Safety Evaluation of Available Stopping Sight Distance using High-Fidelity LIDAR Data

by

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ABSTRACT

Stopping sight distance (SSD) has long been cited as a concern among design engineers, given difficulties in attaining minimum values in certain roadway contexts in consideration of cost constraints. For example, SSD is one of the ten controlling criteria for design and documentation of design exceptions. However, the extant research literature has generally not shown that locations with insufficient SSD experience higher crash risks as compared to locations that meet or exceed recommended design values. This study investigates the relationships between SSD and crash risk using high-fidelity lidar data. These data are used to examine crash trends on the roadway network maintained by the Utah Department of Transportation. Lidar data are used to assess compliance with the current SSD design policy. These data are integrated with crash and roadway geometric information. A series of negative binomial regression models are estimated to assess the relationship between available sight distance and the frequency of crashes while controlling for other important variables of interest. The results show that roadways with limited sight distance tended to experience significantly more crashes as compared to other, similar segments where sight restrictions were not present.

Keywords: Stopping sight distance, lidar, traffic safety, crash modification factor

INTRODUCTION

Sight distance, defined as the length of the roadway ahead that is visible to the driver, is one of the most important design elements that significantly impacts the operational and safety performance of highways including the design of horizontal curves, vertical curves, acceleration lanes, and deceleration lanes [1]. *A Policy on Geometric Design of Highways and Streets* (i.e., the AASHTO Green Book) recommends that "the sight distance on a roadway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path" [1]. This dimension, referred to as stopping sight distance (SSD), is comprised of two components: (1) the distance traversed by the vehicle from the instant the driver sights an object necessitating a stop to the instant the brakes are applied; and (2) the distance needed to stop the vehicle from the instant brake application begins.

SSD significantly affects the design of many highway elements and is one of the ten controlling criteria as outlined by the Federal Highway Administration (FHWA). However, research has generally shown limited evidence as to the true nature of the underlying relationship between available sight distance and crash risk. There are several reasons for this result. First, the extant research literature has generally investigated the effects of limited SSD on crashes at specific roadway locations using field data, which tend to be relatively resource-intensive to collect, reduce, and integrate. Consequently, historical analyses have generally considered limited samples of roadway data. Secondly, there is a significant factor of safety that is included when designing based on existing sight distance policies, which rely on conservative assumptions for key parameters, including brake reaction time, deceleration rate, and eye height. If these parameters are assumed to be independent of one another, the probability of all such conditions being met simultaneously is quite low.

To that end, the American Association of State Highway and Transportation Officials (AASHTO) Highway Safety Manual (HSM) does not include any crash modification factors that can be used to forecast potential impacts of sight distance related design decisions on crash frequency and severity [2]. With that being said, there are some instances where meaningful relationships have been established. For example, research has shown SSD to significantly affect safety along crest vertical curves on two-lane highways where a hidden curve, intersection, ramp, or driveway is present [3,4]. However, the broader literature has generally not shown that locations with insufficient SSD experience higher crash risks across most contexts. Glennon (1987) reviewed several early studies that considered the effect of SSD on traffic crashes [5]. However, these studies did not show consistent results as to the effects of SSD on safety [6-12]. Further, research has also shown that SSD-related crashes tend to occur only when there are sight distance limitations and, another particular event or combination of events occurs to create a critical situation that culminates in a crash [13].

NCHRP Report 783 suggests a need for further research to discern the safety effects of limited stopping sight distance on rural multilane highways, urban and suburban arterials, and freeways. Research is also warranted to determine potential operational impacts in locations with limited sight distance on two-lane highways, as well as each of these other facility types [4]. To that end, this study investigates the relationship between stopping sight distance and crash frequency separately on rural freeways and rural two-lane highways. High-fidelity light detection and ranging (LIDAR) data are obtained from the Utah Department of Transportation (UDOT). These data are used to quantify information about available SSD along corridors at 10-ft intervals. Statistical analyses are then conducted to relate available SSD to crash risk.

LITERATURE REVIEW

The broader available literature has produced inconclusive results as to the relationship between SSD and crashes. One of the primary reasons for this is the limited number of crashes that actually occur as a direct result of SSD limitations and the inability to identify such crashes based on existing crash databases [14]. However, a case study of crashes that occur on a large sample of locations with limited sight distance may show robust relationship between SSD and safety [15]. For example, a matched-paired comparison study [16] reported that crest vertical curve sites with limited SSD tended to experience 50% more crashes than sites with adequate SSD. Another study reported property damage only (PDO) crashes and crashes occurring during non-rainy weather to increase as sight distance is reduced [17]. A study in Kentucky also reported crash reductions of 30% when sight distance is improved at a site through realignment [18].

Other studies have reported no significant differences in safety performance between sites that meet the minimum SSD requirements compared to those that do not. A study aimed at quantifying the effects of curve radius, approach tangent length, and approach sight distance on safety of horizontal curves on rural two-lane highways found that the effects of sight distance on safety were unclear [19]. NCHRP 400 also investigated the effects of providing SSD that are lower than the AASHTO recommended values and found that both limited SSD and moderate reductions in available sight distances did not affect the safety performance of roadways [3]. A Texas study compared crash rates with available sight distance at crest vertical curves [20]. The study reported that limited SSD did not affect safety unless an intersection or any other hazard is present in combination with the sight distance limitation.

With recent advances in technology, more robust methods (e.g., lidar) are available to determine sight distances at large-scale. For example, a study utilizing lidar data reported that crash rates were two to three times higher in regions where SSD demands failed to meet 70% of the driving population compared to regions that met this requirement [21]. Another recent study found inverse relationships between sight distance and crash rates that utilized three-dimensional SSD data determined using LIDAR [22].

Even though the current design guidelines place a strong emphasis on SSD, sufficient literature is not available that can be used to estimate the effect of SSD on safety. Given these gaps and inconsistencies in the results, this study aims to advance the understanding of the complex relationship between SSD and safety by developing regression models that correlate safety with SSD while controlling for other site-specific factors.

