Safety Effects of Two-Lane Two-Way Segment Length Through Work Zones on Normally Four-Lane Divided Highways

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In 1979, an equation was derived for the optimum length of two-lane two-way (TLTW) segments through work zones on normally four-lane divided highways. Solution of this equation for the prevailing conditions on I-80 in Nebraska in 1986 yielded optimum segment lengths that were about 60 percent longer than those used previously in Nebraska. Because of concern expressed about the safety of longer TLTW segments, the applicability of the longer optimum lengths was questioned. The objective of this study was to determine the effects of longer TLTW segments on the safety of traffic operations. The study examined the relationships between segment length and five speed distribution parameters used as indicators of traffic safety. The relationship between segment length and TLTW accident rate was also examined. No relationships were found between TLTW segment length and accident rate or any of the speed distribution parameters. It was concluded that there is no relationship between TLTW segment length and the safety of TLTW operations for the conditions studied.

In 1979, McCoy et al. (*1*) derived an equation for the optimum length of two-lane two-way (TLTW) traffic operations in construction zones on rural four-lane divided highways. The equation, which was derived by using the methods of calculus, defined the optimum length as the length that would minimize the sum of the additional road user and traffic control costs resulting from the construction project. The equation for optimum segment length (l_o) was expressed as follows:

$$l_o = \left[\frac{LC_x/(\mathrm{ADT}.D)}{(10^{-8})\ (c_{al}\, a_l - c_{an}\, a_n) + c_T\,(1/v_l - 1/v_o) + c_{ol}} \right]^{1/2} \quad (1)$$

where

L = project length (mi);
C_x = average cost of constructing a crossover system, which consists of two median crossovers, and providing traffic control devices on the two crossovers and their approaches (dollars per crossover system);
ADT = average daily traffic volume (vehicles/day);
D = project duration (days under TLTW operations);
c_{al} = average cost per segment accident during TLTW operations (dollars);
a_l = segment accident rate during TLTW operations (accidents/100 million vehicle miles, or MVM);
c_{an} = average cost per segment accident during four-lane divided operations (dollars);
a_n = segment accident rate during four-lane divided operations (accidents/100 MVM);
c_T = unit value of time (dollars/vehicle hour);
v_l = average overall speed of TLTW operations (mph);
v_o = average overall speed of four-lane divided operations (mph); and
c_{ol} = increase in average vehicle operating costs due to TLTW operations (dollars/vehicle mile).

Although the functional relationship expressed by this equation remains valid, the values of the unit cost factors used in its solution have changed considerably since the equation was first derived. In addition, improved traffic control measures implemented by the Nebraska Department of Roads (NDOR) have reduced the frequency and severity of accidents that occur with TLTW operations in construction zones. Therefore optimum segment lengths computed with Equation 1 using 1979 unit costs and accident rates are not applicable to current conditions. To compute segment lengths that are appropriate for current conditions, current values for the unit costs and accident rates must be used in Equation 1.

In 1986, McCoy (*2*) conducted a study to update the unit cost factors and accident rates used in Equation 1 to reflect current conditions on I-80 in Nebraska. Accident, delay, and vehicle operating cost analyses were performed to update the road user cost factors in Equation 1. For prevailing roadway and traffic conditions representative of those on I-80 in Nebraska, optimum segment lengths computed using the 1986 values in Equation 1 were found to be about 60 percent longer than those computed using the 1979 values. Optimum segment lengths were generally found to be in the range 3.0 to 5.0 mi with the 1979 values and in the range 4.8 to 8.0 mi with the 1986 values.

However, concern has been expressed about the safety of longer segment lengths. On the basis of intuition and limited data, Pang (*3*) concluded that longer segments tended to

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experience higher accident rates. The Traffic Control Devices Handbook (*4*) states that:

> When segments of TLTWO exceed 3 to 5 mi, there may be operational problems due to lower speed vehicles which can make a section more prone to rear end accidents . . . . Where separation devices are other than positive barrier, there is a high probability of illegal passing maneuvers on longer sections due to frustration and impatience . . . . Therefore, from a safety standpoint short segments are desirable.

