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Safety Performance Functions for Frontage Roads

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Abstract

Frontage roads play a vital role in the U.S.'s highway system because they serve as critical access routes between principal arterials, freeways, and surrounding businesses. Despite their importance, there have been only limited studies conducting an in-depth analysis of frontage road safety. The limited availability of suitable data for frontage roads has been a significant barrier to conducting comprehensive safety studies on these critical road segments. This study developed a robust methodology that allows for the correct attribution of crashes to the corresponding frontage road segments. This methodology is a novel contribution to the field of transportation safety research, as it addresses a critical data challenge that has hindered the advancement of frontage road safety analysis in the past. Moreover, there is limited research into developing the safety performance functions (SPFs) and crash modification factors (CMFs) for frontage roads. In fact, the first edition of the Highway Safety Manual does not include the SPFs for frontage roads. In this study, the authors considered 4 years (2017–2020) of crash data for conducting a comprehensive analysis of four types of frontage road (rural one-way, rural two-way, urban one-way, and urban two-way) and developed the SPFs and CMFs specifically tailored for frontage roadways in Texas, U.S. Several CMFs were developed in conjunction with the SPFs. This study developed CMFs for left and right shoulder widths, access point density, presence of entrance and exit ramps, posted speed limit, and the horizontal curve density.

Keywords

Frontage roads, crash modification factors (CMFs), crash prediction models, crash severity, Highway Safety Manual, modeling and forecasting

A frontage road, referred to by various names such as access road, outer road, service road, feeder road, or parallel road, is a type of local roadway that runs parallel to a higher-speed, limited-access road, such as a freeway or expressway. Its primary purpose is to provide direct access to various properties (e.g., businesses, private driveways/houses, farms, residential areas, and industries) located along the main highway. Frontage roads serve as a convenient route for drivers to reach properties without having to enter the main highway directly. In cases where there are parallel high-speed lanes alongside a major highway, these additional lanes are also known as local lanes, offering drivers a separate path from the main through-traffic flow. By offering a local alternative to access points and providing direct entry and exit options to and from the main thoroughfare, frontage roads contribute to the efficient movement of traffic and promote safe travel. Additionally, frontage roads facilitate smoother transitions for drivers entering and leaving the highway, reducing potential congestion and congestion-related crashes on the main roadway.

The uniqueness of this study lies in its focus on addressing the challenges associated with frontage roadway safety analysis in Texas, U.S. The limited availability of suitable data for frontage roads has been a significant barrier to conducting comprehensive safety studies on these critical road segments. In Texas, crash data are conventionally assigned to the centerline of major roadways, which can lead to inaccuracies and uncertainties when trying to understand the safety performance of frontage

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roadways. Correctly assigning crashes to the appropriate direction of the frontage roadways is essential for obtaining reliable and meaningful safety insights.

To overcome this data limitation and ensure accurate crash assignment, the research study from which this paper is derived developed a robust methodology that allows for the correct attribution of crashes to the corresponding frontage road segments (*1*). This methodology is a novel contribution to the field of transportation safety research, as it addresses a critical data challenge that has hindered the advancement of frontage road safety analysis in the past. Moreover, there is limited research in regard to developing safety performance functions (SPFs) and crash modification factors (CMFs) for frontage roads. In fact, the first edition of the Highway Safety Manual (HSM) does not include SPFs for frontage roads. This study developed SPFs and CMFs specifically tailored for frontage roadways in Texas. SPFs and CMFs are essential tools used by transportation planners and engineers to quantify the safety performance of roadway segments and identify factors that influence crash frequency. By developing SPFs and CMFs for frontage roadways, this study fills a significant research gap and equips decision-makers with valuable resources to enhance safety planning and design strategies for these road segments.

Background

Frontage roads have received limited in-depth exploration in past studies. However, a few current research studies contribute to advancing our understanding of frontage roads to improve roadway design and enhance overall safety.

Some studies focused on improving safety and efficiency in roadway design, specifically focusing on frontage road conversions, intersection signage, and auxiliary lane (AL) design to address increasing traffic volumes and urbanization challenges. Two studies by Eisele et al. focused on the conversion of two-way frontage roads to one-way operation along rural interstate highways and access-controlled principal arterials in Texas (*2*, *3*). The first study discussed the need for frontage road conversion as areas become more urbanized and traffic volumes increase (*2*). The authors emphasized, through their research findings, the importance of updated and statistically valid information with respect to increased traffic flow and urbanization to guide frontage road conversion project planning for roadway designers and decision-makers. The second study addressed the design solution of frontage roads for providing access along rural interstate highways and access-controlled principal arterials (*3*). CMFs were developed, and economic impacts were assessed through parcel-level appraisal data and surveys of managers, business owners, and customers, revealing overall increases in appraised values. Researchers found an overall 57% reduction in all non-Property Damage Only (PDO) crashes (CMF = 0.43). The CMFs for non-PDO angle crashes and non-PDO rear-end crashes were 0.17 and 0.27, respectively. Nelson et al. emphasized the importance of intersection and mandatory movement lane control signs in ensuring safe and efficient intersection operations (*4*). The study evaluated test signs for field deployment, including an enhanced sign depicting roadway widening on a frontage road and a guide sign indicating lane choice when approaching a freeway interchange on a cross street. Sharma et al. highlighted the significance of ALs in providing operational benefits for merging and weaving movements on freeways and through bottlenecks or signalized intersections (*5*). The research systematically examined various design elements of ALs on frontage roads and identified nine design parameters that influence these elements through microsimulation, offering insights to improve frontage road design and safety.

Few studies examined safety performance of frontage roads, particularly in rural areas, and their intersections with interstate highways and principal arterial corridors. Lord and Bonneson explored the safety performance of frontage roads used along interstate highways and fully controlled principal arterial corridors in rural areas (*6*). The researchers considered data from four different highways and developed SPFs and CMFs for rural frontage road segments, both one-way and two-way operations. The study highlighted the impact of lane width and shoulder width on segment-related collisions and emphasized the significance of edgeline markings for rural two-way frontage road safety. Though this study developed SPFs and CMFs, the sample size was limited, and the safety prediction methods cannot be applied to urban frontage roads. In addition, these models are outdated, since they were developed almost 2 decades ago and cannot be used for current conditions. Bonneson et al. presented the development of quantitative tools to assess the safety of rural frontage-road segments in Texas (*7*). The tools include a fundamental model for estimating crash frequency for typical frontage-road segments, along with various CMFs. The findings assisted designers in evaluating alternative geometric design elements, such as lane width, to improve safety. Chen et al. investigated the safety impacts of implementing dual right-turn lanes at frontage road intersections downstream of freeway off-ramps (*8*). They used a two-stage approach with microsimulation models calibrated with field data to estimate vehicle trajectories and surrogate safety measures, particularly weaving conflicts. The study validated that dual right-turn lanes can significantly reduce weaving conflicts compared with single exclusive right-turn lanes, thus enhancing safety.