DATA DESCRIPTION AND SUMMARY

The study analyzes the effect of available SSD on traffic safety considering geometric characteristics of the roadways. Several data sources were identified and utilized as part of this study. The following subsections explain details of each database.

Utah Department of Transportation LIDAR Data

High-fidelity LIDAR data were obtained from UDOT. These data were used to quantify the amount of available sight distance as per the current AASHTO design assumptions (i.e., 2.5 s reaction time, 11.2 ft/s^2 deceleration rate, and 2 ft. object height) [1] and the posted speed limit. A software tool was used to calculate the maximum speed that complied with current AASHTO policy along select road segments, along with the amount of available sight distance, the longitudinal slope, and the radius of curvature. These data were collected using a probe vehicle based on LIDAR system at 10-ft intervals. Figure 1 displays an example of LIDAR data where sight restrictions are indicated in red lines.

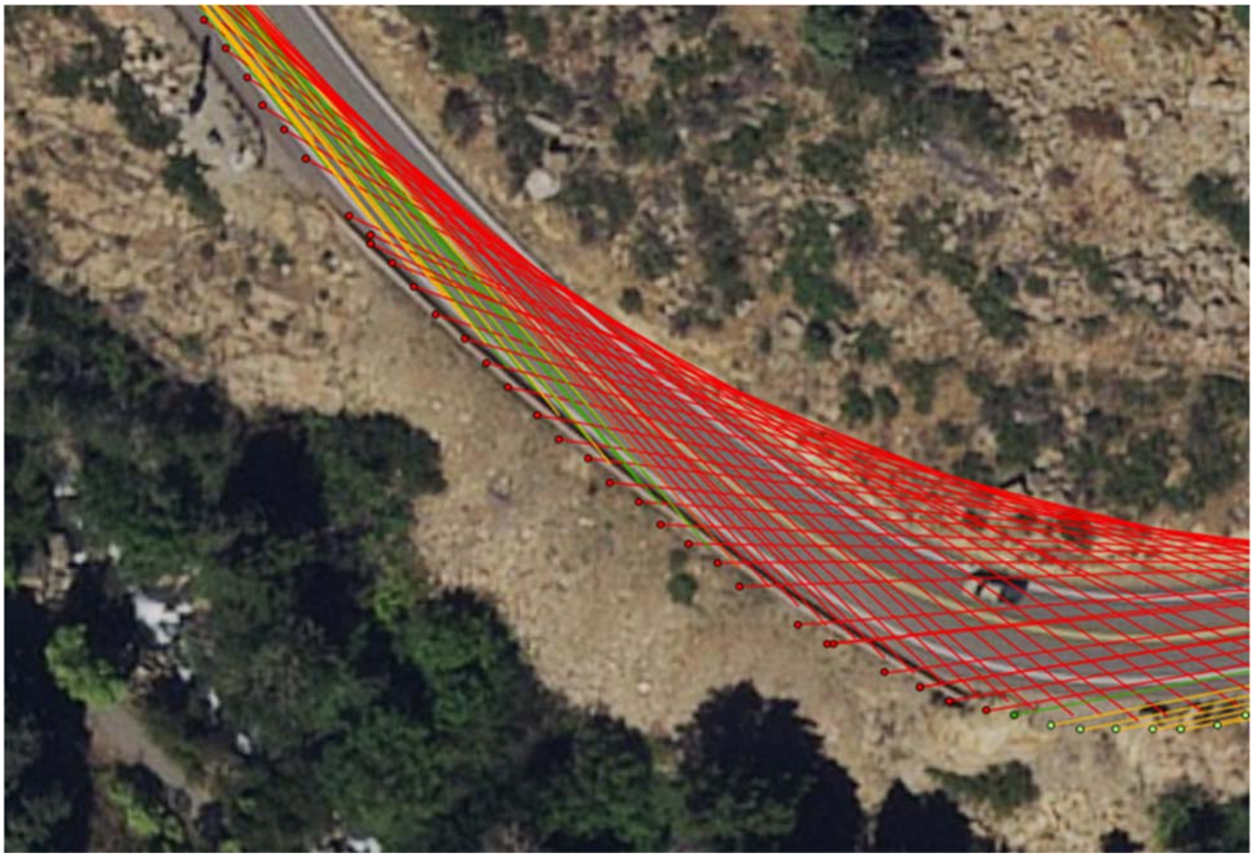
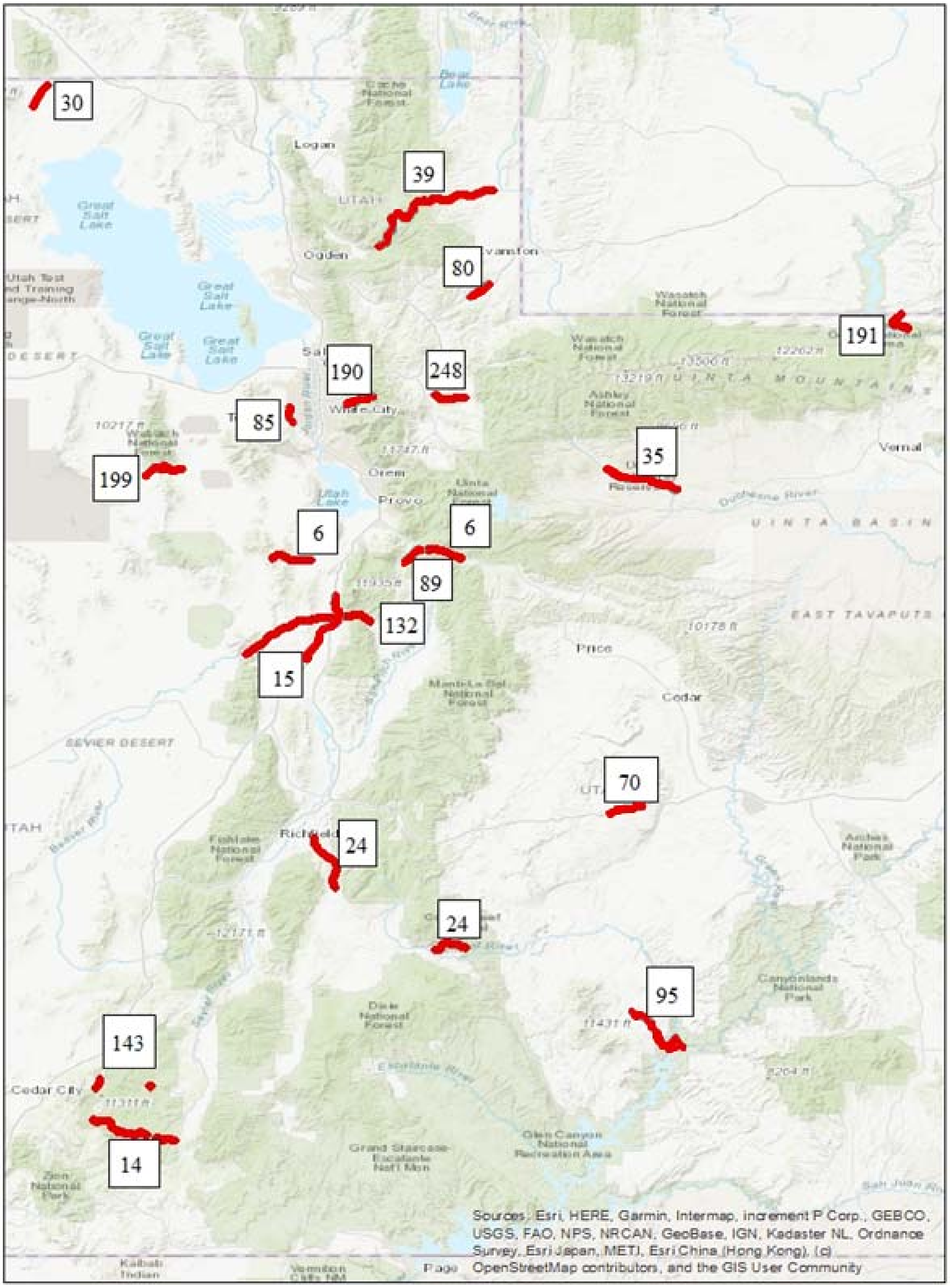


