Injury Severity and Total Harm in Truck-Involved Work Zone Crashes

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Society pays a high cost for work zone crashes in terms of operational disruptions, property damage, injuries, and loss of life. Given narrow lanes in work zones, large trucks are of particular concern. Truck-involved collisions in work zones, as opposed to non-truck-involved collisions in North Carolina, are empirically examined. This examination helps in understanding which work zone attributes are empirically associated with the most seriously injured occupant and total harm in a crash. Specifically, with a unique data set, effects of the following variables were explored: type of work zone, presence of warning signs and cones, type of activity in the work zone, location of the crash in the work zone, and construction impact of the work zone on the roadway. The results show that work zone crashes in North Carolina, especially those involving large trucks, were more injurious than were non–work zone crashes. Rigorous modeling results suggest that truck-involved multivehicle crashes were most injurious and harmful when (*a*) they occurred on two-way undivided or two-way divided but unprotected (without a median barrier) roadways; (*b*) the roadway was closed and a detour was required on the opposite side; (*c*) they occurred adjacent to the work area; and (*d*) the posted speed limits were higher. The results provide valuable information on high-risk factors in work zones.

Highway work zones are increasing because of deterioration of the highway infrastructure, increased maintenance spending, and greater attention to the management of existing highway assets. With the completion of the Interstate highway system, a significant portion of all federal-aid highway funds in the United States are now geared toward roadway maintenance and rehabilitation. Additionally, due to the increase in traffic volumes, closing long segments of the roadway for rehabilitation is becoming very challenging. About 13% of the national highway system is under construction or maintenance at any given time (*1*). The presence of workers, construction machinery, roadside construction barriers, and other paraphernalia associated with work zones creates a high degree of conflict and distraction that leads to hazardous conditions for vehicle occupants.

Society already pays a high cost for work zone crashes in terms of operational disruptions, property damage, injuries, and loss of life. In 2000, work zone crashes across the United States resulted in 829 fatalities (3% of the nation's total automobile deaths) and 52,000 injuries (2% of the nation's total). Large-truck-involved collisions accounted for 30% of work zone crashes and 24% of work zone fatalities (*2*). For North Carolina, 3% of total fatalities occurred in work zone areas (30% of these from large-truck-involved collisions), showing similar outcomes in terms of crashes.

The economic cost of a motor vehicle crash involving a fatality in the United States is estimated at nearly $3 million (*3–5*). Based on this estimate, the annual cost of work zone fatalities alone is more than $2.5 billion. Furthermore, wage and productivity losses, medical and administrative expenses, and property damage from non-fatal-injury crashes result in additional billions of dollars of losses. Accordingly, reducing crashes in work zones is a national priority.

Owing to their larger size, limited maneuverability, and sluggish performance, tractor-trailer trucks may experience more work zone crashes than smaller vehicles, and truck-involved crashes may be relatively more injurious in work zones. In addition, large-truck-involved crashes in work zones have a tendency to be high-profile and newsworthy events, especially if they involve fatalities. This paper examines the possible increase in severity of truck-involved crashes. Importantly, our knowledge of how the attributes of work zones affect work zone safety, especially when large trucks are involved, is very limited. Understanding the role of work zone attributes in injury risk and harm can potentially reduce the associated economic costs. In this paper, the authors empirically investigate the effects of work zone characteristics on the most seriously injured occupant and the total harm in crashes for truck-involved and non-truck-involved collisions. The objective is to identify work zone-related risk factors that can reduce injury severity, given a crash.

LITERATURE REVIEW

The literature indicates rising work zone crashes and fatalities in the United States (*2, 6–8*). A majority of the studies on work zone crashes have focused on analyzing crash rates for preconstruction and during work zone operation periods. Almost all of these studies indicate that crash rates increase during work zone operation compared with the pre-work zone period (*9–15*). Furthermore, rear-end and sideswipe collisions occurred more frequently in work zones than in non-work zones, as expected. A combination of cones, flashing and static signs, and flaggers are used to provide information to travelers and reduce the incidence of work zone crashes.

Despite many studies on work zones, the effect of work zone attributes on injury severity remains largely unexplored. The limited research available has analyzed the distribution and characteristics of injury and non-injury work zone crashes, and the results appear inconsistent. On the one hand, there is evidence that work zone crashes are slightly less severe than non-work zone crashes (*12, 13, 16–18*). For instance, Rouphail et al. (*13*) reported a 20% decrease in fatal- and injury-crash proportions. On the other hand, studies show that work zone crashes are more severe (*19, 20*) or that there is no significant difference between work zone and non-work zone crash

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severity (*14, 15*). In terms of work zone attributes, Khattak et al. (*21*) found that longer work zone durations significantly increase the frequency of both injury and property-damage-only crashes. The location of the crash within the work area (close to activity area) was also significantly associated with more injurious crashes (*22*).

Multivehicle collisions were consistently overrepresented in work zones (*13–15, 20, 22, 23*). This overrepresentation was also significant for large-truck-involved collisions in work zone crashes (*14, 16, 19*). Moreover, large-truck-involved collisions in work zones were more severe than non-truck-involved collisions (*19, 24*), similar to non-work zone situations.

Although crash rates often increase in work zones, questions about the effect of work zone attributes on the severity of these crashes are unanswered. A major gap in the literature is the lack of knowledge regarding work zone-related contributing factors and their relationship to injury severity. While some studies have found that crashes involving large trucks in work zones are important contributors to fatalities, it is still unclear what specific work zone characteristics influence injury severity for truck-involved and non-truck-involved collisions.

METHODS AND DATA

Conceptually, work zones are expected to increase injury risk, given a crash, due to narrower lanes, more objects to strike, greater potential for distractions, and unexpected turns and lane drops. However, this effect might be mitigated if drivers slow down and drive more carefully in work zones. It is possible that crash frequency will increase but injury severity might decrease.