Table 1. Summary of Frontage Roadway Segments

Highway type	No. of segments	Length (mi)			
		Minimum	Maximum	Mean	Total
Urban					
One-way	15,519	0.014	1.379	0.29	4,155.2
Two-way	1,717	0.011	1.609	0.33	534.0
Rural					
One-way	1,549	0.011	1.778	0.33	519.5
Two-way	5,030	0.011	1.977	0.47	2,543.4
Total	23,815	0.011	1.977	0.33	7,752.1

Two studies developed advanced statistical models using frontage road crash data. Li et al. developed generalized additive models (GAMs) for estimating CMFs in the context of rural frontage roads in Texas (*9*). They compared the flexibility of GAMs with traditional generalized linear models in characterizing the safety effects of simultaneous changes in geometric and operational features. The study found that GAMs offer greater flexibility in handling variable interactions, providing valuable insights into safety improvements for rural frontage roads. Das et al. examined the safety performance of frontage roads in the U.S. (*10*). The researchers collected 6 years of frontage road crash data from Texas and used cluster correspondence analysis to identify patterns of associated factors for different crash injury types. This analysis revealed distinct clusters for injury, fatal, and no-injury crashes, enabling the identification of suitable safety countermeasures and policy initiatives to enhance frontage road safety and reduce crash frequencies.

The review of existing literature reveals that there remains a lack of comprehensive understanding of the safety performance of frontage roads, particularly concerning the impact of changing traffic volumes, assignment of crashes on frontage roadways, urbanization, evolving traffic patterns, and safety dynamics in rural settings. An in-depth study can provide valuable insights into the safety challenges and potential improvements required to address the unique characteristics of frontage roads. The current study aims to develop SPFs for one-way and two-way frontage roads on both urban and rural settings.

Data Collection

For obtaining the inventory of frontage road segments in Texas, the authors used the 2019 version of the Road-Highway Inventory Network Offload (RHINO) database maintained by Texas Department of Transportation (TxDOT). The roadbed identifier variable was used to select and extract frontage roadways. The authors developed datasets for four types of frontage roads:

- Rural one-way (R1W)
- Rural two-way (R2W)
- Urban one-way (U1W)
- Urban two-way (U2W)

In total, the authors extracted 23,815 frontage roadway segments from the original RHINO database, comprising a total mileage of 7,752.1 mi. Each roadway segment is homogenous with similar roadway and traffic characteristics throughout the entire length of the segment. Table 1 shows the summary of the frontage roadway segments in Texas.

Crash Data

The authors used 4 years (2017–2020) of crash data from TxDOT's Crash Record Information System (CRIS) database. Only 4 years' crash data are used because of the need to conduct manual reviews of some of the crash reports. One major issue with Texas frontage roadway crashes is that, though the crashes are coded as frontage road related, they cannot be assigned to the proper frontage roadway segment (e.g., the roadbed next to the northbound or southbound side of the mainline) using the variables in the CRIS database. This element makes it challenging to assign crashes to proper frontage roadway segments. The authors developed the following process to identify the side of each crash and assign crashes to an appropriate frontage roadway segment.

- Step 1: Locate frontage roadway crashes.
- Step 2: Find the nearest point on both frontage roadways next to main lanes, separately.
- Step 3: Identify the traveling directions of both frontage roadways.
- Step 4: Compare vehicle traveling direction with road directions.
- Step 5: Determine the side of the crash.

The following section provides an example to illustrate the process. First, the authors extracted the frontage

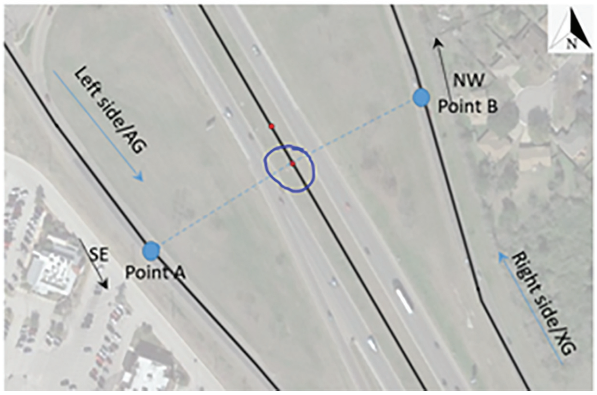

Figure 1. Locating nearest points on frontage roadways of a crash.
Note: AG = right frontage road; XG = left frontage road.

roadway crashes from the CRIS database by selecting only records with the appropriate value in the "road part" variable (service/frontage road).

Second, the authors found the nearest points on the two sides of frontage roadways. As shown in Figure 1, Point A is on the left side, and Point B is on the right side.

Third, the authors identified the traveling directions of Points A and B. In this case, the two directions are approximately 135 and 320 degrees, as shown in Figure 2.

Fourth, the authors identified the traveling directions of the vehicle(s) involved in the crashes. In the case of a wrong-way driving crash, the direction in the CRIS database is adjusted to reflect the actual direction of the roadway. Consequently, the crash location was determined. For example, consider a crash on a north/south freeway that has three vehicles involved. Their traveling directions are noted as southeast, south, and southwest. In this case, since all the three involved vehicles are traveling to the south or southwest, it can be determined that the crash is on the left side frontage roadway.

For each of the crashes in the CRIS database, there are three possible identification results: right side, left side, and cannot be determined (e.g., the vehicle traveling direction is unknown or not reported). The locations of the crashes cannot be determined for certain cases mainly for two reasons: 1) the vehicle direction information in the CRIS database is invalid (including missing and unknown); 2) both sides of the frontage roadway segment meet the criteria (i.e., the process cannot determine which side since both sides are possible based on the crash and roadway information). In addition, the process only applies to one-way frontage roadways. For two-way frontage roadways, both sides have two traveling directions; thus, it is not feasible to identify the location of a crash from the CRIS database. In those cases, the authors reviewed the crash reports manually and assigned crashes to an appropriate frontage road. A variable named "minimum crash count" is created that only includes crashes where direction is determined with certainty.

Sample Selection

Since it is not possible to collect data for all frontage road segments, the authors considered a sampling framework. For each sampling frame, the authors developed a probability sample that allows researchers to draw inferences about quantities of interest at the sampled population level (the population in this case is all frontage road segments in each sampling frame). The authors used a stratified sample balanced for the variable "minimum crash count" as the design variable. The stratification criteria were TxDOT's four regions (north, west, south, and east). Segment lengths shorter than 0.01 mi and longer than 2.0 mi were removed from each sampling frame. The authors confirmed that this removal did not reduce the sampling pools by more than 20%, thereby leaving most segments for sampling.

The authors implemented cube sampling to produce the stratified sample to control for annual average daily traffic (AADT) as the balancing variable, since it is known that this variable is essential in developing SPFs. The method selected to draw the equal-probabilities sample was an implementation of the fast algorithm proposed by Chauvet and Tillé, based on cube sampling methods (*11*). More details on this procedure can be found in their work (*11*).

