Journal of Safety Research 62 (2017) 13–21

Contents lists available at ScienceDirect

Journal of Safety Research

journal homepage: www.elsevier.com/locate/jsr

Crash risk factors for interstate large trucks in North Carolina

Eric R. Teoh, [a,*] Daniel L. Carter, [b] Sarah Smith, [b] Anne T. McCartt [a]

[a] Insurance Institute for Highway Safety, 1005 N. Glebe Road, Suite 800, Arlington, VA 22201, United States
[b] University of North Carolina Highway Safety Research Center, Chapel Hill, NC, United States

ARTICLE INFO

Article history:
Received 4 October 2016
Received in revised form 31 January 2017
Accepted 4 May 2017
Available online 13 May 2017

Keywords:
Large trucks
Tractor–trailers
Crash risk
Vehicle defects
Crash avoidance technology

ABSTRACT

Introduction: Provide an updated examination of risk factors for large truck involvements in crashes resulting in injury or death. *Methods*: A matched case–control study was conducted in North Carolina of large trucks operated by interstate carriers. Cases were defined as trucks involved in crashes resulting in fatal or non-fatal injury, and one control truck was matched on the basis of location, weekday, time of day, and truck type. The matched-pair odds ratio provided an estimate of the effect of various driver, vehicle, or carrier factors. *Results*: Out-of-service (OOS) brake violations tripled the risk of crashing; any OOS vehicle defect increased crash risk by 362%. Higher historical crash rates (fatal, injury, or all crashes) of the carrier were associated with increased risk of crashing. Operating on a short-haul exemption increased crash risk by 383%. Antilock braking systems reduced crash risk by 65%. All of these results were statistically significant at the 95% confidence level. Other safety technologies also showed estimated benefits, although not statistically significant. *Conclusions*: With the exception of the finding that short-haul exemption is associated with increased crash risk, results largely bolster what is currently known about large truck crash risk and reinforce current enforcement practices. Results also suggest vehicle safety technologies can be important in lowering crash risk. This means that as safety technology continues to penetrate the fleet, whether from voluntary usage or government mandates, reductions in large truck crashes may be achieved. *Practical application*: Results imply that increased enforcement and use of crash avoidance technologies can improve the large truck crash problem.

1. Introduction

Large trucks serve a vital function in the U.S. economy. Their large size and weight, while advantageous in transporting freight efficiently, are a disadvantage in terms of highway safety. In 2014, the latest year for which data are available, large trucks were involved in an estimated 410,605 police-reported crashes (estimated from the National Automotive Sampling System — General Estimates System national sample of police reported crashes) that resulted in 3660 deaths (Insurance Institute for Highway Safety (IIHS), 2016). Large truck crashes tend to be severe. Large trucks often are 20–30 times heavier than the average passenger car, and their increased height and ground clearance increases the risk that a smaller vehicle will underride the trailer during a crash (Brumbelow, 2012; Brumbelow & Blanar, 2010). In 2014, 68% of deaths in large truck crashes were passenger vehicle occupants (IIHS, 2016). Another 15% were motorcyclists, pedestrians, or bicyclists, and 16% were the occupants of large trucks.

Large truck safety is regulated at the state and federal level. The National Highway Traffic Safety Administration (NHTSA) sets standards for new truck equipment and has some jurisdiction over equipment standards for trucks currently on the road. The Federal Motor Carrier Safety Administration (FMCSA) regulates the use of large trucks in interstate commerce (operating across state lines). FMCSA regulations cover carrier operations, truck equipment, vehicle inspection and maintenance, and hours-of-service and various other aspects of driver safety such as testing and licensing, medical requirements, and drug and alcohol testing.

Vehicles with gross vehicle weight ratings (GVWR) exceeding 10,000 lb are considered large trucks. Federal rules currently limit trucks on interstate highways to 80,000 lb, although some states allow heavier trucks on some roads within their borders. Federal regulations require a commercial driver license (CDL) to operate a vehicle with a GVWR exceeding 26,000 lb; knowledge and skills testing standards for a CDL are set by FMCSA but administered by state driver licensing agencies. If large trucks cross state lines or carry hazardous materials, their drivers must be 21 or older. States can permit drivers ages 18–20 to operate large trucks within the state.