Work zones are likely to exacerbate the potential for truck–car collisions, given their large mass differentials and their close proximity in work zones, as well as the limited maneuverability and sluggish performance of large trucks. Furthermore, work zones that have more complex layouts might experience more injurious crashes. Typically, roads of lower functional class are also more dangerous. Accordingly, work zones on two-lane, undivided roadways, for instance, might be more harmful. Certain locations within a work zone might be more dangerous than others, due to violations of driver expectations, the presence of more objects, and worker activity or other distractions.

Using a unique work zone crash data set, this study explores the effects of work zone attributes on injury in truck-involved and non-truck-involved collisions. The study uses data from the Highway Safety Information System (HSIS), with additional variables coded from narratives in police reports. Developed and maintained by the FHWA, HSIS contains crash and roadway-inventory data from selected states. HSIS data from 2000 for North Carolina were used because they contained important new work zone–related variables; Figure 1 shows a typical work zone location. The relevant variables follow:

- Whether the work zone was a contributing factor to the crash (in the opinion of the police officer);
- Crash location—that is, whether the crash occurred before the work area, in the work-area approach taper, or adjacent to the actual work area;
- Whether the crash occurred in or near a construction work area, maintenance work area, utility work area, or intermittent or moving work, for example, pothole patching;
- Whether there was ongoing work activity at the time of the crash; and
- Whether the work area was marked with warning signs and cones.

Additional work zone-related data, based on the narrative and crash diagram drawn by police officers, were also coded; Figure 2 provides a sample crash diagram and narrative. The variables are these:

- Whether the construction had an effect on the roadway capacity or traffic pattern, that is, lane closed, shoulder or median closed, roadway closed, lane shift, or other, and
- The type of work being done, such as repaving or resurfacing, shoulder or median work, new roadway, or other.

Because the process of obtaining and coding crash report forms required substantial time and effort, the coding of new variables was limited to truck-involved collisions only. This implies that

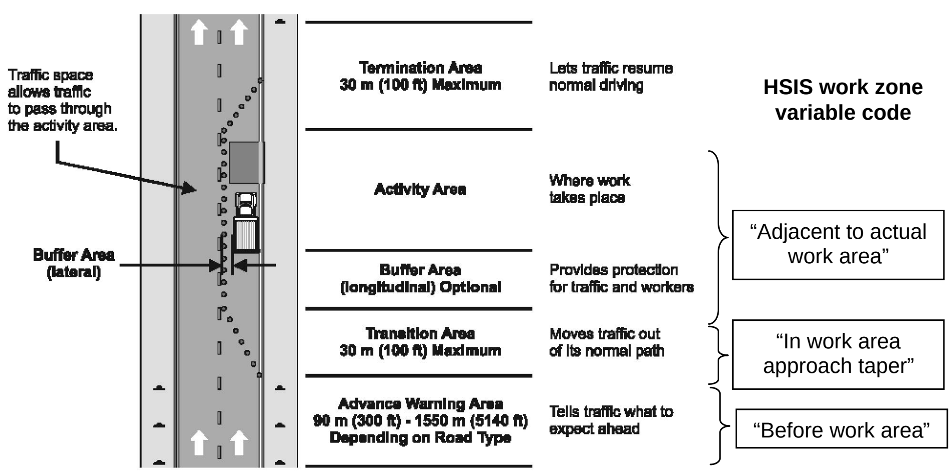

FIGURE 1 Location of the crash in a work zone. [Source: *Manual on Uniform Traffic Control Devices 2000*, U.S. Department of Transportation, Federal Highway Administration. Adapted and modified from Garber and Zhao (*22*).]