This concern about the safety effects of longer segments brings into question the applicability of the optimum lengths computed with Equation 1 using the 1986 values. First of all, in Equation 1, the segment accident rate during TLTW operations (a_l) is a constant value and not a function of segment length. Therefore, if in fact a_l is not a constant and does vary with segment length, the optimum segment lengths computed with Equation 1 would not be valid, and Equation 1 would have to be revised to account for the relationship between a_l and segment length.

Second, the 1986 value used for a_l (30.8 accidents/100 MVM) was the average of the accident rates experienced on 24 TLTW segments on I-80 in Nebraska between 1978 and 1984. These rates, which are presented in Table 1, range from 0 to 178.1 accidents/100 MVM. Although the results of simple linear regression analysis, presented in Table 2, indicate that there is not a statistically significant linear relationship between a_l and segment length, only 2 of the 24 TLTW segments were longer than 5 mi. If segments longer than 5 mi would happen to have average accident rates greater than 30.8 accidents/100 MVM, then the optimum segment lengths computed with Equation 1 using the 1986 values would not be correct. Instead, they would be longer than the "true" optimum segment lengths.

OBJECTIVE

The objective of the study presented in this paper was to determine the effects of longer TLTW segments on the safety of traffic operations. The study examined the relationships between segment length and five speed distribution parameters that have been used as indicators of traffic flow safety. In addition, the relationship between TLTW segment accident rate and segment length was examined. The procedure, findings, and conclusion of the study are presented in this paper.

PROCEDURE

The study procedure involved the conduct of spot speed studies and the analysis of accident experience on four TLTW segments on I-80 in Nebraska in 1986. The segments that were studied are presented in Table 3. They were selected because their lengths, which ranged from 6.68 to 7.22 mi, were longer than the usual maximum segment length of 5 mi. All of the segments were located on level terrain in western Nebraska.

The pavement markings used on each segment are illustrated in Figure 1. The segment cross section consisted of two traffic lanes about 12 ft wide, a 3-ft median, a 3-ft paved shoulder on one side, and a 6.5-ft paved shoulder on the other side. This cross section was possible because the pavement structure of the shoulders on I-80 was of the same strength as the traffic lanes. The median used to separate the opposing traffic lanes consisted of two bidirectional yellow raised pavement markers centered 3 ft apart and installed at 10-ft intervals, plus 18-in. tubular posts installed at 200-ft intervals. Two-way traffic warning signs and "do not pass" regulatory signs were installed on each side of the roadway at ½-mi intervals.

Spot Speed Studies

Spot speed studies were conducted at five locations on each TLTW segment. As shown in Figure 2, each segment was divided into thirds. In the direction in which traffic did not have to cross over the median, spot speed data were collected at three points (the one-third point, two-thirds point, and at the end of the segment). Data were not collected at the beginning of the segment in this direction because of the influence of the transition from four-lane divided to TLTW operations. In the other direction, in which traffic had to cross over the median, spot speed data were collected at only two locations (the one-third and two-third points). Data were not collected at the beginning and end of segment in this direction because of the influence of the crossovers.

The spot speed data were collected by means of radar during daytime hours. All observations made were of free-flowing vehicles during free-flowing conditions (level of service B or better).

Previous research has determined that certain parameters of speed distributions can be used as indicators of the safety of traffic operations. A number of studies have concluded that speed variance and accident frequency are directly related (*5*). From a study of accident data for rural highway sections, Solomon (*6*) found a relationship between accident rate and speed variation. According to this relationship, the accident involvement rate of a vehicle increases as its speed varies from the average speed of traffic. In an AASHTO study of accident experience on Interstate highways (*7*), it was determined that accident rates decreased as the percentage of traffic traveling in the 10-mph pace increased. In another study, Taylor (*8*) found that a relationship exists between the accident rate and the speed distribution on rural highways. He determined that the safest traffic operations occur when speeds are normally distributed and that the best parameter to use as an indicator of the safety of traffic operations is the skewness of the speed distribution.

