-0.3662** (.2001)	-0.2162 (.2010)	-0.5167** (.3068)	0.5626 (.7061)
Bus-Only Lane Within Segment	0.1169 (.3435)	0.0430 (.4307)	0.3423 (.5645)	-1.2378* (.5398)	-0.5886 (.5597)	-1.9338* (.8425)	-0.8405 (1.7110)
Posted Speed	-0.0178 (.0244)	0.0136 (.0329)	-0.0363 (.0397)	-0.0785 (.0520)	-0.0673 (.0567)	-0.0596 (.0761)	-0.0069 (.2381)
Posted $Speed^2$	0.0002 (.0002)	-0.0001 (.0003)	0.0002 (.0005)	0.0011 (.0009)	0.0010 (.0009)	0.0006 (.0013)	-0.0007 (.0042)
Bike Lane Within Segment	-0.4536* (.1706)	-0.3518** (.2163)	-1.0547* (.3161)	-0.4169* (.1753)	-0.1832 (.1791)	-0.7134* (.2625)	-0.3271 (.6499)
Intersections	0.1453* (.0343)	0.1509* (.0442)	0.1338* (.0551)	--	--	--	--
Signalized Intersections	0.5872* (.1565)	0.6287* (.1979)	0.5763* (.2587)	0.5489* (.2558)	0.6983* (.2517)	0.3084 (.3986)	1.6606** (.9027)

Signalized w/ Transit Priority	-0.1368 (.0894)	-0.0794 (.1086)	-0.2191 (.1552)	0.1885 (.2529)	0.1017 (.2540)	0.4162 (.3788)	-1.4013** (.8040)
Route Turns Within Segment	1.0181* (.1660)	0.9486* (.2168)	1.1161* (.2534)	0.4640* (.2135)	0.4259** (.2350)	0.4292 (.2952)	2.0236* (.6906)
On-Street Parking Within Segment	0.0830 (.1737)	-.03953 (.2435)	0.7586* (.2668)	0.2902 (.1800)	0.1707 (.1964)	0.3815 (.2504)	-0.3432 (.7512)
No. of Bus Routes Within Segment	0.1028 (.0791)	0.0253 (.1206)	0.2519* (.0864)	-0.1187 (.0827)	-0.1624** (.0963)	-0.0990 (.1115)	0.0560 (.1913)
Bus Turnout Lane at Stop	--	--	--	-0.0271 (.3084)	0.1690 (.2835)	-0.2756 (.5278)	-0.7273 (1.2238)
Average Passenger Load Per Trip	0.0042 (.0147)	0.0165 (.0189)	-0.0186 (.0234)	0.0275** (.0165)	0.0320** (.0176)	0.0210 (.0233)	0.0269 (.0588)
Near-Side Stop	--	--	--	0.7867* (.2983)	0.6958* (.3086)	1.3060* (.5060)	-1.6211* (.7833)
Far-Side Stop	--	--	--	0.7232* (.3187)	0.8413* (.3233)	0.9966** (.5376)	-0.8717 (.8765)
Transfer Point: Max	--	--	--	-0.3060 (.3796)	-0.1446 (.3406)	-0.8886 (1.1528)	0.3347 (.4993)
Transfer Point: Streetcar	--	--	--	-1.2059 (1.1754)	--	-0.7532 (1.1628)	--
Transfer Point: Commuter Rail	--	--	--	1.4763* (.5949)	1.6206* (.4768)	--	--
Number of Lift Operations	--	--	--	0.0002** (.0001)	0.0001 (.0002)	0.0003 (.0002)	-0.0004 (.0006)
Intercept	-3.9013* (.7546)	-5.4360* (.9868)	-3.6698* (1.166)	-3.9699* (.9759)	-5.3293* (1.0510)	-4.9083* (1.4346)	-10.8458* (4.2877)
ρ***	0.38	0.42	0.64	0.26	0.68	.33	
Likelihood Ratio (χ^2, 26 D.F.)	--	--	--	--	--	--	51.66
Sample Size	7303	7303	7303	6794	6794	6794	6794

* Signicant at the .05 level or lower. ** Significant at the .051-.10 level.