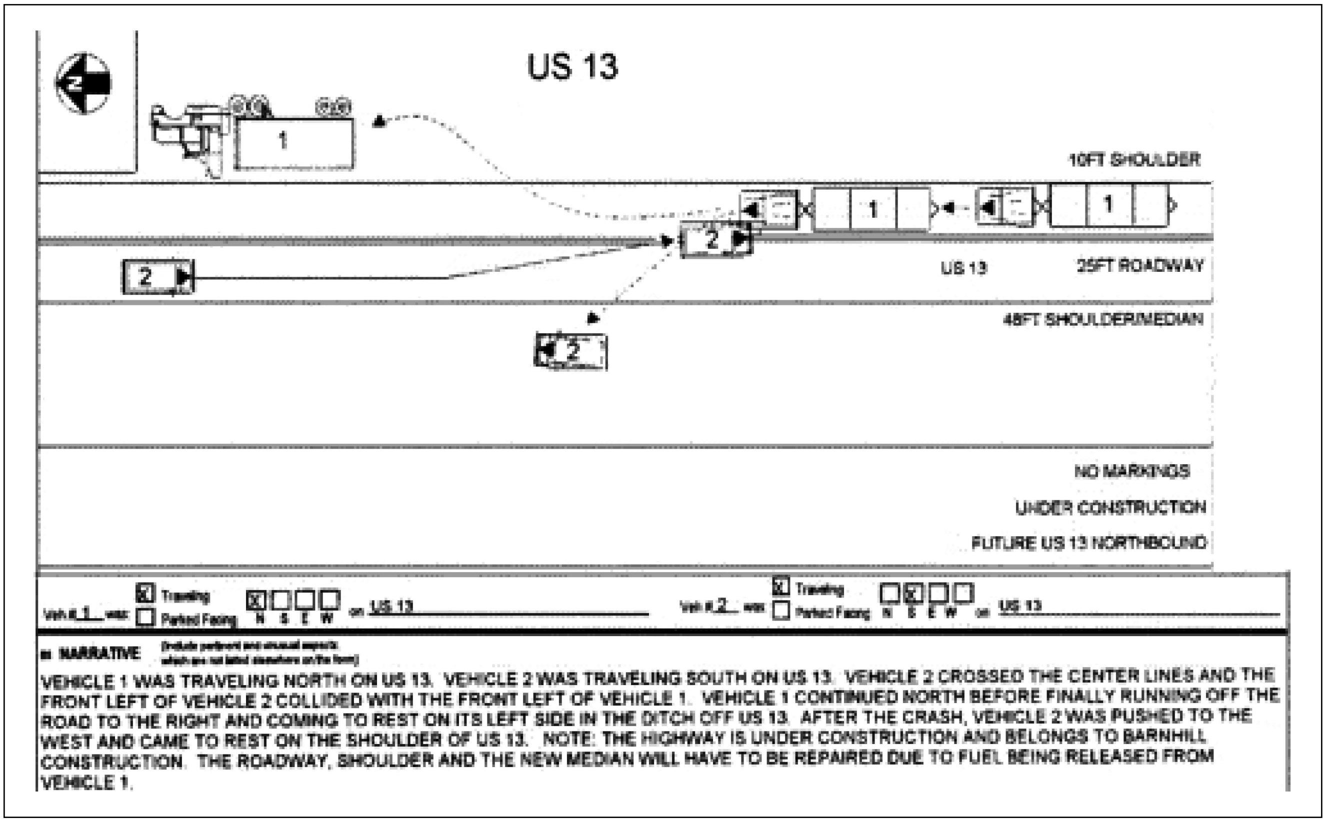

FIGURE 2 Sample crash diagram and police officer narrative.

the effect of the new work zone variables can be explored only for a subset of work zone crashes, that is, those that involve a large truck. This subset is of greatest interest, given the study objectives. Ultimately, a unique data set that contains several new work zone–related variables was developed, allowing exploration of their effects on injury severity.

A majority of the HSIS accident-file data required recoding and variable manipulation to isolate relevant factors for the study. Modeling the data allowed us to rigorously explore the effects of work zone attributes while controlling for other factors. Most of the independent variables used in modeling were categorical and were recoded as binary variables. Only posted speed limit, number of vehicles, and number of persons involved in the crash were continuous variables.

Injury severity is measured on the KABCO scale, which is ordinal and categorical; it was coded as 4 (K, killed), 3 (A, severe or incapacitating injury), 2 (B, moderate or nonincapacitating injury), 1 (C, minor or possible injury), and 0 (O, property damage only). Two measures of crash severity were explored (see Figure 3). One severity measure was the most seriously injured occupant in the crash. Given the ordinal categorical nature of these data, the ordered probit model is appropriate (*25,26*). The model's interpretation is based on coefficient estimated and on marginal effects or discrete changes in predicted probabilities for injury severity. Ordered probit models use a pseudo-R^2 goodness-of-fit measure proposed by McKelvey and Zavoina, as discussed by Hagle and Mitchell (*27*) and by Windmeijer (*28*), respectively.

Another unique severity measure explored in the study is that of total harm. To create this variable, an economic value was assigned to each injury level, and then the costs for each injury (or property damage) were summed. Therefore, the total-harm variable combines both injury frequency and injury severity in a crash. The injury and property-damage costs include medical costs, pain, suffering, and quality of life that the family loses because of a death or injury; emergency-service costs; victim work-loss costs; employer costs; traffic-delay costs; and property-damage costs (*29*). The estimated costs of motor-vehicle crashes in North Carolina, including quality-of-life values, is \$2,925,100 for fatal K injury, \$144,796 for A injury, \$37,486 for B injury, \$17,916 for C injury, and \$3,904 for property damage only (*29*).

The ordinary least-squares regression is appropriate because the cost data are (approximately) continuous. Taking the log transform of cost avoids negative predictions and brings the very high-cost values (associated with fatalities) relatively closer to the lower costs of other injuries. A unit change in the independent variable is associated with $e^{\beta} * 100\%$ change in the dependent variable, where β is the estimated coefficient; the percentage increase in cost is given by $(e^{\beta} - 1) * 100$.

RESULTS

Descriptive Statistics

Table 1 shows that, in terms of share of fatalities versus nonfatal injuries, North Carolina data are comparable with those for the rest of the United States. However, there is a relatively large difference in work zone truck-involved crashes, where fatalities in the United States were a smaller percentage of all motor vehicle injuries (1.66%) compared with fatalities in North Carolina (2.48%). As expected, North Carolina truck-involved collisions had relatively more fatalities than all work zone crashes in North Carolina (2.48% fatalities versus 1.38% fatalities, respectively). In addition, work zone crashes were