Enforcement of federal regulations is shared by FMCSA and the states. The responsibility for regulating and enforcing the safety of intrastate commercial vehicle travel resides with the states. Large trucks are subject to on-the-spot inspections by law enforcement personnel. Carriers' compliance with regulations and their safety records also are reviewed through an FMCSA program called Compliance, Safety, and

* Corresponding author.
E-mail address: eteoh@iihs.org (E.R. Teoh).

http://dx.doi.org/10.1016/j.jsr.2017.05.002
0022-4375/

Accountability (CSA) in which carriers with high violation and crash rates are subject to interventions ranging from warning letters to service suspension.

One set of federal regulations governs the work and rest schedules of interstate drivers. Under current regulations, interstate truck drivers cannot drive for more than 11 h or drive after 14 h since starting a duty shift until they take a 10-h break. Additionally, drivers are required to spend at least 30 min off-duty after no more than 8 h of driving. Drivers cannot drive after accruing 60 work hours during a 7-day period or 70 work hours during an 8-day period, but a "restart" provision allows truckers to get back behind the wheel after 34 h off-duty. Regulations currently allow truck drivers to record their hours in written logbooks that are reviewed by inspectors. As of December 2017, electronic logging devices will be required for all carriers that are required to use logbooks.

With regard to important vehicle standards, antilock braking systems (ABS) have been required on new tractors since March 1997 and on new trailers and single-unit trucks since March 1998. In July 2009, NHTSA issued a final rule that decreased by 30% the maximum stopping distances for air-braked trucks. The rule went into effect on August 1, 2011, for three-axle tractors with GVWRs of 59,600 lb or less. Two-axle tractors and tractors with GVWRs more than 59,600 lb had to comply with the reduced stopping distance requirements by August 1, 2013. Large trucks' high centers of gravity increase their risk of rolling over, particularly on curved roadway segments such as ramps. Vehicle stability control systems are designed to intervene when a truck's motion becomes unstable, possibly resulting in rollover, jackknife, or other loss of control. Electronic stability control (ESC) will be required on all new typical three-axle tractors manufactured on or after August 1, 2017. The remaining types of truck tractors have until 2019 to comply. Other crash prevention technologies are available on large trucks but are not yet required. These technologies include forward collision warning (with and without autobrake), lane departure warning, and blind spot warning.

NHTSA also imposes rear-impact guard standards for large trucks, although several types of trucks are exempt from the current rule including single-unit trucks, trucks with rear wheels set very close to the back of the trailer, and various types of special-purpose trucks. NHTSA issued a proposed upgrade to the rear underride regulations for tractor–trailers in December 2015 and also has proposed that the regulations be extended to new single-unit trucks.

While crash mitigation strategies are important, the best remedy for large truck crashes is prevention. A key step in developing effective strategies for preventing large truck crashes is understanding what factors are associated with increased crash risk. There have been many studies describing truck crashes, but few have examined the factors associated with increased truck crash risk using strong research designs. Controlling for exposure is one of the most important considerations in studying risk factors. For example, if one observes a factor in, say, 12% of crash-involved trucks, this would not be considered a risk factor if 12% of all trucks on the road also have that factor. The Large Truck Crash Causation Study (LTCCS) collected highly detailed information on a sample of large trucks involved in crashes (FMCSA, 2006). However, no control data were collected, so researchers studied crash risk indirectly by measuring the relative likelihood that the truck was the vehicle with the last action that made the crash unavoidable (termed the "critical event" and not necessarily the chief contributory factor in the crash). For instance, Blower, Green, and Matteson (2010) found that a truck with out-of-adjustment brake violations was 1.8 times as likely to be the vehicle with the critical event, compared with a truck without such violations, but could not estimate the relative overall crash risk associated with such violations.