*** $\rho = 1-(LL_\beta/LL_0)$, where LL_β = the log likelihood value at convergence and LL_0 = the log likelihood value with all parameters set a zero.

Given the very small number of incidents, it was not possible to obtain robust estimates for a model of cyclist-involved bus collisions. However, the existence of a bike lane was estimated to be inversely related to vehicle and clearance collisions in line haul segments, and with clearance collisions in stop segments, indicating that these facilities may be providing a buffer space between buses and various other collision hazards.

The expected number of vehicle and clearance collisions was estimated to increase with the number of intersections contained in line haul segments. This result is consistent with Yang's (*2007*) analysis of NTD data, which found that about 80% of major bus collisions occurred at or near intersections. Estimated collision frequencies are yet greater for signalized intersections, likely reflecting the correspondingly greater volumes of cross traffic and turning movements that occur in that setting.

A notable finding is the estimated increased likelihood of a pedestrian-involved collision at signalized intersections in stop zones. However, this likelihood is nearly offset when the signalization includes a transit priority feature. Thus, while the intent of transit priority signalization is to give late-running buses an opportunity to gain on their schedule, it appears that it is providing a safety benefit as well. Alternatively, these findings may also indicate that in the absence of transit priority, some late-running operators may be pressing their luck in attempting to "beat the signal" and catch up to their schedule, which is consistent with Strathman et al.'s (*2010*) finding that late-running bus operators had a greater estimated likelihood of collisions.

The existence of route turns in both line haul and stop segments is estimated to result in increases in nearly all types of collisions. Even when a turn is properly executed, bus clearances narrow with opposing and cross-street vehicle traffic, parked cars, fixed objects, cyclists, and pedestrians. Blind spots from posts and pillars in the operator's cabin and in the field of vision covered by bus mirrors can also attenuate turning-related safety risks (*Pecheaux et al., 2008; Technology and Management Systems, 2001*).

Not surprisingly, the presence of on-street parking in line haul segments increases the estimated expected frequency of clearance collisions. Similar findings were obtained by Chimba et al. (*2010*) and Wahlberg (*2004*).

Beyond the number of bus trips, the collision models account for the number of bus routes that traverse the line haul and stop segments. Considering that buses serving a given route are separated by their scheduled frequencies, increasing the number of routes in a segment thus adds to the number of distinct schedules and increases the potential for bus-to-bus conflicts. This circumstance is most apparent in Portland's downtown transit mall, where many of TriMet's radial bus routes converge. One evident consequence of this concentration of routes is the incidence of bus-to-bus mirror strikes, which may underlie the positive clearance collision parameter for line haul segments. Also, buses travel along exclusive bus lanes in the transit mall, and this may underlie the logic of the negative vehicle collision parameter for stop segments.

Passenger loads were estimated to positively affect the expected frequency of collisions with vehicles in stop segments. The greatest passenger loads on TriMet's bus system tend to occur on crosstown routes, which make fairly frequent stops. Bus rear-end collisions can thus result from the vehicle queues that build up behind buses. If so, the estimated load effect may be confounded with factors associated with operating conditions that vary across the route typology.

Regarding the placement of bus stops, locations at both the near and far side of intersections are estimated to experience an increase in vehicular and clearance collisions, compared to mid-block stop locations. Differences between the estimated near- and far-side parameters themselves are not significant, in contrast to other studies that have found a lower incidence of collisions at far-side stops (*Shahla et al., 2009; Cheung et al., 2008*). In contrast, logit parameter estimates indicate that the odds of a pedestrian collision are lower at near-side than mid-block stop locations. This finding is consistent with a reported disadvantage of mid-block stop locations – that intending and alighted passengers are more likely to jaywalk rather than use the nearest marked crossing (*Technology and Management Systems, 2001*).