The sampling procedure was fine-tuned by resampling methods to verify achievement of balance by AADT, and an acceptable level of precision was achieved for the mean value of the design variable (i.e., crash count). Figure 3 shows the sampling performance for R2W frontage roads when the sample size is set at 450. On the left side, this figure shows a very good match between the population and sample distributions of AADT, which means balance by this variable has been achieved. The sampling distribution for the mean of the design variable is shown on the right side of Figure 3. The sampling distribution seems to be free of bias (i.e., roughly normal shape) and produces a relative precision of 0.139 (i.e., gamma), which means, in this case, that the standard error of a sample of size 450 should be about 13.9% of the population mean. This shows that the selected sample provides good representation of the population.

Similar to Figure 3, Figure 4 shows the resampling metrics corresponding to a sample size of 300 for R1W frontage roads. In this case too, the figure shows a very good balance by AADT and absence of bias for the crash mean. The precision for the sample mean, however, is slightly smaller, having a gamma value of 0.125.

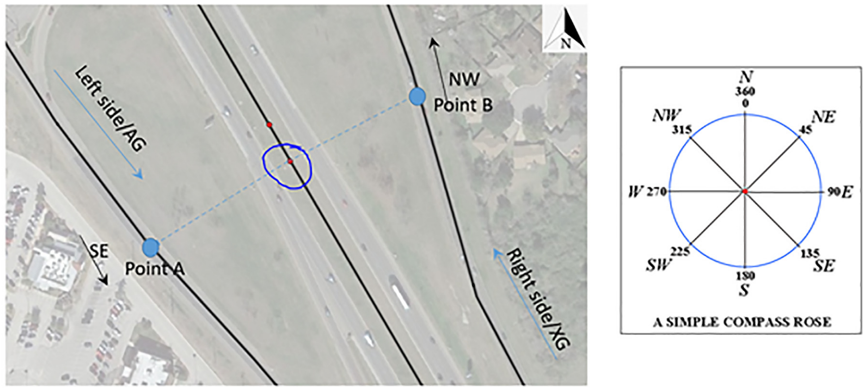

Figure 2. Directions of the nearest points on the left and right side frontage roads.
Note: AG = right frontage road; XG = left frontage road.

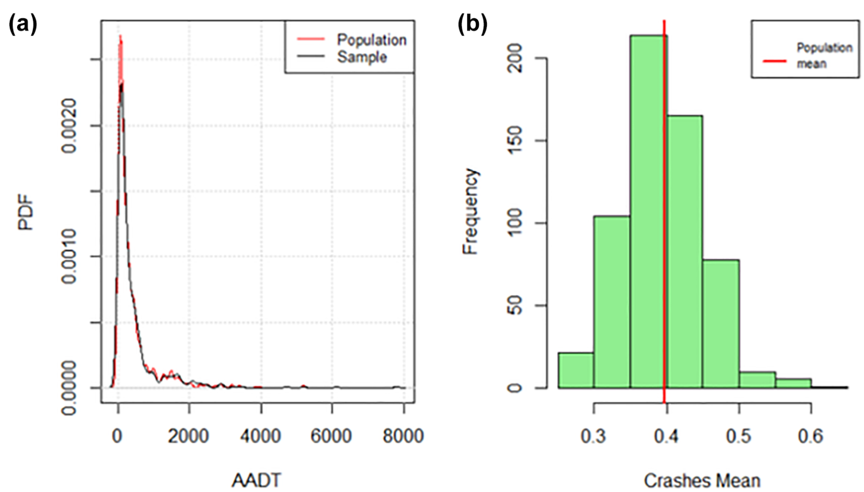

Figure 3. Rural two-way resampling results ($n = 150$): (*a*) balance by annual average daily traffic (AADT) and (*b*) sampling distribution.
Note: PDF = probability density function.

Figure 5 shows the resampling metrics for U1W frontage roads and a sample size of 111, which was determined as the maximum size feasible for the resources available for this effort. Although the balance is slightly worse than for rural frontage roads, the match between the AADT population and sample distributions is acceptably good. The sampling distribution has a slight positive skewness, but the authors considers that skewness very minimal given the size of the precision achieved (about 20.9% of the population mean, which is roughly two crashes in the scale of the mean crashes).

Finally, Figure 6 shows the resampling metrics for a sample size of 111 U2W frontage road segments. Similar to Figure 5, the balance by AADT is acceptable, and the precision of 0.247, though slightly larger than U1W, is acceptable for the purposes of this research (i.e., developing the SPFs and CMFs). The slight positive skewness is also acceptable.

The authors developed a stratified simple random sample for a 0.15 precision, using the values in Table 2 inflated by a 10% factor (i.e., multiplied by 1.1) to account for any data loss—as is common in data collection efforts. For this effort, the strata selected were the four TxDOT regions. Table 2 shows the final sample sizes drawn for this effort.

After the sample was selected, the task was to assign the crashes the direction of which could not be determined earlier. For those crashes, the authors further verified the crash assignment through manually investigating

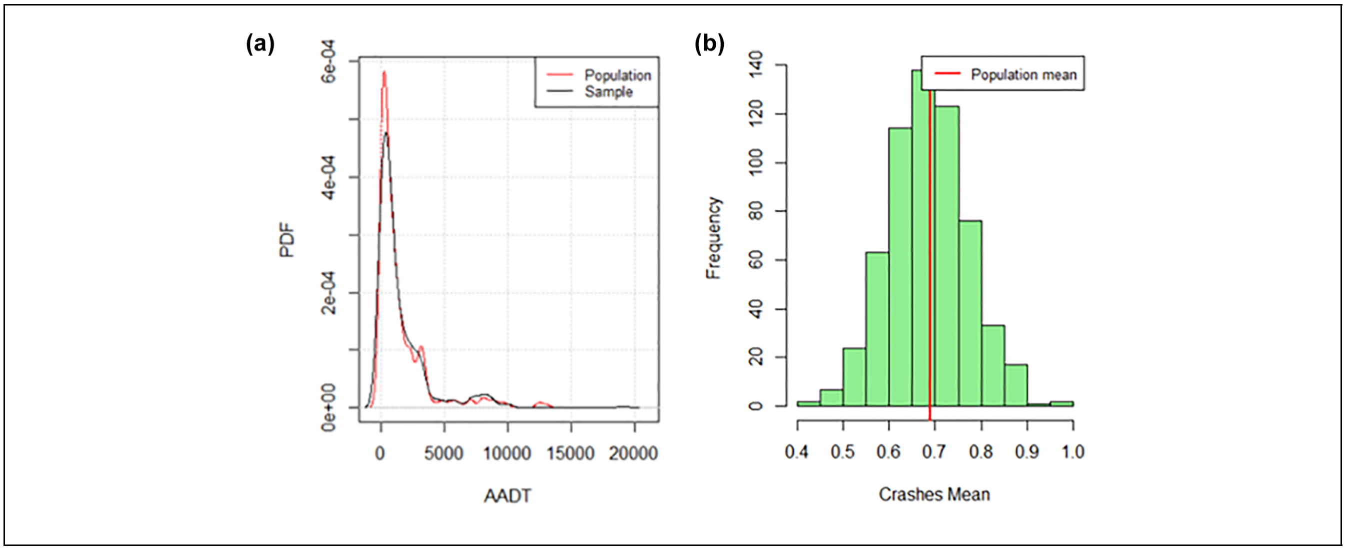

Figure 4. Rural one-way resampling results ($n = 300$): (*a*) balance by annual average daily traffic (AADT) and (*b*) sampling distribution.
Note: PDF = probability density function.