Therefore, for the purpose of this study, the following speed distribution parameters were used as indicators of the safety of traffic operations:

- standard deviation,
- range,
- percentage in the 10-mph pace,
- skewness, and
- expected accident involvement rate.

It was assumed that the safety of traffic operations improved with higher values of the percentage in the 10-mph pace. Conversely, it was assumed that the safety of traffic operations worsened with higher values of the other four parameters. The expected accident involvement rate was computed by applying the observed speed distribution to the relationship between

TABLE 1 ACCIDENT RATES UNDER TLTW OPERATIONS

Project	Year	Segment	Length (miles)	ADT	Days of Operation	No. of Accidents	Accident Rate (acc/100 MVM)
IR-80-6(37)	1978	1	2.63	11,800	30	0	0
		2	3.48	9,800	33	2	178.1
IR-80-7(55)	1978	1	4.83	15,700	72	2	36.7
IR-80-3(71)	1979	1	3.85	10,100	46	0	0
		2	3.71	13,500	38	0	0
		3	3.66	12,400	43	0	0
IR-80-5(31)	1979	1	3.43	10,900	40	0	0
		2	3.81	9,100	71	2	81.5
IR-80-7(56)	1979	1	4.49	9,700	47	0	0
IR-80-4(60)	1980	1	3.82	9,100	36	0	0
		2	3.60	11,900	27	0	0
IR-80-4(64)	1980	1	3.24	9,500	36	0	0
		2	2.43	11,100	27	0	0
IR-80-4(58)	1980	1	4.57	6,600	68	1	48.4
		2	4.80	8,000	41	1	63.8
IR-80-5(33)	1980	1	3.10	10,900	57	1	51.7
		2	3.26	12,500	40	1	61.2
		3	3.81	10,900	56	0	0
IR-80-4(66)	1981	1	3.29	11,300	49	1	54.9
		2	4.23	8,100	71	0	0
IR-80-7(68)	1983	1	4.91	14,500	114	5	61.6
IR-80-7(72)	1984	1	4.91	10,500	93	0	0
IR-80-6(48)	1984	1	6.46	9,100	65	3	78.5
IR-80-7(73)	1984	1	6.78	10,700	174	3	23.7
						Average	30.8

TABLE 2 ANALYSIS OF VARIANCE FOR REGRESSION ANALYSIS TLTW ACCIDENT RATES FROM PREVIOUS STUDY

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob > F
Due to b_0	1	22,822.83	22,822.83		
Due to b_1/b_0	1	908.86	908.86	0.472	0.499
Residual	22	42,340.89	1,924.59		
Total	24	66,072.58			

NOTE: $\hat{Y} = b_0 + b_1X$, where $\hat{Y}$ is the segment accident rate during TLTW operations (accidents/100 MVM), b_0 is the y intercept, b_1 is the slope, and X is the segment length (mi).

TABLE 3 TLTW SEGMENTS STUDIED

Project	Segment Length (mi)
IR-80-3(81), Sutherland West	6.78
IR-80-3(88), Hershey East	6.86
IR-80-4(82), Brady East	7.22
IR-80-5(44), Elm Creek–Odessa westbound	6.68