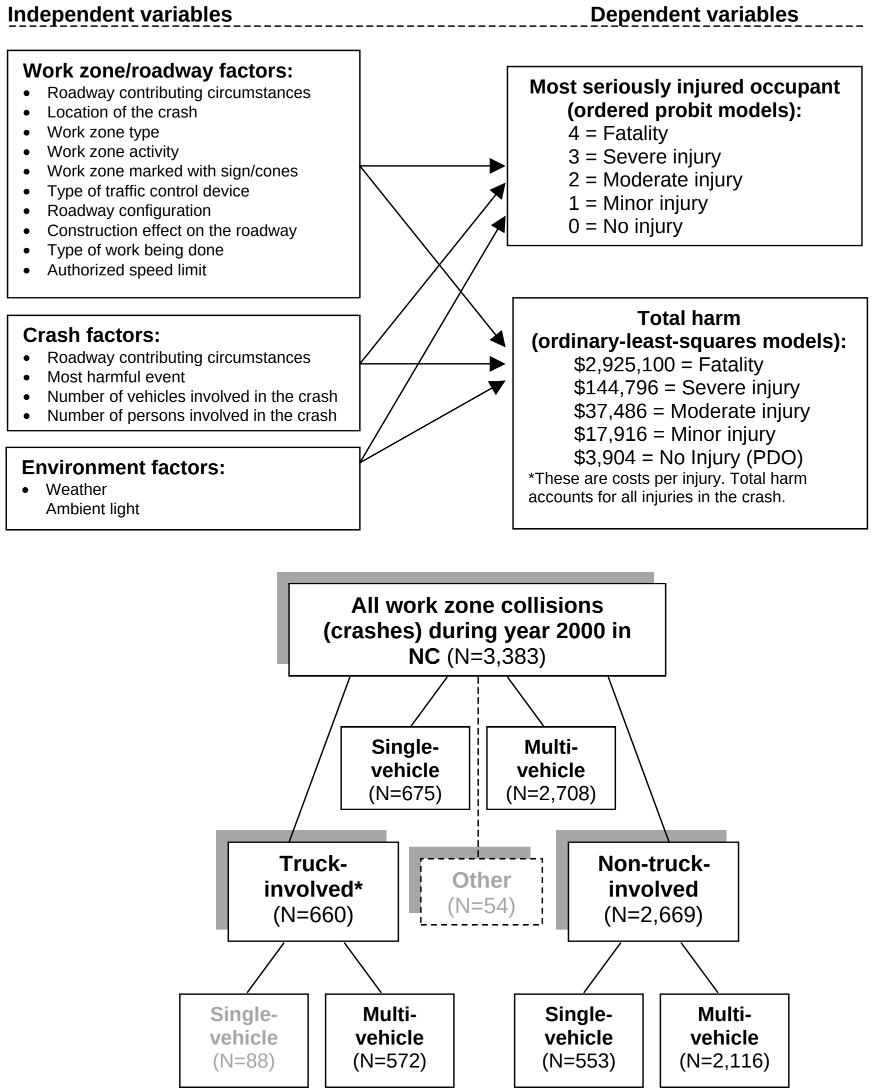

FIGURE 3 Conceptual and data structure.

more injurious than non-work zone crashes as indicated by 1.03% fatalities in all North Carolina crashes compared with 1.38% fatalities in work zone crashes.

During 2000, 3,383 crashes occurred in North Carolina work zones; 20.0% (675) were single-vehicle collisions and 80.0% (2,708) involved more than one vehicle (Figure 3). Of the 3,383 collisions, 19.5% (660) involved at least one truck (88 single-vehicle and 572 multivehicle collisions), and 80.5% (2,669) did not involve any truck but involved a car, a sports utility vehicle, or a van (553 single-vehicle and 2,116 multivehicle collisions). Though most crashes resulted in no injuries (property-damage-only crashes ranged from 63% in non-truck-involved crashes to 56% in truck-involved,

TABLE 1 Fatalities and Nonfatal Injuries from Motor Vehicle Collisions in 2000

	United States			North Carolina		
	Fatalities	Nonfatal injuries	Total	Fatalities	Nonfatal injuries	Total
Total crashes	41,821	3,189,000	3,230,821	1,472	141,209	142,681
Row %	1.29%	98.71%	100%	1.03%	98.97%	100%
Work zone crashes	829	52,000	52,829	33	2,354	2,387
Row %	1.57%	98.43%	100%	1.38%	98.62%	100%
Work zone truck-involved crashes	264	15,600	15,864	10	394	404
Row %	1.66%	98.34%	100%	2.48%	97.52%	100%

NOTE: The property damage collisions that do not involve an injury are not reported.
SOURCES: Fatal Accident Reporting System, 2002, and HSIS, 2000.

single-vehicle crashes), multivehicle truck-involved crashes appear to be the most injurious (Figure 4). Specifically, among truck-involved, multivehicle collisions, 1.1% were fatal and 4.4% resulted in severe injuries. Moreover, if all injuries in the crash are accounted for by assigning a dollar value as discussed earlier, truck-involved, multivehicle collisions are the most costly, at $81,300 per crash (Figure 4). The least-costly collisions are single-vehicle, truck-involved, at $16,800 per crash.

A brief description of the coding scheme for the variables and descriptive statistics for truck-involved and non-truck-involved collisions is presented in Table 2. Although analysis of crash frequencies is not the focus of this study, we briefly discuss them for completeness. Truck-involved collisions occurred more frequently on two-way divided and protected (with a barrier in the median) roadways as opposed to two-way undivided configurations. This is logical, given greater truck exposure on higher functional-class roads. Truck-involved collisions occurred more frequently when work zone activity was ongoing and there was no traffic-control device present. (Traffic-control devices are placed as part of work zone implementation, and they include stop, yield, and warning signs as well as human control.) Many crashes (57.7%) occurred in work zones that did not have active traffic-control devices. However, this does not necessarily mean that there were no warning signs or cones whatsoever in the entire work zone. The data are police reported, so it is possible that the police officer did not observe or record the presence of warning signals or perhaps looked for them only in the immediate vicinity of the crash.

Although truck-involved collisions totaled 675 for the study period, only 88 of these were single-vehicle collisions, precluding any modeling of such collisions. Given that single vehicle–truck collisions are the least costly ($16,800 per crash, on average), they seem to be the least problematic. They are not analyzed further.

Modeling Results

Table 3 reports estimates from six models for multivehicle collisions: three ordered probit models for injury severity and three ordinary least squares (OLS) log-transformed models for total harm in the crash.