Some stops on the bus system serve as transfer points to other bus routes, as well as to the commuter rail, light rail, and streetcar services that TriMet provides. The expected number of collisions with other vehicles is estimated to be greater at transfer locations to commuter rail, compared to transfer locations to other bus routes.

Compared to the collision models, the estimation results for the non-collision models (shown in Table 3) are more predominantly associated with exposure-related variables. As one might expect, slip, trip and fall incidents of on-board passengers in line haul segments are estimated to increase with the volume of bus trips, the number of intersections, and the number of route turns. Such incidents are also estimated to be inversely related to segment length.

On-board slips, trips and falls in stop segments are the only type of non-collision incident that is estimated to be related to traffic volume, possibly as a result of hard stops or evasive actions taken to avoid other vehicles as a bus pulls out of or into the traffic stream in serving a stop. The expected frequency of these incidents is also estimated to be positively related to the number of lift operations, a possible indication of inadequate or non-securement of wheelchair passengers. Such incidents are also estimated to occur more frequently at transfer points to commuter rail service. Lastly, these incidents are estimated to be positively related to average loads, indicating a relatively greater likelihood of slips, trips and falls involving standing passengers.

Table 3 Estimation Results for Non-Collision Models

	Line Haul	Stop Segments			
Variable	**Slip: On-Board**	**Slip: On-Board**	**B/A Slip: Stairs**	**B/A Slip: Lift**	**Slip: Off Vehicle**
Bus Trips (0000s)	0.6375* (.1447)	0.3255* (.0701)	.3827* (.0907)	0.2535* (.1060)	0.4631* (.1530)
Bus Trips $(000s)^2$	-0.0326* (.0111)	-0.0106* (.0045)	-0.0168* (.0054)	-0.0052 (.0056)	-0.0167* (.0027)
Traffic Volume (000s)	0.0352 (.0472)	0.0837** (.0481)	0.0250 (.0422)	0.1239 (.0796)	0.1089 (.0979)
Traffic Volume $(000s)^2$	-0.0005 (.0015)	-0.0034** (.0019)	-0.0011 (.0017)	-0.0031 (.0033)	-0.0052 (.0048)
Boardings+Alightings (000s)	--	0.0036* (.0015)	0.0072* (.0015)	0.0020 (.0013)	0.0068* (.0027)
Boardings+Alightings $(000s)^2$	--	-0.00001* (.000005)	-0.00001* (.000005)	--	-0.00001* (.000005)
Number of Lift Operations	--	0.0003* (.0001)	0.0002 (.0001)	0.0004* (.0002)	0.00001 (.00001)
Segment Length (ft.)	-0.0002** (.0001)	--	--	--	--
No. of Directional Travel Lanes	0.1258 (.2361)	0.1391 (.1572)	0.2725 (.1677)	0.0584 (.2890)	-0.1473 (.3243)
Lane Width (ft.)	-0.0047 (.0563)	-0.0170 (.0344)	0.0680* (.0239)	0.0242 (.0520)	0.0512 (.0437)
One-way Street	-0.9050 (.4865)	0.1260 (.2778)	-0.4000 (.3086)	0.3475 (.5091)	0.0061 (.5212)
Center Turning Lane(s) in Segment	0.3071 (.2714)	0.1124 (.1863)	0.0567 (.2172)	0.5405 (.3725)	0.2057 (.4185)
Bus-Only Lane Within Segment	0.6317 (.4990)	-0.5362 (.4576)	0.0424 (.3866)	0.5107 (.6628)	0.2289 (.6449)
Posted Speed	-0.0485 (.0400)	0.0247 (.0556)	0.0757 (.0576)	0.1711 (.1125)	-0.0251 (.0870)
Posted $Speed^2$	0.0004 (.0004)	-0.0001 (.0009”)	-0.0015 (.0010)	-0.0043* (.0021)	0.0005 (.0015)
Bike Lane Within Segment	0.2107 (.2614)	0.0027 (.1700)	0.0103 (.1859)	-0.4023 (.3428)	0.2567 (.3674)
Intersections	0.1493* (.0611)	--	--	--	--
Signalized Intersections	0.7811* (.2489)	0.7059* (.2396)	0.6993* (.2913)	1.1633* (.4457)	0.2339 (.5932)
Signalized w/ Transit Priority	-0.1549 (.1475)	-0.0704 (.2388)	-0.2398 (.2868)	-0.8124** (.4598)	0.2373 (.5544)
Route Turns Within Segment	1.2098* (.2643)	0.1772 (.2587)	-0.0622 (.2777)	0.3219 (.4490)	0.3248 (.4725)
On-Street Parking in Segment	-0.2480 (.2939)	0.0688 (.1962)	0.1086 (.2161)	-0.0224 (.3755)	-0.0137 (.4338)
No. of Bus Routes in Segment	0.1169 (.1142)	-0.0562 (.0697)	-0.0505 (.0609)	-0.4284* (.1937)	-0.0965 (.1194)
Bus Turnout Lane at Stop	--	-0.2717 (.2992)	0.3492 (.2666)	0.6878 (.4477)	0.7253 (.4817)
Average Passenger Load Per Trip	0.0363 (.0238)	0.1473* (.0708)	0.0126 (.0189)	-0.0293 (.0325)	0.0684 (.1302)
Near-Side Stop	--	0.1865 (.2503)	-0.1909 (.2418)	-0.2654 (.4348)	-0.0192 (.4596)