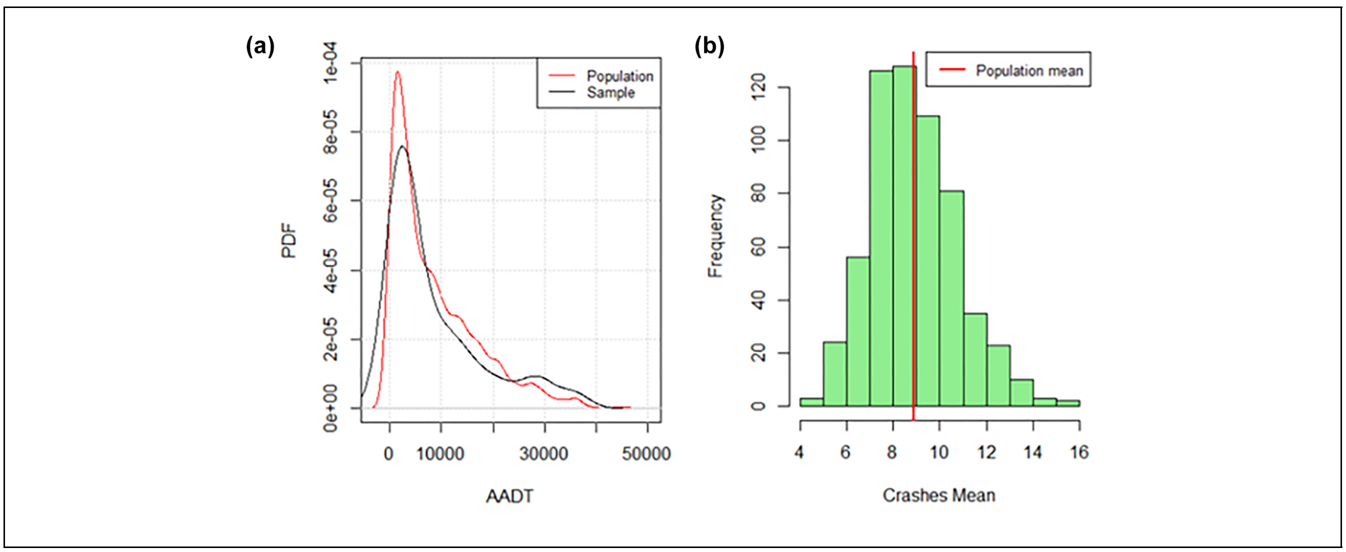

Figure 5. Urban one-way resampling results ($n = 111$): (*a*) balance by annual average daily traffic (AADT) and (*b*) sampling distribution.
Note: PDF = probability density function.

the crash reports from the CRIS database for the sampled frontage road segments. The authors examined 574 frontage roadway crash cases. For each case, the authors primarily looked at the crash diagram in the crash report and compared it with the roadways on Google Earth. Figure 7 shows an example of how the authors conducted the manual check. On the left side of Figure 7 is the diagram from the crash report and, on the right side, it shows a Google Earth image of the roadway based on the location mentioned in CRIS. From the crash diagram and Google Earth image—together with the crash narrative—the authors identified the side and location of the crash. After manually checking the crash cases, the authors obtained crash counts on all the selected frontage roadway segments.

For the selected sample, the authors also obtained data that are not available from TxDOT's RHINO database but are required for developing new SPFs. Mainly, the authors used Google Earth and Google Street View for collecting missing variables such as edgeline markings, rumble strips, lighting, curb presence, and cross-sectional widths. Tables 3 and 4 show the summary statistics for continuous and categorical variables by frontage road type, respectively.

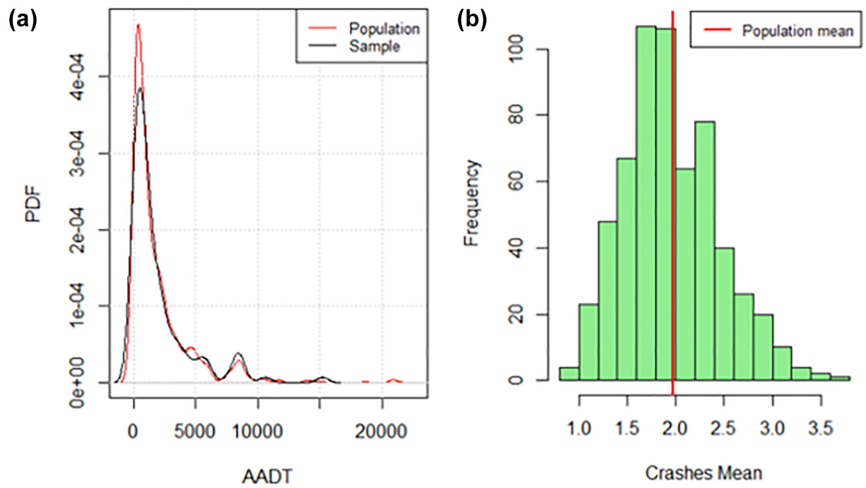

Figure 6. Urban two-way resampling results ($n = 111$): (*a*) balance by annual average daily traffic (AADT) and (*b*) sampling distribution.
Note: PDF = probability density function.

Table 2. Final Sample Size for Frontage Roads

Facility type	Population size	Final sample size by region				
		Total	East	North	South	West
R1W	1,549	276	48	141	78	9
R2W	5,030	413	25	149	94	145
U1W	15,519	128	30	45	37	16
U2W	1,717	100	10	36	15	39

Note: R1W = rural one-way; R2W = rural two-way; U1W = urban one-way; U2W = urban two-way.

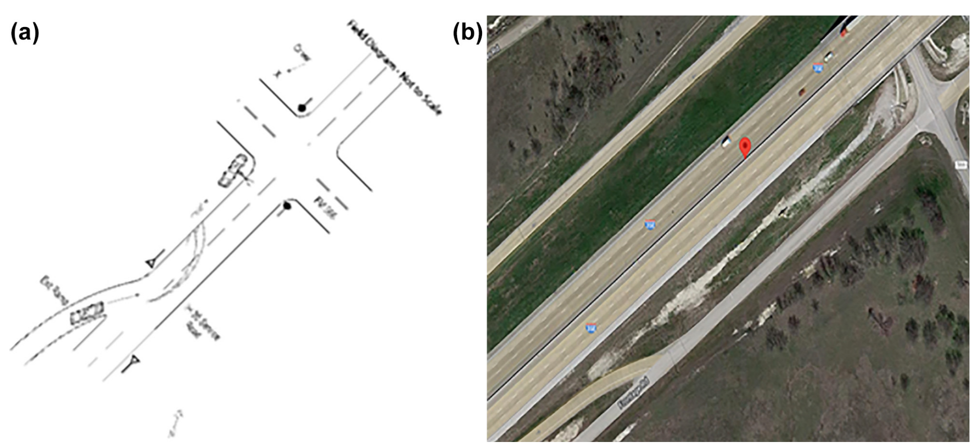

Figure 7. Example procedure used for manual check of crash reports: (*a*) crash report and (*b*) Google Earth image.
Note: Red marker shows the spatial location mentioned in CRIS.