Figure 1. Sample of Available Sight Distance Data

The LIDAR data used in this study were collected from a total of 19 state-maintained routes with a total length of 274 miles. Figure 2 presents the locations of these routes across the state of Utah. Three of these routes were freeways, all with a posted speed limit of 80 mph. For non-freeways, the posted speed limit ranged from 30 mph to 65 mph. The lidar data were used to assess available sight distance at several locations for each route, including both edges of the traveled way for freeways (see Figure 3a). While for undivided non-freeways, similar analyses were conducted in each direction of travel on both the right edge of the travel lane and the roadway centerline as shown in Figure 3b.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 2. Location of Various Stopping Sight Distance Road Segments in Utah


(a) **(b)**

Figure 3. Raw LIDAR Data on (a) Non-Freeway and (b) Freeway

Utah Department of Transportation Open Data

In addition to the LIDAR data, this study utilized other roadway information from the UDOT Data Portal that are publicly available [23]. This subsection briefly explains how each database was integrated with the crash and LIDAR data into the final analysis dataset.

The UDOT functional classification database was used as the base file to integrate all of the other datasets. This database was developed at the segment-level where streets and highways in Utah were grouped according to their functional class (e.g., interstate, major collector, minor collector, etc.). Additional information included in the database that were used as s part of the data reduction process are route type (i.e., to remove ramps on freeway) and route direction (i.e., to properly join the crash data based on their direction of travel).

Additionally, a lane database was used, which provided details of lane configurations and counts for all state-maintained roadways. Descriptive information in this database included types of lanes (e.g., auxiliary lane, thru lane, deceleration lane, acceleration lane, turning lane, passing lane, bike lane, two-way left-turn lane, high-occupancy vehicle lane, etc.), GIS coordinates, direction of travel, route name, and milepost. A median database provided information including the median type (e.g., undivided, concrete barrier, depressed median, raised median, etc.) and width. In addition, a shoulder database was used to identify whether barriers or roadside walls were present at the edge of the roadway. This database also provided other information related to shoulder including shoulder width, shoulder type (e.g., no shoulder, asphalt, concrete, and polymer), and edge type (e.g., gravel, paved ditch, gutter, curb, etc.). Note that separate shoulder datasets were provided for each direction of travel.

Traffic volume data from the UDOT Transportation Monitoring Unit were utilized. The traffic information in this database included annual average daily traffic (AADT) for all state-maintained roadways and federal-aid highways. The AADT were collected by UDOT based on one of two methods: (1) continuous counts from permanent vehicle count stations that record traffic volumes for 24 hours per day, 365 days per year; and (2) short-term counts that estimate the AADT based on 48-hour traffic counts and several adjustment factors, such as seasonal and time-of-day factors.

Utah Department of Transportation Crash Data

Crash data were obtained were obtained through a web-based data portal [24],which allows users to conduct queries at the crash-, vehicle-, or person-level. Since the LIDAR data provided by UDOT were based on route identification (ID) and milepost, these pieces of information were used to identify crashes that occurred on the given routes within the boundaries of interest. However, there were some changes that occurred in the linear referencing system of the crash database after 2015. Thus, the mileposts obtained from the LIDAR data were adjusted to ensure all crashes that occurred on the given routes were correctly identified. Crashes that were beyond the boundary of the study sites were manually removed from the dataset.