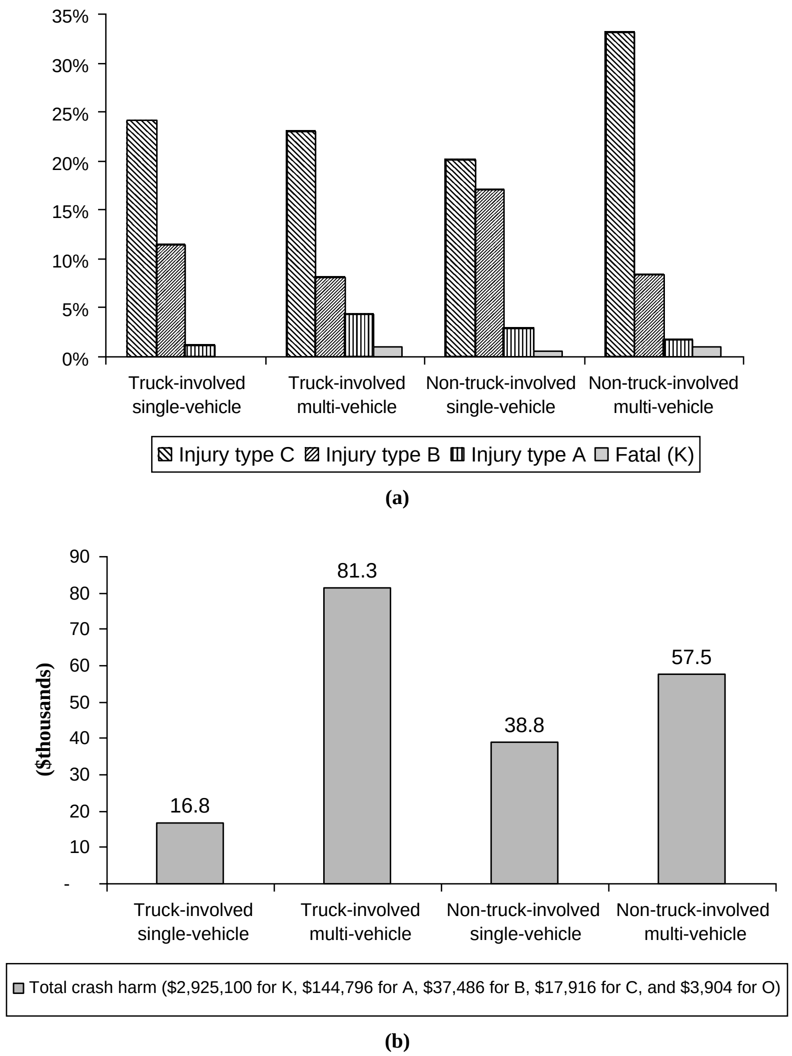

FIGURE 4 Most severe injury and total crash harm distribution by type of collision: (*a*) percentage of total crashes (most severe injury in crash); (*b*) average total harm per crash (in thousands of dollars).

TABLE 2 Descriptive Statistics for North Carolina Work Zone Crashes in 2000, Summarized at Accident Level

Variable	All Collisions		Truck-involved Collisions		Non-truck-involved Collisions	
	Valid *N*	Mean or Proportion	Valid *N*	Mean or Proportion	Valid *N*	Mean or Proportion
Roadway contributing circumstances						
Work zone	3,366	21.3%	656	24.8%	2,656	20.5%
Other	3,366	6.5%	656	6.1%	2,656	6.4%
None	3,366	72.2%	656	69.1%	2,656	73.1%
Location of the crash						
Before work area	3,383	21.2%	660	20.0%	2,669	21.7%
In work area approach taper	3,383	33.9%	660	34.4%	2,669	33.7%
Adjacent to actual work area	3,383	44.9%	660	45.6%	2,669	44.6%
Work zone type						
Construction	3,383	81.6%	660	82.0%	2,669	81.5%
Maintenance	3,383	9.2%	660	8.6%	2,669	9.3%
Utility	3,383	5.5%	660	3.9%	2,669	5.9%
Intermittent/moving	3,383	3.7%	660	5.5%	2,669	3.3%
Work zone activity (1 = ongoing)	3,383	51.1%	660	61.8%	2,669	48.6%
Work zone marked with sign/cones (1 = yes)	3,383	95.1%	660	95.6%	2,669	95.0%
Type of traffic control device						
Stop/Yield/Warning sign	3,383	23.3%	660	18.3%	2,669	24.6%
Stop/Yield/Warning flashing sign	3,383	1.2%	660	1.1%	2,669	1.3%
Human control	3,383	6.3%	660	5.9%	2,669	6.3%
Other	3,383	11.6%	660	11.4%	2,669	11.6%
No control present	3,383	57.7%	660	63.3%	2,669	56.2%
Dummy for missing cases	3,383	6.7%	660	7.3%	2,669	6.5%
Roadway configuration						
One-way, undivided	3,363	3.7%	658	3.3%	2,653	3.8%
Two-way, undivided	3,363	45.7%	658	31.9%	2,653	48.9%
Two-way, divided, no barrier in median	3,363	17.0%	658	16.7%	2,653	17.3%
Two-way, divided, with median barrier	3,363	33.5%	658	48.0%	2,653	30.0%
Construction effect on the roadway[a]						
Lane closed			660	15.5%		
Shoulder/median closed			660	17.0%		
Roadway closed, detour opposite side			660	2.6%		
Lanes shift/become narrow			660	1.8%		
Other/unknown			660	21.5%		
None			660	41.7%		
Type of work being done[a]						
Repaving/resurfacing			660	8.8%		
Shoulder/median work			660	14.5%		
New roadway			660	2.1%		
Other			660	6.1%		
Unknown			660	68.5%		
Most harmful event (crash)						
Ran off road	3,367	2.3%	656	2.1%	2,657	2.1%
Rollover	3,367	4.1%	656	5.0%	2,657	3.5%
Collision with pedestrian/bicyclist/animal	3,367	2.5%	656	1.5%	2,657	2.5%
Collision with movable object	3,367	2.6%	656	3.2%	2,657	2.3%
Collision with fixed object	3,367	13.6%	656	9.1%	2,657	14.5%
Collision with 2+ motor vehicles (head on)	3,367	1.1%	656	0.9%	2,657	1.1%
Collision with 2+ motor vehicles (angle)	3,367	6.9%	656	6.9%	2,657	7.0%
Collision with 2+ motor vehicles (other)	3,367	67.0%	656	71.2%	2,657	66.9%
Authorized speed limit (mph)	3,351	50.08	653	52.51	2,646	49.56
Number of vehicles involved in the crash	3,383	1.97	660	2.07	2,669	1.96
Number of persons involved in the crash	3,383	3.01	660	2.78	2,669	3.07
Weather (1 = not clear)	3,383	28.5%	660	26.5%	2,669	29.0%
Ambient light (1 = nondaylight)	3,382	22.6%	660	20.0%	2,668	22.7%

[a]Coded only for truck-involved collisions from North Carolina police reports.

Each three-model set is estimated for the pooled-collisions data, truck-involved collision data, and non-truck-involved collision data. Truck-involved collisions are of primary interest; the non-truck-involved collisions serve as a comparison group. Interpretation for the truck-involved injury-severity model is also based on the marginal effects (Table 4). Model results for statistically significant coefficients at the customary 99%, 95%, and 90% confidence levels will be discussed.

The model specification includes several new work zone variables and many controls. However, some variables are not presented for the following reasons:

- The variable was not statistically significant in the model, and it was dropped from further consideration; for example, the road surface was wet.