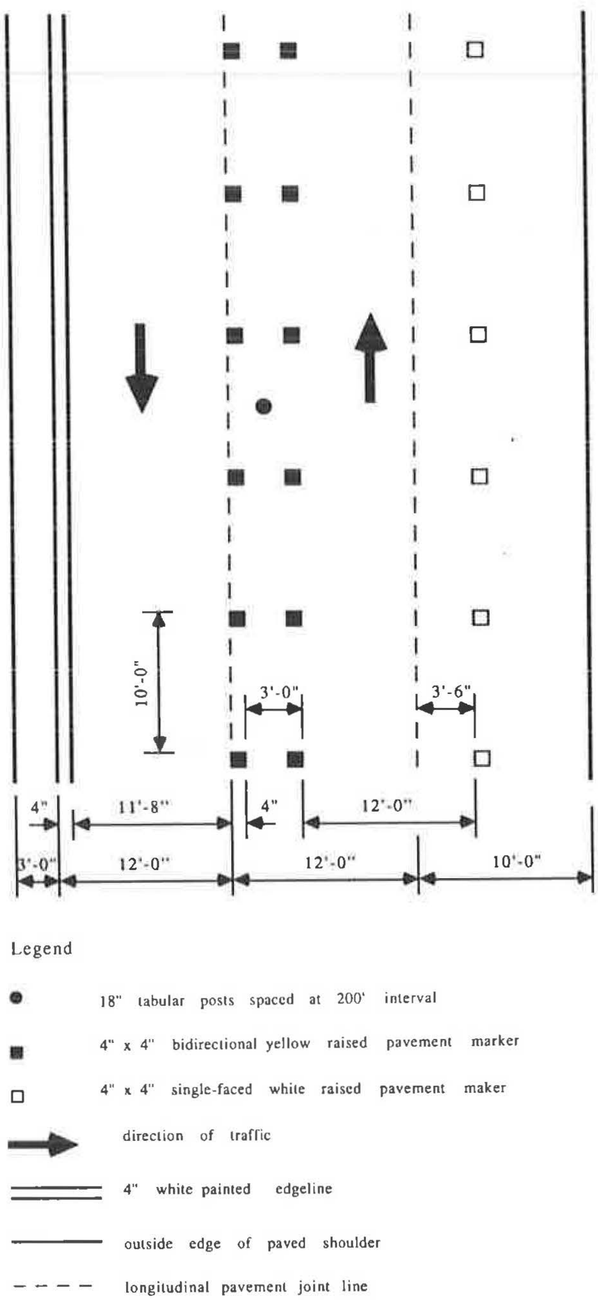

FIGURE 1 TLTW segment pavement markings.

accident involvement rate and speed variation, which was determined by Solomon (*6*).

The five speed distribution parameters were computed from the spot speed data collected at each study location in the TLTW segments. Spot speed studies were conducted at 20 locations (five locations in each of the four TLTW segments). Thus 20 sets of speed distribution parameters were computed.

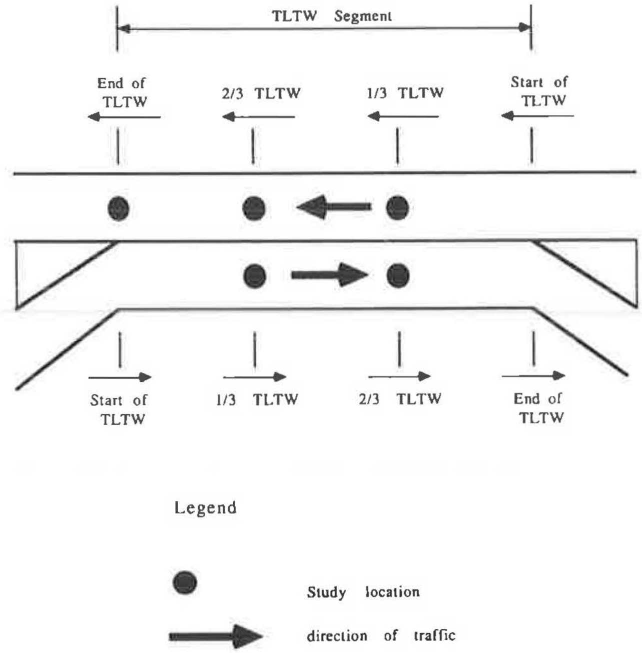

FIGURE 2 Spot speed study locations.