Five years of crash data from 2015 to 2019 were selected for analysis purposes. Several attributes from the database were selected and considered in the analysis including severity level, type of collision, lighting condition, weather condition, surface condition, driver condition, animal involvement, distracted driving involvement, and horizontal alignment among others. Table 1 shows the frequency of crash data from 2015 to 2019 based on route and severity level. On average, the freeway network experienced approximately 1.75 crashes per mile per year, while for non-freeways, 1.39 crashes per mile per year were recorded. In terms of severity level, a total 21 fatal crashes were recorded across all sites for a period of five-years. The highest number of fatal crashes recorded were on SR-85 which was 0.2 crashes per mile per year. This segment of roadway had speed limit between 55 mph and 65 mph, with four at-grade signalized intersections.

Table 1. Summary of Crash Data from 2015 to 2019 by Route and Severity

Route	Beginning Mile Point	Ending Mile Point	Fatal	Major Injury	Minor Injury	Possible Injury	No Injury	Total Crashes
I-15	209.9	231.7	2	6	17	27	202	254
I-70	130.9	138.7	0	1	0	2	7	10
I-80	178.9	184.7	0	1	5	4	37	47
SR-190	1.8	9.3	1	9	31	18	172	231
SR-35	44.3	62.0	0	0	2	5	34	41
SR-85	10.0	15.0	5	21	37	56	169	288
US-89	306.8	312.8	0	5	8	7	40	60
SR-95	25.1	47.9	0	3	1	1	5	10
SR-199	7.0	18.1	1	2	2	5	39	49
SR-30	68.0	75.1	0	0	2	1	4	7
SR-39	25.9	67.7	1	9	24	13	65	112
SR-248	6.8	14.5	1	3	13	11	132	160
SR-132	8.8	33.2	1	1	6	12	76	96
SR-132	34.8	42.2	2	2	6	9	86	105
US-6	140.8	150.9	1	7	14	9	36	67
US-6	188.8	197.2	2	8	25	7	107	149
US-191	395.8	404.2	0	0	1	1	8	10
SR-14	16.2	32.4	2	3	10	12	77	104
SR-14	35.4	41.0	0	4	4	2	17	27
SR-24	15.8	32.9	1	5	9	10	83	108
SR-24	68.8	77.8	1	0	4	1	10	16
SR-143	10.6	14.2	0	1	1	2	12	16
SR-143	34.8	36.0	0	0	0	0	2	2

Additional summary data related to the full sample of 1,969 crashes are shown in Table 2, for both the freeway and non-freeway routes. The severity distributions were generally similar across the facility types, though the non-freeway system had a significantly larger proportion of crashes that resulted in injuries (29.2 percent versus 20.9 percent). For both types of roadways, the majority of crashes tended to involve single-vehicles (76.5 percent for freeway and 73.5 percent for non-freeway), followed by some combination of rear-end and side-swipe collisions. As the vast majority of crashes were property-damage-only (PDO) and single-vehicle, the subsequent analyses focus on total crashes of all types and severity levels. Additional analyses were conducted for these two subsets (PDO and single-vehicle) of crashes, though the results were generally similar. The other sample sizes were too small for meaningful analyses to be conducted.

Table 2. Descriptive Statistics for Freeway and Non-Freeway Crash Data

	Freeway		**Non-Freeway**	
Variable	**Number**	**Percent**	**Number**	**Percent**
Crashes by Severity Level				
K	2	0.6	19	1.1
A	8	2.6	83	5.0
B	22	7.1	200	12.1
C	33	10.6	182	11.0
O	246	79.1	1174	70.8
TOTAL	311	100.0	1658	100.0
Manner of Collision				
Not Applicable/Single Vehicle	238	76.5	1218	73.5
Front to Rear	25	8.0	164	9.9
Sideswipe Same Direction	39	12.5	64	3.9
Sideswipe Opposite Direction	0	0.0	61	3.7
Parked Vehicle	5	1.6	29	1.7
Head On (front-to-front)	0	0.0	19	1.1
Angle	4	1.3	99	6.0
TOTAL	311	100.0	1658	100.0

Data Integration and Summary

As mentioned previously, the functional classification database was used as the main base file. Due to the changes in the linear referencing of the crash database, a new linear referencing system was developed to make sure all crashes were based on the same system and linked to the appropriate segment. Each route was then divided into a series of 0.1-mile segments as recommended by the HSM [2]. The open source data (e.g., traffic volume and lane information) mentioned previously were then joined spatially to the 0.1-mile segment data. However, due the unavoidable changes in the roadway characteristics for some segments (e.g., number of lanes, shoulder width, speed limit, etc.), these segments were split into smaller segments, while few segments were joined with the adjacent segments. Overall, the average segment length was still approximately equal to 0.1 mile.

Since the LIDAR data provided by UDOT were in a point feature format (Figure 3a and 3b), each point was identified along the route and joined to the associated the roadway segment. On average, there were 49 data points from each LIDAR data file (i.e., left side, right side, center of the road) for every 0.1-mile segment. The minimum, maximum, and average value of each variable from the LIDAR data were calculated from the 49 data points. This was necessary as most variables (e.g., curve radius, available sight distance) tended to vary across the 0.1-mi interval, as well as between the centerline and edge line locations. Table 3 provides the descriptive statistics of the final analysis datasets for both the freeway and non-freeway segments.