TABLE 3 Coefficients for Injury-Severity and Total-Harm Models (Multivehicle Collisions)

Variable	Injury (Ordered Probit)			Harm (Semi-Log)		
	All	Truck	Non truck	All	Truck	Non truck
Roadway contributing circumstances						
Work zone	-0.080	-0.181	-0.049	-0.061	-0.167*	-0.036
Other	-0.003	0.047	0.004	0.006	0.079	-0.010
None[a]						
Location of the crash						
Before work area	-0.010	0.243	-0.078	0.030	0.282**	-0.039
In work area approach taper[a]						
Adjacent to actual work area	0.010	0.321**	-0.082	0.012	0.210**	-0.051
Work zone type						
Construction	-0.072	-0.155	-0.062	-0.049	-0.069	-0.053
Maintenance[a]						
Utility[a]						
Intermittent/moving[a]						
Work zone activity (1 = ongoing)	-0.040	-0.045	-0.036	0.044	0.062	0.025
Work zone marked with sign/cones (1 = yes)	-0.028	0.151	-0.101	-0.022	-0.206	0.039
Type of traffic control device						
Stop/Yield/Warning sign	0.071	-0.120	0.119*	0.059	-0.048	0.090**
Stop/Yield/Warning flashing sign	0.453**	0.922**	0.440**	0.468***	1.207***	0.312**
Human control	0.005	-0.124	0.050	-0.002	-0.036	-0.008
Other	0.140*	0.159	0.180**	0.113**	0.108	0.122**
No control present[a]						
Dummy for missing cases	0.058	0.174	0.025	0.014	0.185	-0.027
Roadway configuration						
One-way, undivided	0.192	0.305	0.168	0.108	0.211	0.076
Two-way, undivided	0.428***	0.510***	0.398***	0.266***	0.313***	0.247***
Two-way, divided, no barrier in median	0.137*	0.362**	0.085	0.104**	0.260**	0.072
Two-way, divided, with median barrier[a]						
Construction effect on the roadway[b]						
Lane closed		-0.166			-0.096	
Shoulder/median closed		0.278			0.230	
Roadway closed, detour opposite side		1.011***			0.889***	
Lanes shift/become narrow		-0.689			-0.381	
Other/unknown		0.122			0.136	
None[a]						
Type of work being done[b]						
Repaving/resurfacing		-0.059			0.033	
Shoulder/median work		0.046			0.069	
New roadway		-0.534			-0.116	
Other		-0.048			0.085	
Unknown[a]						
Most harmful event (crash)						
Ran off road	-0.124	-0.184	-0.093	-0.065	-0.020	-0.069
Rollover	1.133***	0.748	1.481***	0.740***	0.516	1.037**
Collision with pedestrian/bicyclist/animal	1.674***	1.582***	1.698***	1.662***	1.431***	1.880***
Collision with movable object	-0.565**	-0.623	-0.576*	-0.468***	-0.320	-0.387*
Collision with fixed object	0.159	-0.138	0.271	0.007	-0.191	0.059
Collision with 2+ motor vehicles (head on)	1.445***	1.566***	1.456***	1.639***	1.742***	1.618***
Collision with 2+ motor vehicles (angle)	0.175**	0.305	0.137	0.204***	0.307**	0.163**
Collision with 2+ motor vehicles (other)[a]						
Authorized speed limit (mph)	0.016***	0.022***	0.015***	0.013***	0.014***	0.011***
Number of vehicles involved in the crash	0.366***	0.314***	0.360***	0.364***	0.181**	0.323***
Number of persons involved in the crash	0.029***	0.093**	0.024**	0.141***	0.291***	0.146***
Weather (1 = not clear)	-0.104*	-0.050	-0.149**	-0.083**	0.012	-0.111***
Ambient light (1 = nondaylight)	0.190***	0.128	0.210***	0.149***	0.124	0.163***
Constant				7.768***	7.379***	7.973***
Threshold 1	2.172***	2.872***	2.007***			
Threshold 2	3.275***	3.770***	3.181***			
Threshold 3	4.016***	4.383***	4.020***			
Threshold 4	4.690***	5.312***	4.581***			
N	2,649	557	2,074	2,649	557	2,074
Log likelihood intercept only	-2,723.88	-572.26	-2,102.64			
Log likelihood at convergence	-2,548.70	-512.51	-1,971.07			
$P>\chi^2$: LR test (χ^2) / $P>\chi^2$: F test (χ^2)	0.001	0.001	0.001	0.001	0.001	0.001
Adjusted-R^2				0.293	0.343	0.300
McKelvey & Zavoina pseudo-R^2	0.150	0.242	0.146			

***, **, and * denote coefficient significantly different from zero at the 1%, 5%, and 10% level of significance (two-tail test), respectively.
[a] Base category for coefficient comparison.
[b] Coded only for truck-involved collisions (police officer accident reports).
Coefficients for dummy categorical variables in the Harm models are adjusted for interpretation according to Kennedy (*30*) for a semi-log specification. LR = likelihood ratio.

TABLE 4 Marginal Effects for Truck-Involved Injury Model (Multivehicle Collisions)