Far-Side Stop	--	-0.0082 (.2850)	-0.2380 (.2810)	0.1550 (.4738)	-0.4871 (.5834)
Transfer Point: Max	--	-0.0463 (.1989)	-0.0158 (.1691)	-0.2496 (.2772)	0.2603 (.1962)
Transfer Point: Streetcar	--	0.3387 (.5118)	0.3032 (.4627)	0.0210 (1.0223)	--
Transfer Point: Commuter Rail	--	1.4736* (.4961)	0.4632 (.4136)	0.4251 (.6450)	0.7395 (.5310)
Intercept	-6.1491* (1.1920)	-6.9489* (1.1346)	-7.1928* (.9491)	-7.4934* (1.8338)	-7.4457* (1.6963)
ρ	0.21	0.58	0.41	--	0.57
Likelihood Ratio (χ^2, 26 D.F.)	--	--	--	117.05	--
Sample Size	7303	6794	6794	6794	6794

* Significant at the .01 level or lower. ** Significant at the .051-.10 level.

Within stop segments, many slip, trip and fall incidents are either directly or indirectly related to the boarding and alighting process. Separate results were obtained for incidents associated with lift operations and those associated with boarding and alighting via the bus stairs. The latter incidents are estimated to be positively related to the volume of bus trips, the volume of boardings and alightings, lane width, and the location of stops at signalized intersections. Lift incidents are estimated to be positively related to the volume of bus trips, the number of lift operations, and stop locations at signalized intersections. As with the collision results, the positive “signalization effect” is nearly offset when signalization includes a transit priority feature. The expected number of lift-related incidents is also estimated to be negatively related to the number of bus routes serving a stop segment, and this effect may again be potentially attributable to the downtown transit mall, where stops are designed to facilitate the boarding and alighting of larger numbers of passengers.

Lastly, off-bus slip, trip and fall incidents (which mainly involve intending passengers) are estimated to be positively related to two risk exposure variables: the volume of bus trips and the volume of boardings and alightings.

Associated elasticity values for the negative binomial parameter estimates, and odds ratios for the logit parameter estimates, were derived using procedures presented in Washington et al. (*2003*). For continuous variables in the negative binomial models, the elasticity values represent the proportionate change in the expected frequency of collision or non-collision incidents given a proportionate change in a given variable. The elasticity value for dummy variables in the negative binomial models represents the proportionate change in the expected frequency of collision or non-collision incidents when the dummy variable value is equal to one. The logit odds ratio for a continuous variable represents the proportionate change in the odds of an incident occurring given a unit change in the given variable. For dummy logit model variables, the odds ratio represents the relative odds that a given type of incident will occur when the value of the dummy variable is equal to one.