Table 3. Descriptive Statistics for Freeway and Non-Freeway

	Freeway		**Non-Freeway**	
Variable	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Annual average daily traffic (veh/day)	16,093	7,020	2,510	4,129
Segment length (ft.)	0.10	0.02	0.09	0.02
Median width (ft.)	103.83	23.04	11.46	56.42
Right shoulder width (ft.)	9.97	1.35	2.80	1.79
Left shoulder width (ft.)	3.85	0.90	na	na
Lane width (ft.)	12.22	0.41	11.64	0.56
Speed limit (mph)	80.00	0.00	56.27	7.51
Horizontal curve radius (ft.)	9,449	4,616	4,407	4,798
Degree of curvature	0.82	0.51	3.46	3.48
Total crashes per segment-year	0.17	0.44	0.13	0.46

These summary data show the average AADT per segment for freeway and non-freeway segments are 16,093 and 2,510, respectively. For median width, the freeway network had an average width of 104 feet. While for the non-freeway network, a small portion of the data (7 percent) had some type of median (e.g., painted median, two-way left-turn lane, depressed median, etc.) with an average width of 11 feet. across all segments. The outside shoulders were significantly wider on the freeway segments at 10 feet on average as compared to approximately 2.8 feet on non-freeways. On freeways, the left-side shoulders were 3.9 feet wide on average. Lane widths were generally 12 feet, though slightly larger on the freeway system.

The posted speed limit was 80 mph for all of the freeway segments that were included in the sample. For the non-freeway system, speed limits ranged from 30 to 65 mph, with 55 mph comprising the largest portion of the sample (52 percent). As the other speed limits had relatively small sample sizes, the subsequent analyses for the non-freeway network focus exclusively on these 55-mph segments.

The freeway sample was largely comprised of tangent segments whereas the non-freeway dataset had significantly larger numbers of horizontal curves. Finally, the table also provides a summary of the average number of crashes per year on the 0.1-mi segments. On average, the freeway segments experienced 0.17 crashes per year compared to 0.13 crashes per year for the non-freeway facilities.

STATISTICAL METHODS

To examine the relationship between available stopping sight distance and crash risk, a series of regression models were estimated for total crashes on both the freeway and non-freeway segments. As the annual numbers of crashes on specific road segment are comprised of discrete, non-negative integers, negative binomial regression models have emerged as the most widely applied statistical method for the analysis of crash data. Within the context of this study, the probability of *y* crashes occurring on segment *i* during a specific year of the analysis period can be calculated as shown in Equation 1:

$$P(y_i) = \frac{\Gamma((1/\alpha)+y_i)}{\Gamma(1/\alpha)y_i!}\left(\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right)^{1/\alpha}\left(\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right)^{y_i}, \quad (1)$$

where $\Gamma(.)$ is a gamma function, α is an overdispersion parameter, and λ_i is equal to the expected number of crashes on segment i. The λ_i parameter is related to a series of site-specific characteristics as shown in Equation 2:

$$\lambda_i = EXP(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon_i), \quad (2)$$

where X_1 to X_k are a series of independent variables (e.g., traffic volumes, geometric characteristics), β_1 to β_k are a series of parameters estimated from the regression model, and $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean equal to one and variance of α. Segment length is treated as an offset variable, meaning that the parameter estimate is constrained to one. This introduces an implicit assumption that crashes will increase proportionately with respect to the segment length.

RESULTS AND DISCUSSIONS

At the onset of the study, a series of preliminary analyses were conducted to discern the general relationship between crash risk and available stopping SSD. For example, Table 4 presents summary data that relates the average crash rate per million vehicle miles traveled (MVMT) versus the minimum amount of available SSD at any point along the analysis segments based upon the LIDAR data. These same data are presented graphically in Figure 4.

Overall, crash rates increase slightly as the available SSD is decreased from 1010 ft. There is a slight decrease in rates in the 600-700 ft. range. Below this amount, substantive increases are found to occur. It should be noted that the sample sizes among many of these groups is relatively modest. Nonetheless, it does appear that substantive sight distance limitations are associated with higher crash rates.

Table 4. Crash Rate per MVMT vs. Minimum Available SSD, Freeways

Minimum Available SSD (ft)	No. of Segments	No. of Miles	Avg. AADT	Total MVMT	Total Crashes	Crash Rate per MVMT
≤495	72	7.14	18702	242.76	104	0.43
570	13	1.26	17468	40.02	15	0.37
645	34	3.41	15550	94.65	20	0.21
730	37	3.57	18146	117.17	31	0.26
820	54	5.17	15952	149.54	43	0.29
910	26	2.52	14749	67.36	18	0.27
1010	132	12.46	14392	322.37	80	0.25

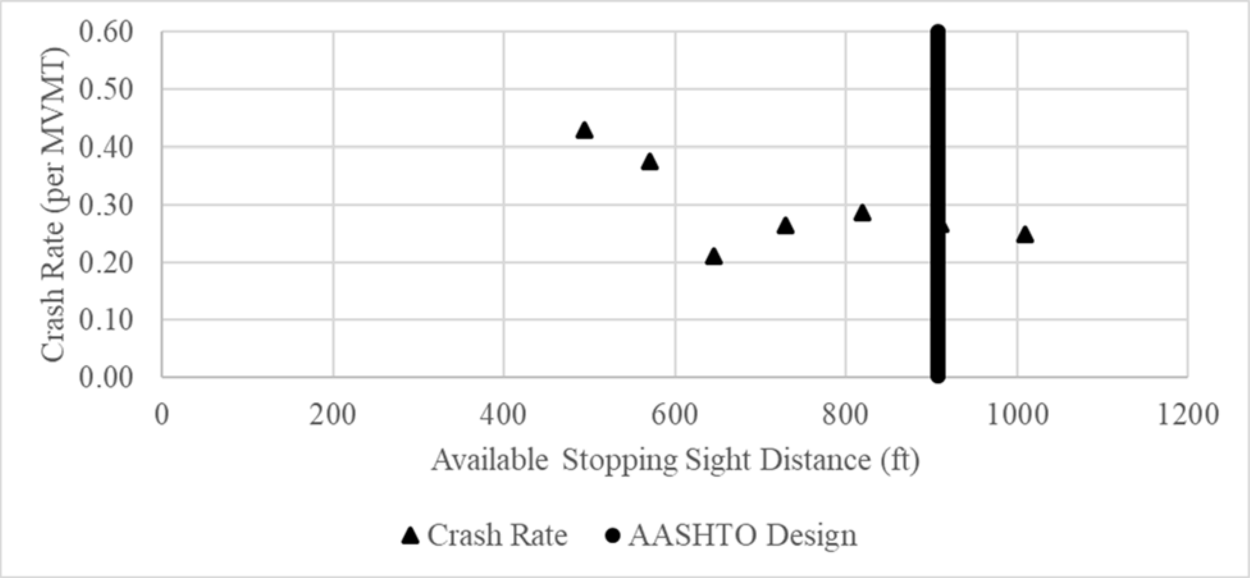


Figure 4. Crash Rate per Million Vehicle Miles Traveled (MVMT) vs. Available Stopping Sight Distance, Freeways