In addition, the distance that each study location was from the beginning of TLTW operations was determined.

Next, a series of simple linear regression analyses was performed to determine the relationship between each speed distribution parameter and the distance from the beginning of TLTW operations. The regression model used was

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \qquad (2)$$

where

Y_i = value of parameter at the *i*th study location;
β_0 = *y*-intercept regression parameter;
β_1 = slope regression parameter;
X_i = distance of the *i*th study location from beginning of TLTW operations (mi); and
ε_i = random error at the *i*th study location.

The regression parameter of particular interest in this study was β_1. If β_1 were equal to zero, then there would have been no linear relationship between the speed distribution parameter and the distance from the beginning of TLTW operations. This would indicate that on the basis of the particular speed distribution parameter involved, the safety of traffic operations was not related to the lengths of TLTW segments. If β_1 were not equal to zero, it would indicate that the safety of traffic operations was related to the lengths of TLTW segments.

Accident Analysis

The accident reports for all reported accidents that occurred in each segment during TLTW operations were obtained from the Nebraska Department of Roads. These reports were reviewed to ensure that all of the reported accidents did in fact occur on the TLTW segment and not on the median crossovers or their approaches. Accident rates were computed for the TLTW segments. These rates, together with the TLTW segment accident rates from the previous study (*2*), were analyzed by using simple linear regression to determine the relationship between the accident rates on TLTW segments and the lengths of TLTW segments. The regression model used was

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{3}$$

where

- Y_i = accident rate for the *i*th TLTW segment (accidents/100 MVM);
- β_0 = *y*-intercept regression parameter;
- β_1 = slope regression parameter;
- X_i = length of *i*th TLTW segment (mi); and
- ε_i = random error for *i*th TLTW segment.

As was the case in the analysis of the speed distributions, β_1 was the regression parameter of interest. If β_1 were equal to zero, then there would be no linear relationship indicated between the TLTW accident rate and segment length. On the other hand, if β_1 were not equal to zero, a linear relationship between these two variables would be indicated.

SPEED DISTRIBUTION PARAMETERS

Over 100 spot speeds were observed at each of the 20 study locations in the four TLTW segments. The number of observations made at each location, as well as the speed distribution parameters computed from these data, are shown in Tables 4–7. Each of these tables contains the values of the speed distribution parameters computed from the spot speed data collected at the five study locations in one of the four TLTW segments. Also presented in these tables are the mileposts at the ends of the TLTW segments and those at the two intermediate data collection points. The distances from the beginning of TLTW operations, which are also shown in these tables, were computed from these mileposts. As mentioned previously, data were not collected at the beginning of TLTW operations in either direction or at the end of TLTW operations in the direction of the traffic that had to cross over the median. Data were not collected at these locations because of the influence of the crossovers, the transition from four-lane divided to TLTW operations, or both.

The results of the analysis of variance for the simple linear regression analysis of each speed distribution parameter are shown in Table 8. In each case, no statistically significant linear relationship was found between the speed distribution parameter and the distance from the beginning of TLTW operations. Therefore these results indicate that the safety of TLTW operations, as measured by these parameters, was not related to the length of the TLTW operations for the conditions studied.

ACCIDENT RATES

A total of 15 accidents was reported on the four TLTW segments. Only five of these reports, however, were for accidents that actually occurred on the TLTW segments. The other 10 were for accidents that occurred on the median crossovers or on the approaches of the TLTW segments. Of the five accidents that occurred on the TLTW segments, two involved collisions with deer. To be consistent with the procedures of the previous study (*2*), these two accidents were eliminated from the analysis because the occurrence of this type of accident depends primarily on the population of deer along I-80 and not on the design and operation of the TLTW segments. Therefore only three accidents of interest occurred on the four TLTW segments.