Variable	Injury (Ordered Probit)				
	No injury	Minor	Moderate	Severe	Fatality
Roadway contributing circumstances					
Work zone	0.067	-0.035	-0.020	-0.011	-0.001
Other	-0.018	0.009	0.006	0.003	0.000
None[a]					
Location of the crash					
Before work area	-0.088	0.048	0.026	0.013	0.002
In work area approach taper[a]					
Adjacent to actual work area	**-0.119**	**0.062**	**0.035**	**0.019**	**0.002**
Work zone type					
Construction	0.059	-0.029	-0.018	-0.011	-0.001
Maintenance[a]					
Utility[a]					
Intermittent/moving[a]					
Work zone activity (1 = ongoing)	0.017	-0.009	-0.005	-0.003	-0.000
Work zone marked with sign/cones (1 = yes)	-0.055	0.030	0.016	0.008	0.001
Type of traffic control device					
Stop/Yield/Warning sign	**0.044**	**-0.024**	**-0.013**	**-0.007**	**-0.001**
Stop/Yield/Warning flashing sign	-0.353	0.088	0.124	0.114	0.028
Human control	0.045	-0.025	-0.013	-0.007	-0.001
Other	-0.061	0.029	0.019	0.011	0.002
No control present[a]					
Dummy for missing cases	-0.067	0.032	0.021	0.012	0.002
Roadway configuration					
One-way, undivided	-0.111	0.060	0.032	0.017	0.002
Two-way, undivided	**-0.191**	**0.094**	**0.058**	**0.034**	**0.005**
Two-way, divided, no barrier in median	**-0.133**	**0.070**	**0.039**	**0.021**	**0.003**
Two-way, divided, with median barrier[a]					
Construction effect on the roadway[b]					
Lane closed	0.059	-0.033	-0.016	-0.008	-0.001
Shoulder/median closed	-0.107	0.050	0.034	0.020	0.003
Roadway closed, detour opposite side	**-0.385**	**0.095**	**0.134**	**0.125**	**0.032**
Lanes shift/become narrow	0.207	-0.133	-0.050	-0.021	-0.002
Other/unknown	-0.046	0.023	0.014	0.008	0.001
None[a]					
Type of work being done[b]					
Repaving/resurfacing	0.022	-0.011	-0.007	-0.004	0.000
Shoulder/median work	-0.018	0.009	0.005	0.003	0.000
New roadway	0.177	-0.106	-0.047	-0.022	-0.002
Other	0.018	-0.009	-0.005	-0.003	0.000
Unknown[a]					
Most harmful event (crash)					
Ran off road	0.065	-0.037	-0.018	-0.009	-0.001
Rollover	-0.292	0.095	0.100	0.080	0.016
Collision with pedestrian/bicyclist/animal	**-0.535**	**0.017**	**0.170**	**0.243**	**0.104**
Collision with movable object	0.193	-0.122	-0.048	-0.021	-0.002
Collision with fixed object	0.050	-0.028	-0.014	-0.007	-0.001
Collision with 2+ motor vehicles (head on)	**-0.532**	**0.020**	**0.170**	**0.240**	**0.101**
Collision with 2+ motor vehicles (angle)	-0.118	0.054	0.037	0.023	0.003
Collision with 2+ motor vehicles (other)[a]					
Authorized speed limit (mph)	**-0.008**	**0.004**	**0.003**	**0.001**	**0.000**
Number of vehicles involved in the crash	**-0.118**	**0.060**	**0.035**	**0.020**	**0.003**
Number of persons involved in the crash	**-0.035**	**0.018**	**0.011**	**0.006**	**0.001**
Weather (1 = not clear)	0.019	-0.010	-0.006	-0.003	0.000
Ambient light (1 = nondaylight)	-0.049	0.024	0.015	0.009	0.001

NOTE: For dummy variables the marginal effect corresponds to the discrete change from 0 to 1.
[a] Base category for coefficient comparison.
[b] Coded only for truck-involved collisions (police officer accident reports).

- The variable was considered unreliable; for example, the pre-work zone volumes available were not reliable, as traffic demand often changes during work zone activity. The during-work zone traffic volumes were not available in the database.
- Some variables were simply not available in the database, such as sight distances.

All reported models are statistically significant (99% confidence level) as indicated by F-tests for the OLS models and likelihood-ratio tests for the probit models. Adjusted R^2 ranges from 0.293 (all collisions, pooled data) to 0.343 (truck-involved collisions) for the OLS log-transformed models; the McKelvey and Zavoina pseudo-R^2 ranges from 0.146 (non truck-involved collisions) to 0.242 (truck-involved collisions) for the ordered probit models. Clearly, truck-involved collisions are better explained by the independent variables than non-truck-involved. The goodness-of-fit statistics are quite reasonable.

Work zones located on two-way undivided roadways are associated with 37% [($e^{0.313}$ – 1) ∗ 100] higher truck-involved crash costs compared with work zones on two-way divided and protected (with median barrier) roadways. Furthermore, the marginal effects for the injury-severity model (Table 4) suggest that there is a 19.1% higher chance of injury on such roadways. Similarly, a two-way divided but unprotected (no barrier in the median) configuration also was more injurious than a two-way divided and protected configuration, increasing the chances of injuries by 13.3%. Thus, to reduce injury severity and harm in truck-involved collisions, work zones located on two-way undivided and two-way divided but unprotected roadways need particular attention.

Among the work zone and roadway-related variables coded from the crash report forms (only for truck-involved collisions), "Roadway Closed, Detour Opposite Side" is significantly associated with higher injury and total harm. This situation arises most often on multilane roads, requiring a median crossover. "Roadway Closed" increases the cost of a crash by 143% ($e^{0.889}$ – 1) compared with other types of construction effects on roadways. For instance, a crash costing $17,916 (B injury) will cost $43,584 if it occurs in a work zone where the roadway is closed and traffic is diverted to the opposite side. It also increases the chances of most severe injury substantially. The marginal effects suggest that, if a crash occurs in a work zone where the roadway is closed, requiring a detour on the opposite side, then the chances of injuries increase by 38.5%; that is, the chances of minor injuries are 9.5% higher, moderate injuries are 13.4% higher, severe injuries are 12.5% higher, and fatalities are 3.2% higher. Thus, road closings in work zones are particularly risky in terms of increasing injury severity and total harm in truck-involved collisions.

For truck-involved collisions, the crash location in the work zone is another significant factor. Crashes that occurred adjacent to the work area are associated with higher total harm than crashes in other work zone areas (see Figure 1). The harm model suggests that crashes in the activity or work area cost 23% [($e^{0.210}$ – 1) ∗ 100] more than crashes occurring in the advance-warning area. Table 4 suggests that truck-involved crashes occurring adjacent to the actual activity or work area have an 11.9% higher chance of injuries (i.e., minor injuries increase by 6.2%, moderate injuries by 3.5%, severe injuries by about 2%, and fatalities by 0.2%). This warrants greater attention to the activity or work area as a cause of truck-involved collisions.