Elasticities and odds ratios, derived from the statistically significant parameters in the collision and non-collision incident models, are presented in Tables 4 and 5, respectively. In Table 5, the collision elasticity values associated with the volume of bus trips in the line haul segments are fairly close to unity, indicating that the expected frequency of collisions increases roughly proportionately with the volume of bus trips. The corresponding elasticities for the stop segments are somewhat smaller, which may indicate that higher volume stops are designed to standards with greater safety margins. This distinction is most evident in the line haul/stop segment differences in clearance collision elasticities, which translates into diminishing trip volume-related safety risks associated with mirror strikes, collisions with parked vehicles, and collisions with fixed objects among high volume stops.

The trip volume odds ratio for pedestrian collisions in stop segments indicates that a unit increase in trip volumes (i.e., 10,000 bus trips, or about a 39% gain) would lead to a near 200% increase in the odds that such an incident would occur. This translates into an elasticity of 5.1, a very substantial response, although from a very small basis risk.

A doubling of afternoon peak traffic volume is estimated to produce a 48% increase in the expected number of clearance collisions in line haul segments and a 34% increase in such collisions in stop segments. Stop segments are also estimated to experience a 39% increase in expected collisions with other vehicles, likely a consequence of the greater hazard encountered in pulling back into heavier traffic after serving a stop or of the increased risk of being rear-ended while serving a stop.

A doubling of the length of line haul segments is estimated to reduce the expected frequency of collisions with vehicles by about 17%, which, as previously discussed, likely reflects unaccounted for differences in safety hazards between shorter and longer segments.

The expected frequency of collisions in line haul segments – particularly clearance collisions – is sensitive to the width of travel lanes. Increasing lane width by one foot (8.7%) is estimated to reduce clearance collisions by about 14.4% and collisions with other vehicles by about 8.1%. Also, the presence of on-street parking is estimated to increase the expected number of collisions by 53% in the line haul segments. In contrast to line haul segments, the expected frequency of collisions with other vehicles in stop segments is positively related to lane width. Here, a one-foot increase in lane width (8.6%) is estimated to contribute to a 5.3% increase in collisions.

Table 4 Estimated Elasticities/Odds Ratios for the Collision Models

	Line Haul Segments			Stop Segments			
Variable	**All Collisions**	**With Vehicles**	**Clearance Collisions**	**All Collisions**	**With Vehicles**	**Clearance Collisions**	**With Pedestrians**
Bus Trips (0000s)	.8439	.9012	.7522	.7000	.7522	.4936	2.990
Traffic Volume (000s)	--	--	.4806	.3477	.3854	.3425	--
Segment Length (ft.)	-.1669	-.1669	--	--	--	--	--
Lane Width (ft.)	-1.0411	-.9304	-1.6587	--	.6155	--	--
One-way Street	.3844	.5855	--	--	--	.3490	--
Center Turning Lane(s) in Segment	--	.4134	-.9564	-.4422	--	-.6765	--
Bus-Only Lane Within Segment	--	--	--	-.0235	--	-.0367	--
Bike Lane Within Segment	-.5740	-.4216	-.7845	-.5172	--	-1.041	--
Intersections	.2395	.2488	.2206	.1337	--	--	--
Signalized Intersections	.1246	.1334	.1223	--	.1700	--	5.263
Signalized w/ Transit Priority	--	--	--	--	--	--	.246
Route Turns Within Segment	.6387	.6127	.6724	.3712	.3468	--	7.565
On-Street Parking Within Segment	--	--	.5317	--	--	--	--
No. of Bus Routes Within Segment	--	--	.2994	--	-.2150	--	--
Average Passenger Load Per Trip	--	--	--	.2527	.2940	--	--
Near-Side Stop	--	--	--	.5447	.5013	.7291	.198
Far-Side Stop	--	--	--	.5148	.5689	.6309	--
Transfer Point: Commuter Rail	--	--	--	.7715	.8022	--	--
Number of Lift Operations	--	--	--	.0327	--	--	--