A common finding of research involving LTCCS, as well as other data sources, is that many or most multiple-vehicle truck crashes result from driving mistakes or misbehavior on the part of light vehicle drivers (Blower, 1998; Council, Harkey, Khattak, & Mohamedshah, 2003; FMCSA, 2006; Hanowski, Wierwille, Garness, & Dingus, 2000; Kostyniuk, Streff, & Zakrajsek, 2002). Human error largely is inevitable, so addressing it typically is a matter of laws and regulations targeting risk factors rather than the behaviors themselves. For example, driver fatigue is a well-known, and difficult to measure, problem in truck crashes (Knipling & Shelton, 1999; McCartt, Rohrbaugh, Hammer, & Fuller, 2000; National Transportation Safety Board, 1990). Thus, the hours-of-service rules seek to reduce fatigue by restricting the number of driving and work hours to ensure drivers have adequate off-duty periods to obtain restorative rest.

A pair of papers published in the 1980s took the most direct approach to identify large truck crash risk factors. Stein and Jones (1988) conducted a matched case–control study of trucks involved in crashes of any severity in Washington state. For each crash-involved truck, three control trucks were selected on the basis of location, time of day, and day of week and inspected by police specializing in commercial vehicles. This study design removes any possible confounding effects from these factors and provides a strong measure of exposure. The authors found that trucks with more than one trailer were overrepresented in crashes. They also found that empty trucks, drivers 30 and younger, and interstate carriers were at increased crash risk. Using the same study data, Jones and Stein (1989) investigated the role of defective equipment in large truck crash risk. They found that trucks with defects identified during vehicle inspections, particularly brake and steering violations, were associated with increased crash risk. They also found that driving more than 8 h, drivers 30 and younger, and interstate carriers were associated with increased crash risk.

Using a similar approach, the current study provides an updated examination of the risk factors for large truck involvements in crashes resulting in injury or death.

2. Methods

A matched case–control design was used, focusing on large trucks operated in North Carolina by interstate carriers. Cases were defined as trucks involved in serious crashes, and controls were trucks not involved in crashes matched by location, time, and truck type. This allowed comparing the relative prevalence of various factors to determine which are associated with increased crash risk.

The Insurance Institute for Highway Safety partnered with the University of North Carolina (UNC) Highway Safety Research Center and the North Carolina State Highway Patrol Motor Carrier Enforcement division (hereinafter referred to as the Highway Patrol). UNC developed the data collection methods, coordinated data collection with the Highway Patrol, and maintained all data files. The study protocol was approved by the UNC Institutional Review Board.

The Highway Patrol monitors roadways and responds to crashes in non-municipal areas of North Carolina. Six of the agency's eight regions participated in the current study; two regions were not included because they have relatively little large truck traffic. For large truck crashes involving apparent serious injuries or deaths, it is standard practice for officers to perform a full investigation of the truck and driver conforming to the Commercial Vehicle Safety Alliance (CVSA, 2016a) Level I inspection criteria. CVSA Level I inspections include examination of the driver's logbook, CDL, medical certificate, and other driver requirements, as well as all major vehicle systems such as brakes, tires, lights, and suspension. Inspections are performed by CVSA-certified troopers in the Motor Carrier Enforcement division. The troopers who participated in the current study conducted inspections of the control trucks on an overtime basis and were compensated with project funds.

Cases were defined as large trucks involved in serious crashes. Specifically, the following inclusion criteria were employed:

- Truck operated by interstate carrier
- Truck had GVWR exceeding 26,000 lb and three or more axles

• Truck involved in crash with the following characteristics:
- At least one possible, evident, incapacitating, or fatal (i.e., KABC) injury involved
- If non-fatal injury, emergency medical services transported victim from crash scene
- Occurred on an interstate, U.S. or state highway, or secondary roadway
• Truck and truck driver subjected to CVSA Level I inspection conducted by Highway Patrol
• Crash report filed by Highway Patrol

For each crash-involved truck, one control truck was matched on the following factors:

• Truck type (single-unit or combination-unit)
• Location (within 5 miles of crash site on same roadway in same travel direction)
• Day of week (weekend vs. weekday, exact day matched when possible)
• Time of day (6 a.m.–10 a.m., 10 a.m.–2 p.m., 2 p.m.–6 p.m., 6 p.m.–10 p.m., 10 p.m.–2 a.m., 2 a.m.–6 a.m.)