A higher posted speed limit in the work zone is associated with higher injury severity and total harm, as expected. In terms of harm, every 10-mph increase in the authorized speed limit increases the total cost of a crash by 15%. For the same 10-mph increase in the authorized speed limit, the chances of injuries increase by 8.0%. Figure 5 illustrates the effect of an increase in the work zone posted speed limit on the predicted probabilities of injury (i.e., fatal and nonfatal injuries). The probability of injury increases substantially with higher posted speed limits, given a crash. This increase is somewhat uniform across truck-involved and non-truck-involved crashes. Careful attention should be given to posting speed limits in work zones.

The presence of stop–yield–warning flashing signs (traffic-control devices that are placed as a part of the work zone implementation) is associated with higher injury severity and harm, particularly for truck-involved collisions. However, this effect is unlikely to be causal; that is, these devices typically prevent even more severe crashes from occurring. (An equivalent situation would be the positive association between the number of firefighters responding to a fire and the size of the fire.) These devices are more likely to be placed in larger, complex, and more hazardous work zones. Also note that the base may be measured with error; that is, no active control devices were recorded in 57.7% of the crashes—but it is possible that despite their presence the police officer did not observe or record them. The results suggest the need for a careful reexamination of the data-coding procedures used by the police officers and, if the relationship is reconfirmed, a review of the placement of traffic-control devices in work zones.

In addition to work zone attributes, several other variables were controlled for. Crash-related factors, such as the most harmful event in a crash, were associated with higher injury severity and total harm. In addition, collisions with pedestrians, bicyclists, or animals were more injurious than collisions with other motor vehicles, mainly because the most seriously injured person is either the pedestrian or the bicyclist. Head-on and angle collisions were also more severe than other types of more-than-two-vehicle collisions. Crash exposure measures, such as number of vehicles and number of people involved in the crash, were significantly associated with higher injury severity and total harm, as expected. Finally, environmental factors such as weather and ambient light were significant but only for non-truck-involved collisions.

LIMITATIONS

If nonreporting of crashes varies systematically for work zone collisions—or any other type of collision, such as truck-involved or non-truck-involved collision—then it can bias the results. One could hypothesize both higher reporting in work zones (due to potentially higher police presence and less room to move damaged vehicles to the shoulders) and lower reporting (if vehicles in noninjury crashes

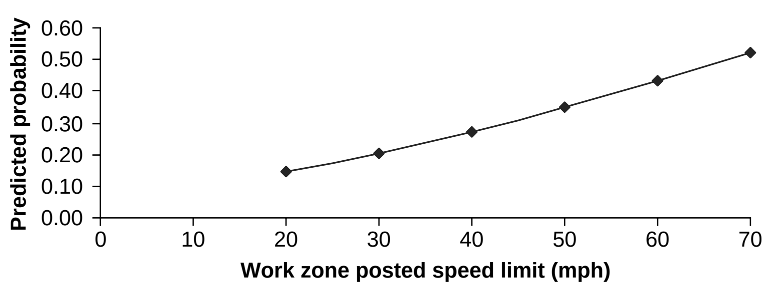

FIGURE 5 Predicted probabilities of injury severity for different posted speed limits in work zones.

are encouraged to leave the scene to decrease queues). By work zone–related variables being coded on the basis of the narrative and crash diagram drawn by the police officer, sometimes limited information is relied on. This might introduce errors, especially if police officers are not consistent in the content and details of the narratives, what they look for, and how they draw crash diagrams. Furthermore, the data on total harm have rounding errors, given that crashes with the same number and levels of injuries can have different costs. Despite these potential biases, the crash data come from a relatively clean, federally maintained HSIS database. Furthermore, there were very little missing data, and the descriptive statistics and model results are quite reasonable.

Correlation among explanatory variables in the modeling context (collinearity) is always a concern. If correlations are relatively low to moderate and the effect of each variable is theoretically distinguishable and empirically estimable, there is no violation of the relevant regression assumptions. In the models reported, the typical symptoms of collinearity, such as unreasonable coefficient magnitudes or wildly changing coefficients when an additional (highly correlated) variable is included, were not observed. The variance inflation factor being less than 10 in the OLS models was relied on to ensure that collinearity was not a problem.

CONCLUSIONS

The purpose of this study was to investigate large truck–involved crashes in work zones. A unique data set that contains new work zone–related variables not previously available in police crash reports and additional variables coded from police reports were used to fill in a key gap in the understanding of truck-involved work zone crashes. Empirical evidence from this study of North Carolina work zone crashes shows that multivehicle, truck-involved collisions are the most injurious and harmful compared with other types of crashes. Harm is a unique measure used in this study to combine the effect of both frequency and severity of injuries, and it helps quantify the effects of work zone and other variables on economic costs of crashes.

Rigorously modeling injury and harm provided new insights into the risks of work zones. Truck-involved, multivehicle crashes were most injurious and harmful when (*a*) they occurred on two-way undivided or two-way divided but unprotected (without a median barrier) roadways; (*b*) the roadway was closed, requiring a detour on the opposite side (as frequently occurs on multilane roadways and requires a median crossover); (*c*) they occurred adjacent to the activity or work area rather than in the advance-warning area; and (*d*) the posted speed limits were higher.

Overall, the study provides valuable information for developing work zone strategies to improve vehicle occupants' safety, especially in costly truck-involved collisions. Clearly, reducing the high-risk factors identified in this study will reduce their severity and associated costs. Specifically, the study points to developing strategies that can deal with the following: (*a*) work zones located on two-way undivided and two-way divided but unprotected roadways; (*b*) problems with the physical layout, with special attention given, first, to lane closings and detours to the opposite side or other similar physical layouts and, second, to the area adjacent to the actual work area; and (*c*) posting speed limits in work zones and managing speed. The analyzed data relate to injury and harm, given a crash, so the countermeasures developed to reduce these risk factors might not necessarily reduce the frequency of crashes but rather might lower their severity and cost. Finally, there is a need to explore innovative safety strategies that can at least inform both the public and truck drivers about the factors that increase injury risk.

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