Holding lane width constant, the added buffer space provided by the presence of a bike lane is estimated to reduce line haul segment vehicle and clearance collisions by 42% and 78%, respectively, while clearance collisions in stop segments are estimated to be (hypothetically) eliminated. Unaccounted for in the estimated bike lane effects on collisions, however, is the safety risk to cyclists themselves, whether associated with their exposure to buses or other vehicles. Also, while the main purpose of bus-only lanes is to improve running time and service regularity, it is estimated that their presence in a stop segment reduces expected clearance collisions by a modest 3.7%.

The expected frequency of collisions with vehicles on one-way line haul segments is estimated to be about 59% greater than otherwise comparable segments with bi-directional travel. In stop segments, the corresponding estimated increase in clearance collisions is about 35%.

The presence of a center turning lane is estimated to have both negative and positive collision consequences. In this case, the expected number of bus collisions with vehicles in line haul segments is estimated to be 41% greater, likely attributable to left-turn conflicts from oncoming traffic. However, the expected number of clearance collisions in this circumstance is estimated to decline by about 96%. Stop segments are also estimated to experience a 68% reduction in clearance collisions when a center turning lane is present.

Intersections present special safety hazards from turning movements and cross traffic. In the present study's stop segments, the relevant collision elasticity generally depends on whether a stop is located at the near or far side of an intersection, as well as whether the intersection is signalized. Thus, the expected number of collisions with vehicles for stops located at the near side of an unsignalized intersection is estimated to be 50% greater than the expected number at a mid-block stop location. If the intersection is signalized, the estimated expected increase grows to 67%. The corresponding estimated changes for far-side stops are 57% (unsignalized) and 74% (signalized). Line haul segments usually contain multiple intersections. In this case, a doubling of the average number of intersections per segment (to 3.3) would lead to an estimated 25% increase in collisions with vehicles if all intersections are unsignalized, and a 38% increase if all are signalized. The corresponding increases for clearance collisions would be 22% and 34%, respectively.

The situation differs for collisions with pedestrians in stop segments. Here, the estimated odds of such a collision are 5.3 times greater for stops at signalized intersections. However, if the signalization includes transit priority, the relative odds fall to 1.3. Furthermore, if the stop is located at the near side of the intersection, the relative odds fall to 1.04.

Intersection-related collision risks are further attenuated when a route turn occurs. For line haul segments, the estimated expected increase in vehicle collisions at a signalized intersection where a route turn occurs would be 99.5%, while the expected increase in clearance collisions would be 101.5%. In stop segments, the estimated expected increase in vehicle collisions would be 101.8% for intersections with near-side stops and 108.6% for intersections with far-side stops. The corresponding odds ratios for collisions with pedestrians at unsignalized intersections with far-side and near-side stops would be 7.565 and 1.50, respectively, and for signalized intersections the relevant far-side/near-side odds ratios would be 12.828 and 2.54. The final stop segment permutation would be a signalized intersection with transit priority, in which case the relevant far-side/near-side odds ratios would be 8.607 and 1.70.

The expected number of clearance collisions is estimated to increase when multiple routes traverse a given line haul segment. In this case, the addition of a route is estimated to result in a 25% increase in such collisions. Conversely, an inverse relationship is estimated to apply to collisions with vehicles in stop segments. Here, a one-route increase is estimated to result in a 16% decrease in the expected number of such collisions.

Lastly, when a stop segment serves as a transfer location to commuter rail service, the expected number of collisions with vehicles is estimated to be 80% greater than what would be expected at transfer locations to other bus routes.

Elasticities and odds ratios for non-collision incidents are presented in Table 5. In this case, odds ratios apply to boarding/alighting incidents involving lift use and elasticities apply to all other incident types.