2.1. Description and source of data

Data were collected from a variety of sources and included large truck crashes occurring from September 2010 to December 2012. Throughout this period, on a weekly basis, the Highway Patrol provided UNC with crash report forms and CVSA Level I inspection report forms from all truck-involved crashes occurring in the six participating regions, from which qualifying crashes were selected by UNC. All crashes meeting the study's inclusion criteria were selected. For each qualifying crash, a control packet outlining control truck type, location, day of week, and time of day was prepared by UNC and delivered to Highway Patrol sergeants, who scheduled control inspections conducted by trained troopers working overtime shifts. Control truck inspections were completed as soon as possible after the crash but always within 2 months of the associated crash. Day of week was matched exactly in 19% of control inspections, within one day in about half, and always weekday vs weekend. Weekday control inspections were more likely to be on Monday and Friday and less likely to be on Wednesday and Thursday, relative to the weekday crashes to which they were matched. To minimize selection bias (e.g., if troopers were to pull over trucks that they perceive as problematic), troopers were instructed to park at the specified location and inspect the third eligible control truck passing that location after the officer arrived. In some cases, troopers would direct the truck to a safer location than the roadside to conduct the inspection, such as a parking lot, but trucks were selected at the specified locations to minimize selection bias. Further, troopers were asked to complete a supplemental data collection form (Fig. 1), developed by UNC and IIHS, at all truck crashes and at the control truck inspections. The supplemental form collected information from the drivers on their experience and schedule and on safety technologies installed on their trucks.

The protocol called for obtaining a copy of the last 7 days of a driver's logbook, but this was not always possible. Some drivers who were using electronic logging devices (ELD) were unable to produce a paper summary of their recent schedules. In some cases, officers photographed the electronic screens.

Troopers noted that some drivers were operating under a short-haul exemption and, thus, not required to maintain a logbook. A short-haul exemption applies when a driver employed by an interstate carrier drives only within a 100 air-mile radius of the normal working location, works less than 12 h each day, and does not spend nights on the road. These drivers must follow the federal hours-of-service regulations for interstate drivers, but they are not required to maintain logbooks.

The inspection form contains identifying information for drivers and carriers and lists all violations identified during the inspection, as well as whether each violation was severe enough to put the truck out-of-service until repaired. Additionally, brake adjustment measurements were tabulated for each axle. The presence of brake measurements indicated the braking system was inspected, which may not be the case if the system is severely damaged in a crash. When studying the effects of brake violations, only case/control pairs in which both trucks' brakes were measured were included.

The inspection form included a code for whether a particular violation resulted from the impact of a crash. For example, a headlight smashed in a crash would be coded as a violation and as caused by the crash. However, there is no way to know if that light was functioning properly prior to the crash. Violations unlikely to result from crash damage (e.g., inoperable warning lamps, placards/administrative violations) were examined, and many were coded as having resulted from the crash, and at a rate similar to other violations. As such, it was not clear that the variable indicating whether a violation was caused by crash damage was reliable, so it was not used in the main analyses.

Information on the carrier was obtained from the U.S. DOT number printed on the truck's driver door. This number was used to obtain the identity of the carrier and information on the carrier's crash and inspection violation histories and number of power units from the Safety and Fitness Electronic Records (SAFER) system maintained by FMCSA (2012). The SAFER website provides data on carriers' records for the past 24 months and was accessed for each crash and control truck within a few weeks of the crash event. When evaluating carriers' crash histories, it is important to consider the size of the carrier because a carrier employing two trucks may have no crashes within the past 24 months, whereas a carrier employing 500 trucks almost certainly had crashes during that period. So the rate of crashes per 1000 power units was evaluated. All DOT-reportable crashes (involving fatality, injury, or a vehicle towed away) were included without regard for which party was responsible.