Table 3. Summary Statistics for Continuous Variables

Variable	Min.	Max.	Mean	SD	Total
R1W					
Segment length (mi)	0.011	1.778	0.33	0.36	91.1
ADT	4	12,515	1,771	2,386	na
Lane width (ft)	0	24	11.76	1.58	na
Left shoulder width (ft)	0	15	2.56	2.68	na
Right shoulder width (ft)	0	13	4.82	3.76	na
No. of driveways	0	16	1.61	2.68	na
Crash count (2017–2020)	0	23	1.15	2.96	317
R2W					
Segment length (mi)	0.011	1.977	0.47	0.48	194.1
ADT	4	7,819	498	882	na
Lane width (ft)	8.5	19	11.22	1.08	na
Left shoulder width (ft)	0	11	2.02	2.34	na
Right shoulder width (ft)	0	11	2.19	2.56	na
No. of driveways	0	37	1.33	3.03	na
Crash count (2017–2020)	0	7	0.29	0.81	120
U1W					
Segment length (mi)	0.014	1.379	0.29	0.32	37.1
ADT	99	36,375	8,233	8,045	na
Lane width (ft)	9	17	12.23	1.17	na
Left shoulder width (ft)	0	13	1.87	2.57	na
Right shoulder width (ft)	0	10.5	1.89	2.79	na
No. of driveways	0	21	2.89	4.52	na
Crash count (2017–2020)	0	196	12.79	26.87	1637
U2W					
Segment length (mi)	0.011	1.609	0.33	0.35	33.0
ADT	32	17,540	1,827	2,652	na
Lane width (ft)	10.25	17	11.97	1.13	na
Left shoulder width (ft)	0	9	2.20	2.24	na
Right shoulder width (ft)	0	8	2.34	2.26	na
No. of driveways	0	19	2.32	3.83	na
Crash count (2017–2020)	0	17	1.00	2.79	100

Note: ADT = average daily traffic; Max. = maximum; Min. = minimum; na = not applicable; R1W = rural one-way; R2W = rural two-way; SD = standard deviation; U1W = urban one-way; U2W = urban two-way.

Methodology

The predictive model calibration process consisted of simultaneous calibration of multiple-vehicle and single-vehicle crash models and CMFs using an aggregate model. The simultaneous calibration approach was needed because several CMFs are common to multiple-vehicle and single-vehicle crash models. The database assembled for calibration included two replications of the original database. The dependent variable in the first replication was set equal to multiple-vehicle crash count. The dependent variable in the second replication was set equal to single-vehicle crash count. Then, the predicted average crash frequency on the frontage road segments can be calculated as follows:

$$N_j = (N_{sv}I_{sv} + N_{mv}I_{mv}) \tag{1}$$

where

N_j = predicted annual crash frequency for crash type j (single-vehicle or multiple-vehicle),

N_{sv} = predicted annual single-vehicle crash frequency,

I_{sv} = indicator variable for single-vehicle crashes (= 1.0 for single-vehicle crash data, = 0.0 otherwise),

N_{mv} = predicted annual multiple-vehicle crash frequency, and

I_{mv} = indicator variable for multiple-vehicle crashes (= 1.0 for multiple-vehicle crash data, = 0.0 otherwise).

The authors considered various functional forms and interactions before finalizing the model form. All variables were first included in both multiple-vehicle and single-vehicle models and the ones that are significant and intuitive were retained in the final models. For the variables that had similar effect, the authors introduced those as common variables for both models. For one-

Table 4. Summary Statistics for Categorical Variables

Category	Frontage road type			
	R1W (%)	R2W (%)	U1W (%)	U2W (%)
Presence of edgeline markings				
None	1.1	29.8	30.7	23
One side	1.1	0.0	68.5	0
Both sides	97.8	70.2	0.8	77
Number of lanes				
1	7.6	0.7	5.5	6
2	86.6	98.6	59.1	91
>3	5.8	0.7	35.4	3
Number of minor intersections				
0	41.7	51.6	40.2	36
1	45.3	26.2	35.4	37
2	9.1	16.0	15.0	15
>3	3.9	6.4	9.4	12
Presence of shoulder rumble strips				
No	98.6	98.3	100	100
Yes	1.4	1.7	0	0
Presence of lighting				
No	76.1	94.2	56.7	92
Yes	23.9	5.8	43.3	8
Presence of curb				
None	70.3	95.9	30.7	81
One side	18.8	2.9	15.0	8
Both sides	10.9	1.2	54.3	11
Posted speed limit (mph)				
<40	12.3	3.4	24.3	23
45	19.9	21.3	34.4	27
50	20.7	10.2	18	15
55	42.8	60.5	20.3	34
>60	4.3	4.5	3.1	1
Number of horizontal curves				
0	70.3	51.1	49.2	38
1	23.6	24.7	30.5	37
>2	6.1	24.2	20.3	25

Note: R1W = rural one-way; R2W = rural two-way; U1W = urban one-way; U2W = urban two-way.

way frontage roads, the predicted annual single- and multiple-vehicle crash frequencies are calculated as follows:

$$N_j = (N_{sv}I_{sv} + N_{mv}I_{mv})CMF_{rur}CMF_{lsw}CMF_{rsw} \quad (2)$$

$$N_{sv} = N_{spf,sv}CMF_{psl} \quad (3)$$

$$N_{mv} = N_{spf,mv}CMF_{dw}CMF_{int}CMF_{ent} \quad (4)$$

with

$$N_{spf,sv} = L\ e^{b_{sv,0} + b_{sv,1}\ln(AADT)} \quad (5)$$

$$N_{spf,mv} = L\ e^{b_{mv,0} + b_{mv,1}\ln(AADT)} \quad (6)$$

$$CMF_{rur} = e^{b_{rur}I_{rur}} \quad (7)$$

$$CMF_{lsw} = e^{b_{lsw}(W_{lsw}-2)} \quad (8)$$

$$CMF_{rsw} = e^{b_{rsw}(W_{rsw}-4)} \quad (9)$$

$$CMF_{psl} = e^{b_{psl}(PSL-45)} \quad (10)$$

$$CMF_{int} = e^{(b_{int}[n_{int}/L])} \quad (11)$$

$$CMF_{dw} = e^{(b_{dw}[n_{dw}/L])} \quad (12)$$

$$CMF_{ent} = e^{(b_{ent}[n_{ent}/L])} \quad (13)$$

where

$N_{spf,sv}$ = base predicted annual single-vehicle crash frequency (crashes/year),
$N_{spf,mv}$ = base predicted annual multiple-vehicle crash frequency (crashes/year),
CMF_{rur} = rural area CMF,
CMF_{lsw} = left shoulder width CMF,
CMF_{rsw} = right shoulder width CMF,
CMF_{psl} = posted speed limit CMF,
CMF_{int} = number of minor intersections CMF,
CMF_{dw} = number of driveways CMF,
CMF_{ent} = number of entrance ramps CMF,