The elasticities associated with the volume of bus trips provide the most consistent risk exposure metric across the various types of non-collision incidents. In stop segments, the interpretation of the trip volume elasticities is also relatable to other variables representing passenger boarding and alighting volumes. For example, holding the number of boardings and alightings constant, the expected frequency of slips, trips and falls would increase 76% if that given passenger movement volume were distributed across twice as many trips. Conversely, holding the volume of trips constant, the expected number of slips, trips and falls would increase about 20% with a doubling of boarding and alighting movements. Thus, the incident risk associated with the boarding and alighting process can be distinguished between vehicle and passenger flow related sources, with the marginal risk attributable to vehicles being the greater of the two. A similar interpretation applies to off-vehicle incidents at stops, where incidents involving intending passengers are relatable to the volume of boardings and alightings, as well as to the volume of bus trips.

Table 5 Estimated Elasticities/Odds Ratios for Non-Collision Models

	Line Haul	Stop Segments			
Variable	**Slip: On-Board**	**Slip: On-Board**	**B/A Slip: Stairs**	**B/A Slip: Lift**	**Slip: Off Vehicle**
Bus Trips (0000s)	1.213	.698	.763	1.586	.971
Traffic Volume (000s)	--	.245	--	--	--
Boardings+Alightings (000s)	--	.091	.199	--	.202
Number of Lift Operations	--	.049	--	1.001	--
Segment Length (ft.)	-.167	--	--	--	--
Lane Width (ft.)	--	--	.790	--	--
One-way Street	--	--	--	--	--
Intersections	.246	--	--	--	--
Signalized Intersections	.166	.173	.170	3.201	--
Signalized w/ Transit Priority	--	--	--	.444	--
Route Turns Within Segment	.702	--	--	--	--
No. of Bus Routes in Segment	--	--	--	.952	--
Average Passenger Load Per Trip	--	1.353	--	--	--
Transfer Point: Commuter Rail	--	.771	--	--	--

For boarding and alighting passengers using the lift, the odds ratios indicate that a doubling of bus trip volumes would lead to a 151% increase in the odds of an incident. Alternatively, holding trip volumes constant, a doubling of lift operations would lead to a 32.7% increase in the odds of an incident. In this case, both the trip volume and lift volume incident odds elasticities are greater than the stair-related elasticity counterparts, and the relative importance of vehicle-related risk is greater for lift-using passengers as well.

Boarding and alighting incidents of lift users are also sensitive to the location of stops at (either side of) signalized intersections, where the odds of incident occurrence increase 220%. As was the case for pedestrian collisions, the presence of transit priority at the signalized intersection diminishes the estimated odds increase to 42%.

Slip, trip and fall incidents of on-board passengers in stop segments can be related to the boarding and alighting process in several respects. For example, the relatively small elasticity values for such incidents associated with the boardings/alightings and lift operations variables can be potentially attributed to pre-alighting or post-boarding movements of passengers within the bus as it pulls into or away from a stop. This effect is further attenuated by variations in PM peak traffic volume, where a doubling of traffic volumes is estimated to lead to a 25% increase in such incidents, as well as by the average passenger load, where a doubling is estimated to lead to a 135% increase.

Lastly, the presence of a route turn in line haul segments is estimated to lead to a 70% increase in on-board slips, trips and falls, and stops that serve as a transfer point to commuter rail service are estimated to experience a 77% increase in such incidents.

CONCLUSIONS

There are several general conclusions that can be reached from the analysis of collision and non-collision incidents on TriMet's bus system. The first is that a substantial majority of the incidents occurred in the stop segments of the system. Differences in incident risk between stop and line haul segments are further distinguished when accounting for risk exposure, using such measures as vehicle or passenger miles and the number of passenger boardings and alightings. The exposure controls also serve to highlight the heightened relative risk encountered by mobility-impaired passengers.

A second general conclusion is that intersections present a complex set of hazards with respect to both collision and non-collision incidents, with risk levels being sensitive to levels of intersection control. In this context, the level of intersection control is found to effectively represent differences in safety risks attributable to the volumes of cross traffic and turning movements.