Similar data are shown in Table 5 and Figure 5 for the non-freeway system. In this case, crash rates are shown to increase consistently as the amount of available SSD becomes more limited. This holds until values of less than 250 ft., which correspond to a curve advisory speed of 35 mph. As the sample sizes within these lowest available SSD groups are again somewhat limited, further investigation is warranted. However, crash rates are clearly elevated at levels below the corresponding AASHTO design value for a 55-mph facility.

Table 5. Crash Rate per MVMT vs. Minimum Available SSD, Non-Freeways

Minimum Available SSD (ft)	No. of Segments	No. of Miles	Avg. AADT	Total MVMT	Total Crashes	Crash Rate per MVMT
≤155	53	5.01	1,054	9.41	8	0.85
200	56	5.28	881	8.45	14	1.66
250	95	8.84	1,237	19.31	49	2.54
305	172	16.40	1,102	31.82	77	2.42
360	164	15.70	831	23.03	54	2.34
425	265	25.66	683	32.00	71	2.22
495	82	7.85	884	12.14	22	1.81
570	84	8.27	842	12.85	30	2.33
645	59	5.34	911	8.82	14	1.59
730	51	4.69	821	6.61	13	1.97
820	46	4.61	862	6.99	12	1.72
910	55	5.32	1,083	10.87	12	1.10
1010	95	8.97	1,690	27.66	23	0.83

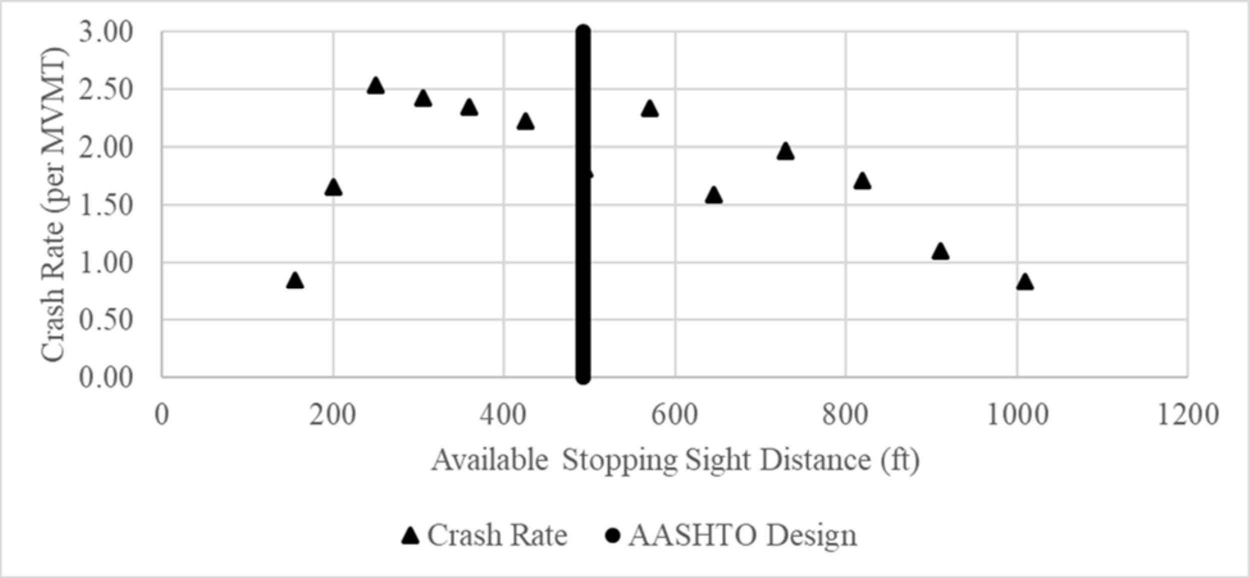


Figure 5. Crash Rate per Million Vehicle Miles Traveled (MVMT) vs. Available Stopping Sight Distance, Non-Freeways

To further investigate these relationships, a series of SPFs were estimated for both the freeway and non-freeway datasets. These empirical models account for the effects of other important factors, including annual average daily traffic (AADT) and degree of curvature. Three alternative model specifications were estimated, each of which provided similar goodness-of-fit for the crash data. These models included: (1) available SSD; (2) the natural log of available SSD; and (3) the ratio of available SSD to required SSD at the prevailing speed limit.

In the case of the freeway system, the posted limit was 80 mph. Table 6, Table 7, and Table 8 show the results from these three model specifications. In each case, the model results include the parameter estimates, along with the associated standard errors, *t*-statistics, and *p*-values. When interpreting the model results, a positive parameter estimate indicates that crashes increase as that independent variable is increased. The converse is true for negative parameter estimates. The three model results are illustrated graphically in Figure 6, which was developed for average values of the other input parameters from Table 3. This plot shows the expected number of crashes per mile per year that would be expected for these conditions on an 80-mph freeway with various amounts of available SSD.