Table 5. Calibrated Coefficients for One-Way Frontage Roads

Coefficient	Variable	Value	SD	*t*-statistic	*p*-value
$b_{sv,0}$	Intercept, SV crashes	−2.741	0.822	−3.34	0.0009
$b_{mv,0}$	Intercept, MV crashes	−6.024	0.987	−6.1	<.0001
$b_{sv,1}$	AADT, SV crashes	0.227	0.100	2.26	0.024
$b_{mv,1}$	AADT, MV crashes	0.644	0.117	5.53	<.0001
b_{rur}	Rural area indicator	−0.476	0.250	−1.9	0.0577
b_{lsw}	Left shoulder width	−0.049	0.019	−2.64	0.0086
b_{rsw}	Right shoulder width	−0.049	0.019	−2.64	0.0086
b_{psl}	Posted speed limit	0.022	0.021	1.04	0.2996
b_{dw}	Driveway density	0.021	0.008	2.64	0.0084
b_{int}	Minor intersection density	0.021	0.008	2.64	0.0084
b_{ent}	Entrance ramp density	0.101	0.094	1.08	0.2822
δ_{sv}	Dispersion parameter, SV crashes	1.030	0.415	2.49	0.0132
δ_{mv}	Dispersion parameter, MV crashes	1.229	0.428	2.87	0.0042

Note: AADT = annual average daily traffic; MV = multiple-vehicle; SD = standard deviation; SV = single-vehicle.

L = segment length (mi),
$AADT$ = annual average daily traffic on the frontage road (vehicles per day),
I_{rur} = indicator variable for the rural area (= 1 if rural; = 0 otherwise),
W_{lsw} = left shoulder width (ft),
W_{rsw} = right shoulder width (ft),
PSL = posted speed limit (mph),
n_{int} = number of minor intersections on the frontage road,
n_{dw} = number of driveways on the frontage road,
n_{ent} = number of entrance ramps on the frontage road, and
b_i = calibration coefficient for variable i.

For two-way frontage roads, the predicted annual single- and multiple-vehicle crash frequencies are calculated as follows:

$$N_j = (N_{sv}I_{sv} + N_{mv}I_{mv})CMF_{rur}CMF_{sw}CMF_{hc} \quad (14)$$

$$N_{sv} = N_{spf,sv} \quad (15)$$

$$N_{mv} = N_{spf,mv}CMF_{dw}CMF_{int}CMF_{ent}CMF_{ext} \quad (16)$$

with

$$CMF_{hc} = e^{(b_{hc}[n_{hc}/L])} \quad (17)$$

$$CMF_{ent} = e^{(b_{ext}[n_{ext}/L])} \quad (18)$$

where
CMF_{hc} = number of horizontal curves CMF,
CMF_{ent} = number of exit ramps CMF,
n_{hc} = number of horizontal curves on the frontage road, and
n_{ext} = number of exit ramps on the frontage road.

Modeling Results

Tables 5 and 6 contain the calibrated coefficients for one-way and two-way frontage road segments for total crashes, respectively. Because of the small sample size, separate models could not be developed for different severity levels. The authors considered a significance level of 5% for retaining the variables in the models. A few variables that were not significant at a 5% level but significant up to 30% level were also retained if those variables were important to the model and their trend was found to be consistent with previous research findings (even if the specific value was not known with a great deal of certainty). The SPF coefficients show that rural frontage roads experience fewer crashes than the urban frontage roads. Figure 8 shows this trend graphically.

Figure 8 shows the relationship between the number of single- and multiple-vehicle crashes and traffic flow for frontage roads. In general, rural frontage roads experienced fewer crashes than urban frontage roads. In addition, one-way frontage roads experienced more crashes than two-way frontage roads for similar conditions. Figure 9 shows the comparison of the SPFs developed in this research project and the models developed by Lord and Bonneson (*6*). Both studies show similar results for the two-way frontage roads. However, for one-way frontage roads, models developed in this research project predict a slightly higher number of crashes than Lord and Bonneson (*6*). The difference could be attributed to a different set of base conditions and the total number of variables considered in the models.

Table 7 shows the severity distribution of crashes occurring on the frontage road segments. The study results show, although two-way frontage roads experience fewer crashes than one-way frontage roads, the

Table 6. Calibrated Coefficients for Two-Way Frontage Roads

Coefficient	Variable	Value	SD	*t*-statistic	*p*-value
$b_{sv,0}$	Intercept, SV crashes	−3.606	0.682	−5.29	<.0001
$b_{mv,0}$	Intercept, MV crashes	−5.627	0.859	−6.55	<.0001
$b_{sv,1}$	AADT, SV crashes	0.274	0.097	2.84	0.0047
$b_{mv,1}$	AADT, MV crashes	0.477	0.121	3.95	<.0001
b_{rur}	Rural area indicator	−0.720	0.248	−2.91	0.0037
b_{sw}	Average shoulder width	−0.110	0.052	−2.1	0.0356
b_{psl}	Posted speed limit	0.016	0.013	1.21	0.2282
b_{dw}	Driveway density	0.016	0.013	1.21	0.2282
b_{int}	Minor intersection density	0.255	0.102	2.5	0.0125
b_{ent}	Entrance ramp density	0.095	0.056	1.69	0.0905
b_{ext}	Exit ramp density	0.027	0.016	1.7	0.0904
δ_{sv}	Dispersion parameter, SV crashes	0.945	0.602	1.57	0.117
δ_{mv}	Dispersion parameter, MV crashes	0.689	0.612	1.13	0.2602

Note: AADT = annual average daily traffic; MV = multiple-vehicle; SD = standard deviation; SV = single-vehicle.