None of the three TLTW accidents resulted in a fatality. Two of them were property damage–only accidents, one a rear end collision and the other a vehicle running over an object lying in the roadway. The third accident was a nonfatal injury accident in which a vehicle attempting to make a U-turn from one

TABLE 4 SPEED DISTRIBUTION PARAMETERS FOR PROJECT IR-80-3(81), SUTHERLAND WEST

	Mile Post			
	150.96	153.00	155.51	157.74
Eastbound				
Distance (mi)[a]	0.00	2.04	4.55	6.78
Number of observations		113	156	160
Standard deviation (mph)		5.0	4.6	4.0
Range (mph)		24	21	21
Percentage in 10-mph pace		72	72	84
Skewness		+0.14	−0.33	+0.20
Accident involvement rate (accidents/100 MVM)		140	100	140
Westbound				
Distance (mi)[a]	6.78	4.74	2.23	0.00
Number of observations		193	154	
Standard deviation (mph)		6.3	4.7	
Range (mph)			35	25
Percentage in 10-mph pace		65	73	
Skewness		−0.14	−0.14	
Accident involvement rate (accidents/100 MVM)		170	140	

[a]Distance from beginning of TLTW operations.

TABLE 5 SPEED DISTRIBUTION PARAMETERS FOR PROJECT IR-80-3(88), HERSHEY EAST

	Mile Post			
	164.08	167.00	169.62	170.94
Eastbound				
Distance (mi)[a]	0.00	2.92	5.54	6.86
Number of observations		142	109	
Standard deviation (mph)		4.4	4.3	
Range (mph)		20	22	
Percentage in 10-mph pace		73	82	
Skewness		−0.14	0.00	
Accident involvement rate (accidents/100 MVM)		140	140	
Westbound				
Distance (mi)[a]	6.86	3.94	1.32	0.00
Number of observations	155	164	200	
Standard deviation (mph)	4.8	3.6	4.0	
Range (mph)	28	24	21	
Percentage in 10-mph pace	80	85	82	
Skewness	0.00	0.00	−0.20	
Accident involvement rate (accidents/100 MVM)	150	140	140	

[a]Distance from beginning of TLTW operations.

TABLE 6 SPEED DISTRIBUTION PARAMETERS FOR PROJECT IR-80-4(82), BRADY EAST

	Mile Post			
	198.40	201.00	203.10	205.62
Eastbound				
Distance (mi)[a]	0.00	2.60	4.70	7.22
Number of observations		155	153	
Standard deviation (mph)		5.3	5.3	
Range (mph)		25	24	
Percentage in 10-mph pace		62	65	
Skewness		+0.25	0.00	
Accident involvement rate (accidents/100 MVM)		150	130	
Westbound				
Distance (mi)[a]	7.22	4.62	2.52	0.00
Number of observations	159	154	156	
Standard deviation (mph)	4.7	5.3	4.5	
Range (mph)	22	24	26	
Percentage in 10-mph pace	70	71	76	
Skewness	0.00	−0.14	0.00	
Accident involvement rate (accidents/100 MVM)	140	140	140	

[a]Distance from beginning of TLTW operations.

TABLE 7 SPEED DISTRIBUTION PARAMETERS FOR PROJECT IR-80-5(44), ELM CREEK–ODESSA WESTBOUND

	Mile Post			
	256.64	259.08	261.93	263.32
Eastbound				
Distance (mi)[a]	0.00	2.44	5.29	6.68
Number of observations		169	153	161
Standard deviation (mph)		4.2	3.9	3.9
Range (mph)		21	23	19
Percentage in 10-mph pace		76	84	81
Skewness		0.00	+0.20	0.00
Accident involvement rate (accidents/100 MVM)		140	140	140
Westbound				
Distance (mi)[a]	6.68	4.24	1.39	0.00
Number of observations		146	157	
Standard deviation (mph)		4.2	4.6	
Range (mph)		22	25	
Percentage in 10-mph pace		80	75	
Skewness		0.00	−0.33	
Accident involvement rate (accidents/100 MVM)		140	140	

[a]Distance from beginning of TLTW operations.

shoulder to the opposing lane was struck by an oncoming vehicle in the near lane. The vehicle making the U-turn was a construction vehicle that was turning around so that its occupants could replace one of the 18-in. tubular posts that was missing from the centerline of the TLTW segment.