Data on drivers' traffic violation histories were obtained from FMCSA through the drivers' names and CDL numbers recorded on the inspection forms. The final data set analyzed was stripped of all personal identifying information. Rates were computed by dividing drivers' counts of moving traffic violation convictions by number of years of data obtained from FMCSA records. Drivers with less than 5 years of data in FMCSA records were excluded from the moving traffic violations analysis.

In total, data on 197 crash and control pairs were collected. Sample sizes analyzed varied by the factor in question. For example, analyses of driver age used 195 crash/control pairs, whereas analyses of brake defects used only 137 pairs. Based on the analysis techniques described below, if one member of a crash/control pair had a missing value for the factor in question, the pair was excluded from that analysis. Sample sizes are reported for all analyses and are reported as number of crash/control pairs.

2.2. Analyses

The statistical analyses, in terms of both estimation and the statistical significance of estimates, accounted for the paired nature of the study design. In a non-matched case–control design, the prevalence of various factors can be compared directly between the crash and control samples. However, to optimize the benefits of a paired design, a factor's contribution to crash risk was estimated on the basis of the matched pair odds ratio. Fig. 2 illustrates the estimation of the matched pair odds ratio and calculation of a 95% confidence interval. In this approach, each pair falls into one cell of the table based on the presence of a given factor for the crash truck and its matched control truck. Only discordant pairs, or pairs where one member has the factor and the other does not, provide information on the risk estimate. Conditional logistic regression, which is equivalent to the matched pairs odds ratio if the factor in question is the only covariate, was used to estimate odds ratios

Supplemental Data Collection Form
UNC-CH Research Study on Large Truck Crashes

Answer all shaded areas
Electronic users can use tab to move through shaded areas

Date	County	Time

ENF-500 Report Number

(Highway Name or Number)

Post-crash inspection?		**1** - Yes, **2** - No
Was anyone transported from the scene by EMS?		**1** - Yes, **2** - No

Digital Photos Checklist

- Roadway
- Left Side of Truck
- Mirrors (left)
- Front of Truck
- Right Side of Truck
- Mirrors (right)
- Rear of Truck
- Logbook

Vehicle Information (Enter number according to answer)			Description
Electronic Stability Control (ESC) or Roll Stability Control (RSC)		**1** - Yes, **2** - No, **3** - Don't know	Brakes individual wheels if loss of control detected - mainly to prevent rollovers
Antilock Braking System (ABS)		**1** - Yes, **2** - No, **3** - Don't know	Prevents the wheels from locking in hard braking events, and helps prevent jacknifing
Speed governor		**1** - Yes, **2** - No, **3** - Don't know	Limits the maximum possible speed of the truck
Electronic On Board Recorder (EOBR)		**1** - Yes, **2** - No, **3** - Don't know	Monitors time spent driving and stopped, some systems monitor speed and other events
Any other advanced crash avoidance technologies? (Please list)			Examples include: forward collision warning, blind spot detection, lane departure warning

Driver Information (Please read questions to the driver as they are written below)		
How many miles do you typically drive in one year?		
In what year did you first start driving trucks professionally?		
How long, in hours, has it been since your last main sleep? How long, in hours, was this sleep?		
How long, in hours, has it been since the last time you stopped (that is – got out of your driver seat)? How long, in hours, was this stop?		

- Please obtain copies (photograph, photocopy, scan into computer, or tear out one of the triplicate copies) of the driver's logbook for the past 7 days and attach to this form.

Questions on this form? Contact Daniel Carter, UNC Chapel Hill,

Fig. 1. Supplemental data collection form used for crash and control trucks.

when the factor was not dichotomous (e.g., when categorizing age or driving hours into three groups) and to adjust for other factors such as years of driving a truck. The paired design directly controls for the confounding effects of the matching variables because, by definition, the crash and control samples do not differ by truck type, location, weekend/weekday, or time of day.

Statistical significance was reported by providing 95% confidence intervals for all odds ratios, with intervals containing 1.0 being not significant. However, because the sample size was relatively small and many factors were considered, both statistically significant and promising but not significant results were reported and discussed.