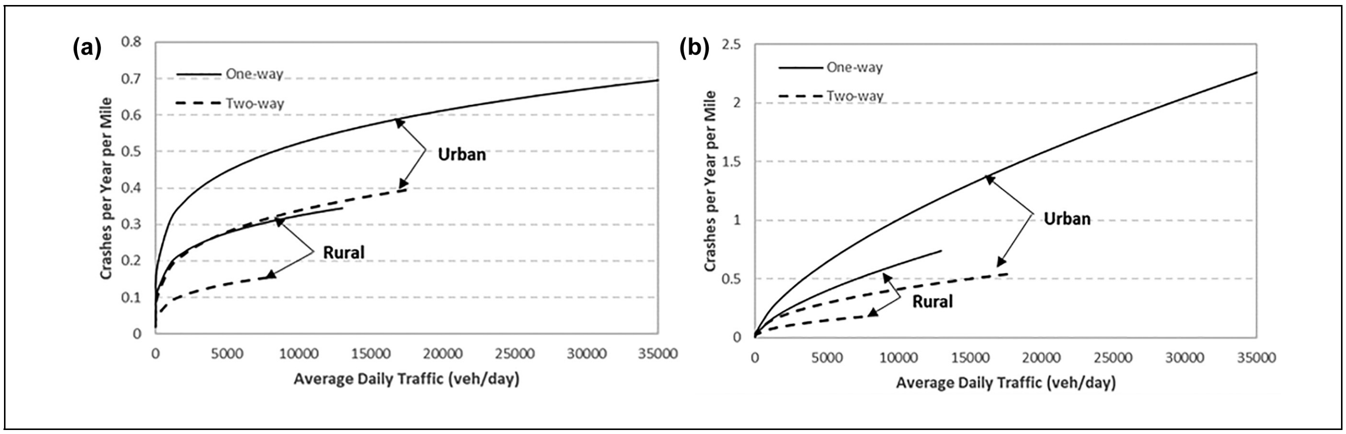

Figure 8. Graphical form of the frontage road safety performance functions: (*a*) single-vehicle crashes and (*b*) multiple-vehicle crashes.

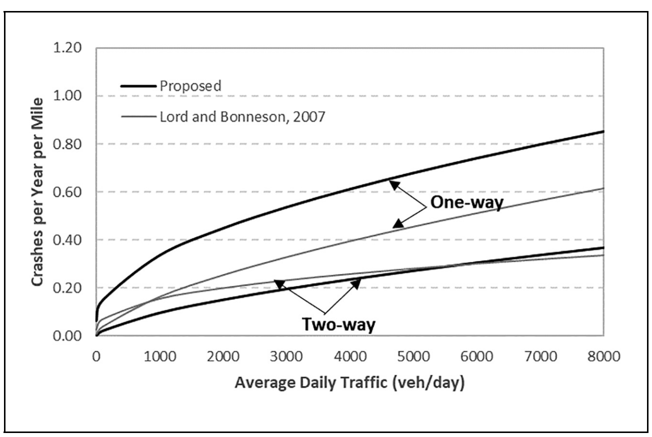

Figure 9. Comparison of total crashes estimated by different studies.

crashes on two-way frontage roads are more severe, as evident from the high severe crash distribution. Table 7 also shows that the crashes on rural two-way frontage roads are much more severe than those on urban two-way frontage roads. This could be attributed to higher operating speeds on rural frontage roads.

Crash Modification Factors (CMFs)

Several CMFs were developed in conjunction with the SPFs. They describe the relationship between various operational and geometric factors and crash frequency.

Shoulder Width CMF. The right shoulder width CMF of the one-way frontage roads is described using Equation 19:

Table 7. Severity Distribution of Frontage Road Crashes

	One-way		Two-way	
Severity	Rural (%)	Urban (%)	Rural (%)	Urban (%)
K	0.9	0.4	4.4	0.6
A	4.6	1.3	6.1	0.6
B	8.7	10.4	11.4	10.3
KAB	14.2	12.1	21.9	11.5
C	13.3	18.2	16.7	12.8
PDO	72.4	69.6	61.4	76.3

Note: A = incapacitating injury; B = non-incapacitating Injury; C = minor injury; K = fatal; PDO = property damage only.

Figure 10. Crash modification factor for shoulder width on frontage roads.

$$CMF_{sw} = e^{-0.049(rsw-4)} \quad (19)$$

The left shoulder width CMF of the one-way frontage roads is described using Equation 20:

$$CMF_{sw} = e^{-0.049(lsw-2)} \quad (20)$$

The average shoulder width CMF of the two-way frontage roads is described using Equation 21:

$$CMF_{sw} = e^{-0.1102(sw-4)} \quad (21)$$

The base condition for this CMF is a right shoulder width of 6 ft and a left shoulder width of 2 ft for one-way frontage roads. For two-way frontage roads, the average shoulder width at base conditions is 2 ft. The width used in this CMF is an average for outside shoulders in both directions for two-way frontage roads. The shoulder width CMF developed in this study was compared against the CMF developed by Lord and Bonneson and is shown in Figure 10 (*6*). The shoulder width has a more pronounced safety effect on two-way frontage roads than on one-way frontage roads.

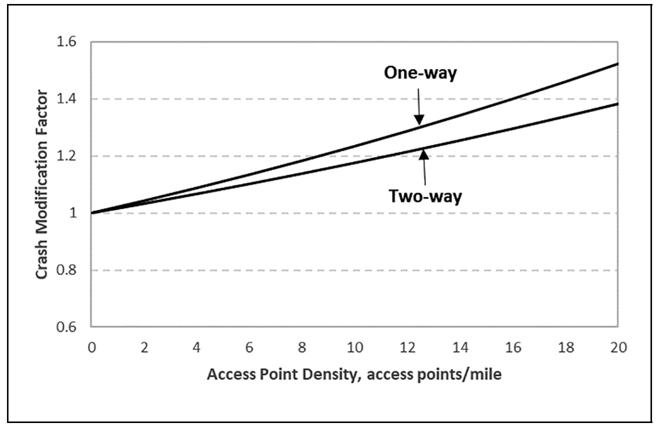

Figure 11. Crash modification factor for access-point density on frontage roads.

Access Point Density CMF. Two types of access point considered in this study are minor intersections and driveways. The minor intersection and driveway density CMFs for one-way frontage roads are described using Equations 22 and 23, respectively:

$$CMF_{int} = e^{0.021([n_{int}/L])} \quad (22)$$

$$CMF_{dw} = e^{0.021([n_{dw}/L])} \quad (23)$$

The minor intersection and driveway density CMFs for two-way frontage roads are described using Equations 24 and 25, respectively:

$$CMF_{int} = e^{0.016([n_{int}/L])} \quad (24)$$

$$CMF_{dw} = e^{0.016([n_{dw}/L])} \quad (25)$$

The base condition for this CMF is no minor intersections or driveways on the segment. This CMF is applicable to multiple-vehicle crashes only. Figure 11 shows the access-point density CMF developed in this study. The access points have more pronounced safety effect on one-way frontage roads than on two-way frontage roads.

Ramp Presence CMF. This CMF quantifies the effect of the presence of entrance or exit ramps on the frontage road. This is identified by the presence of gore point on the segment. The entrance ramp density CMF on one-way frontage roads is described using Equation 26:

$$CMF_{ent} = e^{(0.101[n_{ent}/L])} \quad (26)$$

The entrance ramp density CMF on two-way frontage roads is described using Equation 27:

$$CMF_{ent} = e^{(0.255[n_{ent}/L])} \quad (27)$$

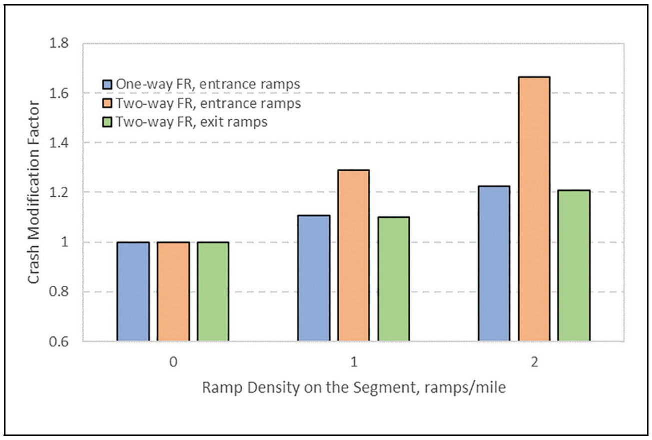

Figure 12. Crash modification factor for ramp presence density on frontage roads.