In each case, crashes are found to increase from approximately 1.35 per mile per year at the maximum available SSD to 2.05 per mile per year at the minimum available SSD. The results show that crashes are increasing at an elastic rate with respect to traffic volume. For every one-percent increase in AADT, crashes increase by approximately 1.2 percent. Crashes also tend to increase with horizontal curvature, though this result is not significantly at 95-percent confidence and the subject freeways generally included limited curvature. In general, a one-percent increase in available SSD was associated with a 0.4-percent decrease in crash frequency.

Table 6. SPF Results for Freeways as a Function of Available SSD

Parameter	Estimate	Std. Err.	*t*-Statistic	*p*-Value
Intercept	-11.3000	1.7840	-6.3350	0.0000
Natural log (Annual average daily traffic)	1.2320	0.1775	6.9400	0.0000
Degree of curvature	0.2399	0.1322	1.8140	0.0697
Available SSD (ft)	-0.0006	0.0003	-2.2610	0.0238

Table 7. SPF Results for Freeways as a Function of the Natural Log of Available SSD

Parameter	Estimate	Std. Err.	*t*-Statistic	*p*-Value
Intercept	-9.0654	2.1437	-4.2290	0.0000
Natural log (Annual average daily traffic)	1.2313	0.1771	6.9530	0.0000
Degree of curvature	0.2449	0.1308	1.8730	0.0610
Natural log (Available SSD)	-0.4120	0.1620	-2.5420	0.0110

Table 8. SPF Results for Freeways as a Function of Available SSD divided by Required SSD

Parameter	Estimate	Std. Err.	*t*-Statistic	*p*-Value
Intercept	-11.2041	1.7832	-6.2830	0.0000
Natural log (Annual average daily traffic)	1.2244	0.1772	6.9080	0.0000
Degree of curvature	0.2405	0.1316	1.8280	0.0675
Available SSD divided by Required SSD	-0.6083	0.2548	-2.3870	0.0170

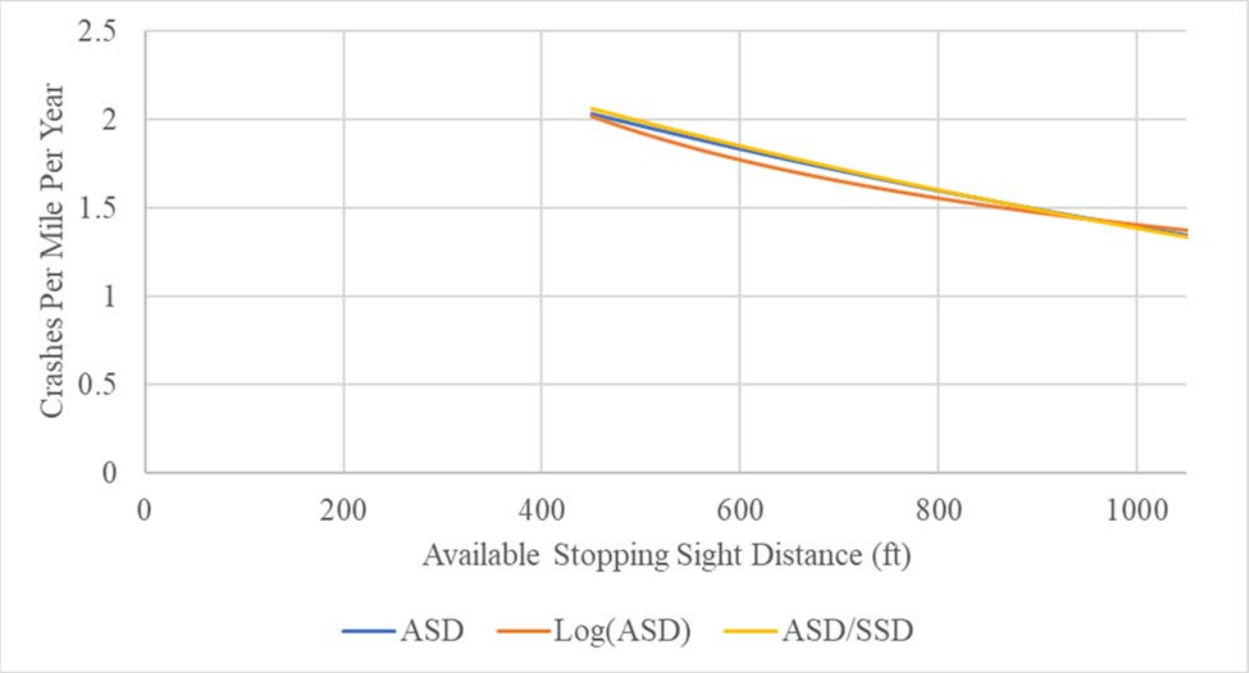


Figure 6. Comparison of SPFs for Freeways for Various SSD Specifications

Similar SPFs were estimated for the non-freeway system. As noted previously, this analysis focused only on highways with a 55-mph posted speed limit due to variability in results across the other limits, where sample sizes were considerably smaller. Similar predictor variables were tested for each model. Only those segments with available SSD of at least 250 ft. were included in this analysis as the trends varied considerably below this threshold as detailed in the preceding crash rate discussion and the sample sizes were too small to discern a statistically significant effect.

As in the freeway case, three models were estimated, which included specifications based on: (1) available SSD; (2) the natural log of available SSD; and (3) the ratio of available SSD to required SSD at the 55-mph speed limit. Results for each model are shown in Table 9, Table 10, and Table 11 for the non-freeway network. A graphical comparison of the three models is shown in Figure 7, which was again developed for average values of the other input parameters from Table 3. This plot shows the expected number of crashes per mile per year that would be expected for these conditions on a 55-mph non-freeway with various amounts of available SSD.

Crashes increase with traffic volume, though the effect is less pronounced as compared to the freeway analysis. Every one-percent increase in traffic volume was associated with only a 0.8-percent increase in crashes. Crashes also consistently increased with degree of curvature as the two-lane segments included numerous sections with advisory speed curves.