Third, route turns are consistently found to attenuate both collision and non-collision incident risks. Fourth, several treatments implemented to improve bus running times and service reliability – bus-only lanes and signal priority – were found to produce safety benefits as well. Furthermore, while passenger loads are typically interpreted as indicators of comfort and convenience, they are also found to have an interpretation in the safety dimension.

Fifth, although the focus of the analysis has been on route and roadway design attributes, several findings imply underlying operator behavior effects. Such implicit effects were most evident in boarding and alighting incidents, where risk exposure was distinguished between the volume of passenger movements and the volume of bus trips. Operator-related effects were also implied by the estimated reduction in incident risk associated with transit signal prioritization.

Lastly, selected characteristics of roadway design are found to affect the expected frequency of bus-involved collisions, similar to their more general effects on traffic safety. Apart from intersections, lane width emerged as a significant contributor to collision risk. Although the types of collisions typically involved – mirror strikes, parked vehicles, and fixed objects – represent comparatively minor incidents, they do disrupt service and count toward disciplinary measures taken against operators. Also, 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.

Before discussing the more general implications of the results, the limitations of the present study should be noted. Although this study's near-1,700 count of total incidents may seem substantial, it is nevertheless limiting with respect to allowing more detailed analysis. For example, although it is fortunate that the frequency of collisions involving pedestrians and cyclists is very small, this also challenges efforts to analyze factors that contribute to their occurrence. Thus, it was not feasible to estimate a collision model for cyclists, and the model estimated for pedestrian-involved collisions was only weakly robust. Lastly, for the purposes of safety planning, it is important to be able to look beyond incident frequencies to also consider the severity of outcomes. A period of three to five years would likely provide a more suitable time frame (with sufficient incident data) for addressing these issues.

With these limitations in mind, this study yet allows some consideration of opportunities to improve safety through implementation of selected countermeasures, given that severity is somewhat imbedded in the typology of collision and non-collision models. For example, at one end of the typology are clearance collisions with associated modest property damage consequences, while pedestrian collisions are at the other end, with likely injury or potential fatality consequences. Both this study's findings and NTD major incident statistics show that collisions with pedestrians are overrepresented at bus stops and in intersections where buses are turning. These risks may be mitigated by pedestrian warning technologies that are beginning to be deployed in bus systems, which alert persons crossing at intersections that a bus is turning, or persons at stops that a bus is deploying its lift, or pulling in, or pulling out. Low-cost barriers and channelization designs can also be implemented to maintain a space between pedestrians and moving buses in stop zones (*Pecheaux et at., 2008*).

More generally, analysis tools have been developed to identify safety "hot spots," or locations where the greatest concentrations of incidents are occurring. For example, a GIS-based tool developed by Truong and Somenhalli (*2011*) creates a safety index, based on a severity-weighted aggregation of incidents, to aid in identifying bus stops with the most serious safety problems. Such a tool could be extended to account for exposure and thereby also identify locations with the greatest incident risks. The route segmentation scheme employed in the present study would clearly be compatible with this or other tools whose purpose is to identify the most hazardous locations for subsequent safety countermeasure treatment.

Although the role of operators in this study has been implicit, their performance takes a more central position in the larger domain of bus safety. For example, in the only in-depth examination to date of a sample of bus fatality and injury crashes (covering both commercial and transit buses), the Federal Motor Carrier Safety Administration (FMCSA) identified operator behavior as being principally responsible in 79% of the cases in which the critical reason for a crash was attributed to the bus (*FMCSA, 2009*). Thus, by following safe driving practices, operator behavior can strongly complement virtually all of the countermeasures intended to reduce the frequency of bus collision and non-collision incidents. Yet, a survey by Moffat et al. (*2001*) found that only about one transit agency in three maintains an ongoing program of safety refresher training for its operators. Thus, for two-thirds of the transit industry at least, the most effective plan to improve safety would begin here.

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