The accident rates computed for the TLTW segments are shown in Table 9. The segment lengths, average daily traffic rates (ADTs), days of operation, and numbers of accidents that were used to compute these rates are also included in this table. Two of the four segments did not experience any accidents, therefore they had zero accident rates. The accident rates on the other two segments, which did experience accidents, were 11.4 and 28.6 accidents/100 MVM.

The analysis of variance for the simple linear regression analysis of these TLTW accident rates is presented in Table 10, together with that from the previous study (*2*), which is also presented in Table 2. This analysis shows that there was no statistically significant linear relationship between the accident rates on the TLTW segments and the lengths of the segments. Therefore the result of this analysis indicates that the safety of TLTW operations was not related to the length of the TLTW segment for the conditions studied.

CONCLUSION

In this study, no relationships were found between TLTW segment length and either the accident rate or any of the speed distribution parameters that were used as indicators of the safety of TLTW operations. Therefore it was concluded that there is no relationship between TLTW segment length and the safety of TLTW operations for the conditions studied. It was also concluded that the longer optimum segment lengths computed with Equation 1 using the 1986 cost factors are applicable from the standpoint of safety.

Of course, it must be noted that the maximum TLTW segment length in this study was 7.22 mi. Consequently, the findings and conclusion of this study are limited to TLTW segments no longer than 7.22 mi. Similar studies of longer TLTW segments are needed to determine the safety effects of segment lengths longer than 7.22 mi. Also, it should be noted that the TLTW segments in this study were on level terrain and that they had the paving markings shown in Figure 1, which featured a 3-ft median composed of raised pavement markers and 18-in. tubular posts. The findings and conclusion of this study may not be applicable to TLTW segments in rolling or mountainous terrain or with other types of centerline treatments.

TABLE 8 RESULTS OF ANALYSIS OF VARIANCE FOR SPEED DISTRIBUTION PARAMETER REGRESSIONS

Parameter	Degrees of Freedom	F	Prob > F	Conclusion[a]
Standard deviation	1,18	0.047	0.832	$\beta_1 = 0$
Range	1,18	0.038	0.847	$\beta_1 = 0$
Percentage in 10-mph pace	1,18	1.455	0.243	$\beta_1 = 0$
Skewness	1,18	1.757	0.302	$\beta_1 = 0$
Accident involvement rate	1,18	0.102	0.753	$\beta_1 = 0$

[a]On the basis of 0.05 level of significance.

TABLE 9 TLTW SEGMENT ACCIDENT RATES

Project	Length (mi)	ADT[a]	Days of Operation	Number of Accidents	Accident Rate (accidents/100 MVM)
IR-80-3(81), Sutherland West	6.78	9,220	93	0	0
IR-80-3(88), Hershey East	6.86	13,075	78	2	28.6
IR-80-4(82), Brady East	7.22	11,510	106	1	11.4
Elm Creek–Odessa westbound	6.68	11,425	54	0	0

[a]During TLTW operation.

TABLE 10 ANALYSIS OF VARIANCE FOR REGRESSION ANALYSIS OF ACCIDENT RATES ON ALL TLTW SEGMENTS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob > F
Due to b_0	1	21,734.14	21,734.14		
Due to b_1/b_0	1	44.22	44.22	0.025	0.875
Residual	26	45,242.15	1,740.08		
Total	28	67,020.51			

NOTE: $\hat{Y} = b_0 + b_1X$, where $\hat{Y}$ is the TLTW segment accident rate (accidents/100 MVM), b_0 is the y intercept, b_1 is the slope, and X is the segment length (mi).

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