As with the freeway analysis, the amount of available SSD was again shown to be a strong predictor of traffic crashes, as crashes are found to persistently decrease as the ASD increases. These effects increased at a rate that was very similar in magnitude to the freeway facilities. In each case, crashes are found to increase from approximately 0.70-0.80 per mile per year at the maximum available SSD to 1.50-1.60 per mile per year at the minimum available SSD.

Table 9. SPF Results for Non-Freeways as a Function of Available SSD

Parameter	**Estimate**	**Std. Err.**	***t*-Statistic**	***p*-Value**
Intercept	-6.0679	0.4369	-13.8880	< 2e-16
Natural log (Annual average daily traffic)	0.8024	0.0479	16.7600	< 2e-16
Degree of curvature	0.0628	0.0284	2.2100	0.0271
Available SSD (ft)	-0.0008	0.0003	-2.6030	0.0092

Table 10. SPF Results for Non-Freeways as a Function of the Natural Log of Available SSD

Parameter	**Estimate**	**Std. Err.**	***t*-Statistic**	***p*-Value**
Intercept	-3.7147	1.0931	-3.3980	0.0007
Natural log (Annual average daily traffic)	0.8006	0.0479	16.7230	< 2e-16
Degree of curvature	0.0598	0.0287	2.0810	0.0374
Natural log (Available SSD)	-0.4485	0.1653	-2.7130	0.0067

Table 11. SPF Results for Non-Freeways as a Function of Available SSD divided by Required SSD

Parameter	**Estimate**	**Std. Err.**	***t*-Statistic**	***p*-Value**
Intercept	-6.0549	0.4347	-13.9290	< 2e-16
Natural log (Annual average daily traffic)	0.8043	0.0480	16.7730	< 2e-16
Degree of curvature	0.0598	0.0286	2.0930	0.0364
Available SSD divided by Required SSD	-0.4445	0.1609	-2.7620	0.0057

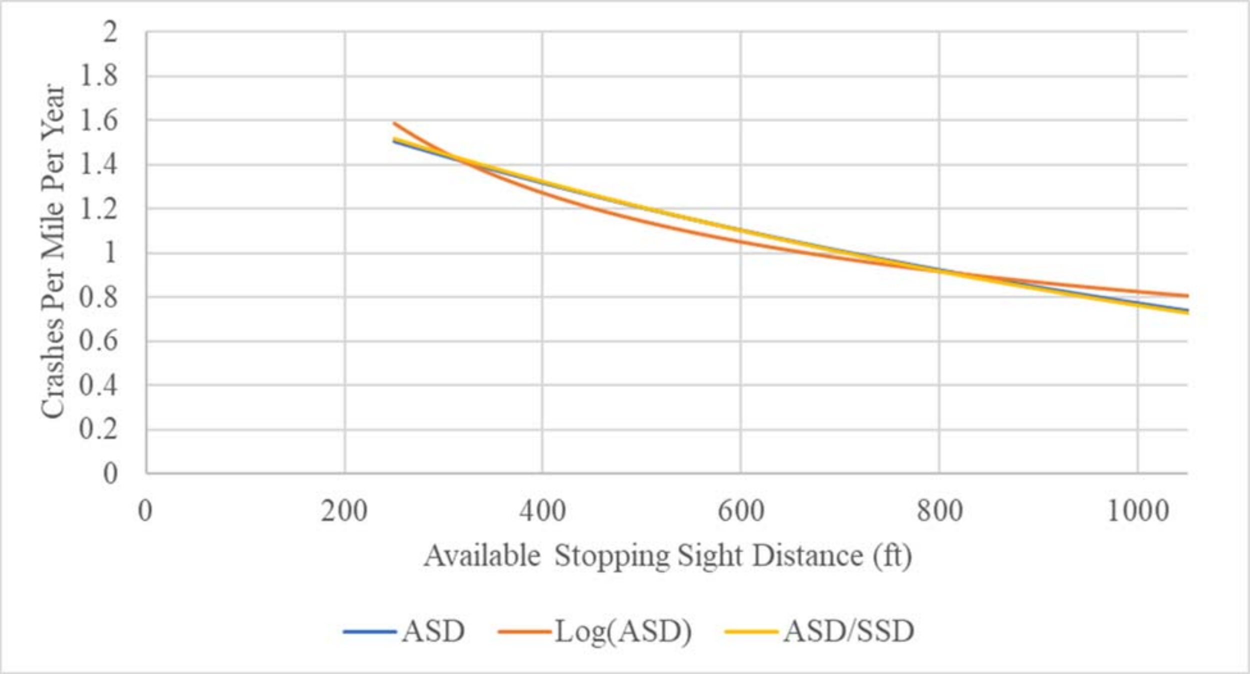


Figure 7. Comparison of SPFs for Non-Freeways for Various SSD Specifications

CONCLUSIONS

Stopping sight distance is one of the most important criteria for highway design. However, the literature has shown limited quantitative evidence as to the nature of this relationship. As such, the results from this study provide an important contribution to the research literature. The study demonstrated the value of high-fidelity LIDAR data, which allowed for a large-scale investigation of the relationship between crash risk and available sight distance on a diverse set of roadway facilities. Negative binomial regression models were estimated separately for freeway and non-freeway facilities while controlling for the effects of other important variables.

The results show similar relationships for both facility types, with crashes persistently increasing as the amount of available sight distance is reduced. The safety performance functions estimated as a part of this study provide an empirical basis for estimating the potential impacts of design scenarios where it may be impractical to satisfy the minimum recommendation distances from the AASHTO Green Book. The results can also help to inform agency practices and the development of projects to mitigate the sources of the sight distance limitations.

While these results provide critical insights, additional research is warranted to better understand the nature of these relationships. This includes examining the consistency of these results across sites with different posted speed limits and/or design speeds, comparing transferability of the results across other geographic locations, and assessing differences in terms of the manner in which the available SSD is specified in the analysis.

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