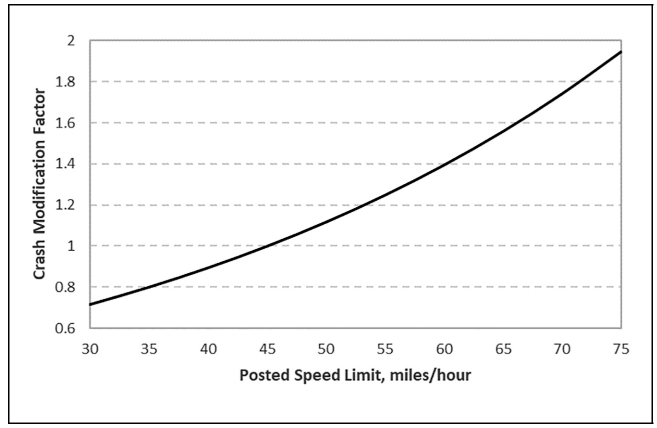

Figure 13. Crash modification factor for posted speed limit on one-way frontage roads.

The exit ramp density CMF on two-way frontage roads is described using Equation 28:

$$CMF_{ent} = e^{(0.095[n_{ext}/L])} \tag{28}$$

The base condition for this CMF is no entrance or exit ramps on the frontage road. The effect of exit ramp density on traffic crashes was not statistically significant for one-way frontage roads. Figure 12 shows the ramp presence density CMF on the frontage roads developed in this study.

Posted Speed Limit CMF. This CMF quantifies the effect of speed on the one-way frontage road. The posted speed limit CMF on frontage roads is described using Equation 29:

$$CMF_{psl} = e^{0.022(PSL-45)} \tag{29}$$

The base condition for this CMF is 45 mph. This CMF is applicable to single-vehicle crashes only and is not significant for two-way frontage roads. Figure 13 shows the posted speed limit CMF on one-way frontage roads developed in this study.

Horizontal Curve Density CMF. This CMF quantifies the effect of horizontal curves on the frontage road. The horizontal curve density CMF on two-way frontage roads is described using Equation 30:

$$CMF_{hc} = e^{(0.027[n_{hc}/L])} \tag{30}$$

The base condition for this CMF is no horizontal curves. The safety effect of horizontal curves on one-way frontage roads is not statistically significant. Figure 14 shows the horizontal curve density CMF on two-way frontage roads developed in this study.

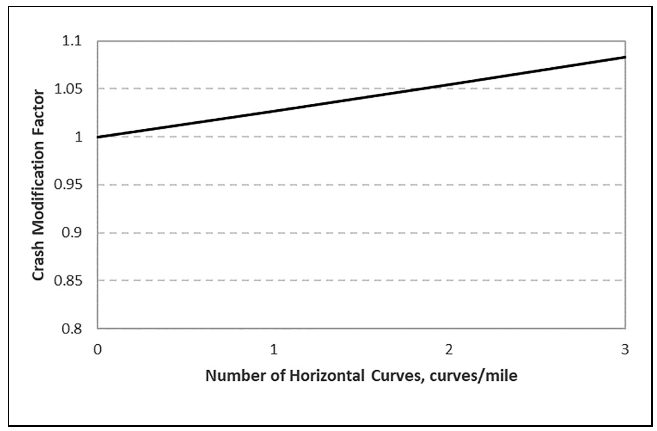

Figure 14. Crash modification factor for horizontal curves on two-way frontage roads.

Conclusions

Frontage roads serve a dual purpose: they provide access for adjacent landowners while also fulfilling operational functions, including segregating high- and low-speed traffic, offering flexibility and continuity to transportation networks, and promoting or preserving vibrant commercial development along freeways. Frontage roads can fulfill various roles based on the type of highway they run alongside. In the case of freeways, their primary objective is to facilitate the distribution and collection of traffic between local streets and freeway interchanges. They also alleviate traffic congestion on the main lanes of the freeway, especially during peak periods or when disruptions such as crashes or incidents occur, thereby offering an alternate route for drivers. Aside from granting access from local roads to the highway, frontage roads also play a crucial role in providing access to properties situated along the highway. This function becomes particularly significant in areas experiencing high traffic volumes, such as urban corridors where commercial and residential development necessitates access points.

Despite the important role played by frontage roads, only limited studies have evaluated their safety performance. Importantly, the first edition of HSM does not include SPFs for frontage road segments. This study fills the research gap by developing SPFs and CMFs for frontage roads. To ensure a comprehensive analysis, four types of frontage road database (rural one-way, rural two-way, urban one-way, and urban two-way) were prepared based on the specific roadway characteristics of rural and urban areas. However, a challenge arose, as all crashes on frontage roads in Texas are typically assigned to the centerline of the main roadway, making it difficult to ascertain the precise location of the crash (whether it occurred on the left or right frontage road). To address this issue, the authors developed a procedure to assign each crash to the appropriate frontage road segment. This method successfully located approximately 70% of the relevant crashes. For the remaining 574 frontage road crash cases where location assignment was not automated, the authors meticulously reviewed the crash reports, examining crash diagrams and cross-referencing them with aerial photographs of the roadways to ensure accuracy and completeness of the data.

The authors developed SPFs for one-way and two-way frontage roads separately. They also developed SPFs for single- and multiple-vehicle crashes separately for each frontage road type. The authors used the simultaneous modeling approach because some CMFs were common to both crash types. The SPFs developed in this study showed that, for a given condition, two-way frontage roads experience fewer crashes than the one-way frontage roads. However, it was found that the crashes on two-way frontage roads are more severe than the ones on one-way frontage roads. Similarly, the crashes on rural frontage roads are more severe than the ones on urban frontage roads. This study developed CMFs for left and right shoulder widths, access point density, presence of entrance and exit ramps, posted speed limit, and the horizontal curve density.

For future research, it is suggested to develop SPFs focusing solely on injury crashes to mitigate the impact of underreporting crash concerns. Additionally, researchers should explore the transferability of the SPFs developed in this study to other jurisdictions to assess their applicability and effectiveness in different settings. It is also recommended that a future study investigate the influence of the interchange intersection configurations on the frontage road safety.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: S. Geedipally, S. Das, L. Wu, Pratt; data collection: S. Geedipally, L. Wu, M. Pratt; analysis and interpretation of results: S. Geedipally; draft manuscript preparation: S. Geedipally, S. Das. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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