3. Results

In all of the tables evaluating risk factors, the matched pair odds ratio was the primary effect measure. However, counts of crashes and controls also were included to provide the reader with some sense of how common these were in crashes. The crash sample was designed to be a random sample of crashes fitting the inclusion criteria, but because this was a paired design, the control sample does not form a random sample of trucks in operation. Also, because crashes are rare events, the odds ratio is a good approximation of relative risk and all results are interpreted in terms of changes in crash risk.

Table 1 provides the distribution of crash-involved trucks in the study by matching criteria and crash severity. The majority of trucks were combination unit trucks (e.g., tractor–semitrailers), and about 95% of both crash-involved and control combination unit study trucks were tractor–semitrailer configuration. Crashes usually occurred on weekdays and on major roadways. Most of the crashes occurred during daylight hours, and most involved another vehicle besides the truck. Thirty-eight percent of the crashes were fatal, and 11% involved only the least severe category of injuries (i.e., possible injury).

Analyses of inspection vehicle violations are presented in Table 2. Violations relating to brakes, tires, and lighting systems were analyzed because they are common and relevant to safety, and all analyses were repeated for multiple-vehicle crashes, crashes in which the truck was the striking vehicle, and crashes in which the truck was the struck vehicle. Having any vehicle defects, which was the case for 73% (143/197) of crash-involved trucks, was statistically significantly associated with triple the risk of being involved in a crash. Brake violations, which were present in 42% (57/137) of crashed trucks, were associated with a nonsignificant 45% increase in crash risk, but this increased for

		Control trucks	
		Factor present	Factor not present
Crash trucks	Factor present	a	b
	Factor not present	c	d

with a, b, c, and d equal to number of matched cases with/without factors

$$\mathrm{OR} = \frac{\mathrm{b}}{\mathrm{c}}$$

with 95% confidence interval: $e^{\log(\mathrm{OR}) \pm 1.96\mathrm{se}[\log(\mathrm{OR})]}$

where $\mathrm{se}[\log(\mathrm{OR})] = \sqrt{\frac{1}{\mathrm{b}} + \frac{1}{\mathrm{c}}}$

Fig. 2. Calculation of matched pair odds ratio (OR).

multiple-vehicle crashes and especially when the truck was the striking vehicle. Tire violations were associated with large, statistically significant increases in crash risk. Lighting system defects were associated with statistically significant increases in crash risk.

Fifty-four percent (77/143) of crash-involved trucks' vehicle violations were out-of-service violations, compared with 30% (30/99) for the vehicle violations of the matched control trucks. Thirty-nine percent (77/197) of the crash-involved trucks had at least one out-of-service violation. When restricting vehicle violations to those severe enough to put the truck out-of-service (Table 3), virtually all violation types were more strongly and statistically significantly associated with increased crash risk. This is an important finding because trucks are placed out-of-service for violations that are believed to represent an immediate threat to safety. Having an out-of-service vehicle violation of any type was associated with a 362% increase in the risk of crashing. This climbs to a 900% increase for multiple-vehicle crashes where the truck was the striking vehicle. Both findings were statistically significant.

Table 1
Distribution of characteristics of crash-involved trucks.

	N	Percent
Truck type		
Single-unit truck	20	10
Combination-unit truck	177	90
Day of week		
Weekday	178	90
Weekend	19	10
Type of road		
Interstate highway	86	44
US highway	60	30
State highway	32	16
Minor arterial/collector	4	2
Local road	7	4
Time of day		
2 a.m.–5:59 a.m.	15	8
6 a.m.–9:59 a.m.	63	32
10 a.m.–1:59 p.m.	40	20
2 p.m.–5:59 p.m.	38	19
6 p.m.–9:59 p.m.	19	10
10 p.m.–1:59 a.m.	22	11
Crash type		
Single-vehicle crash	40	20
Multiple-vehicle crash[a]	156	79
Crash severity		
Fatal crash	75	38
Incapacitating injury crash	33	17
Evident injury crash	67	34
Possible injury crash	22	11

[a] One crash had unknown number of vehicles.

Table 4 presents analyses of driver-related potential risk factors. Driver younger than 30 and drivers 60 and older were associated with increased crash risk, although only the latter effect was statistically significant; 72% of the crash-involved drivers were ages 30–59. Years of experience driving trucks did not have a strong or significant effect, but the study lacked the sample size to estimate the effect of likely more meaningful times such as less than 1 year. Driving a truck fewer than 60,000 miles annually was associated with a statistically significant increased crash risk relative to driving 100,000 miles or more. Having at least one prior moving traffic violation conviction per year (10% of crash-involved truck drivers) was not significantly associated with increased crash risk. Having an out-of-service, hours-of-service, or logbook violation (6% of crash-involved truck drivers) when inspected for the current study also was associated with increased crash risk, but not significantly so. Logbook violations occur for reasons other than long driving hours, but having driven more than 12 h since the last main sleep, as reported by drivers, was associated with an 86% increase in crash risk, relative to less than 8 h. Having driven more than 5 h since stopping prior to the inspection (defined as having gotten out of the driver seat) more than doubled the risk of crashing, although the estimate was not statistically significant.

The analyses of factors associated with carriers are presented in Table 5. It was unknown if a truck was owned by the driver, so two working definitions of owner-operator were considered based on information taken from the SAFER website using the carrier name and U.S. DOT number: carrier operates one power unit and carrier employs one driver. Both were associated with increased crash risk, although neither was statistically significant. Having at least 100 reported crashes per 1000 power units in the last 24 months was associated with a statistically significant 72% increase in the risk of crashing. For prior rates of at least 100 reported injury crashes per 1000 power units, this rose to a 225% increase, also statistically significant. Fatal crashes are much

Table 2
Distribution of inspection violations and associated crash risk estimates.

Type of violation		N (pairs)	Crash/control trucks with violations	Matched-pair odds ratio	95% confidence interval
Brakes[a]	All crashes	137	57/48	1.45	(0.82, 2.56)
	Multiple-vehicle	121	51/41	1.67	(0.88, 3.16)
	Truck striking	50	26/11	8.50	(1.96, 36.79)
	Truck struck	70	25/30	0.62	(0.26, 1.48)
Tires	All crashes	197	48/17	3.38	(1.82, 6.28)
	Multiple-vehicle	157	40/12	4.11	(1.98, 8.52)
	Truck striking	70	15/3	13.00	(1.70, 99.38)
	Truck struck	86	24/8	3.00	(1.35, 6.68)
Lighting systems	All crashes	197	81/46	2.25	(1.44, 3.51)
	Multiple-vehicle	157	71/38	2.57	(1.55, 4.26)
	Truck striking	70	30/12	4.60	(1.75, 12.10)
	Truck struck	86	41/26	1.94	(1.06, 3.54)
Any vehicle defect	All crashes	197	143/99	3.10	(1.89, 5.06)
	Multiple-vehicle	157	117/81	3.12	(1.80, 5.38)
	Truck striking	70	51/32	4.80	(1.83, 12.58)
	Truck struck	86	65/48	2.42	(1.23, 4.74)

[a] Includes crash/control pairs where both trucks' brakes were measured

rarer, so the cutoff point of 10 fatal crashes per 1000 power units in the past 24 months was used and was associated with a statistically significant 950% increase in crash risk.

A driver operating under a short-haul exemption was associated with a 383% increase in crash risk, and this was statistically significant (Table 5). Additional analyses (Table 6) revealed that crash-involved trucks and control trucks operating under a short-haul exemption were less likely to be sampled on interstate roads, more likely to be single-unit trucks, and more likely to represent owner-operators. These trucks also reported fewer annual miles compared with trucks not using the exemption at the time of sampling. Further, having a short-haul exemption was associated with more inspection violations among crash-involved trucks, but not among control trucks. The sample was too small to estimate a matched-pair odds ratio restricted to short-haul exemption trucks. However, the pattern of differences between these trucks and other trucks suggests that inspection violations have a greater deleterious effect for short-haul exemption trucks than for conventional interstate operation trucks.

Table 7 presents estimates of the effect of various vehicle safety technologies. Information on the presence of these technologies on the truck was based on drivers' reports. All technologies were estimated to be beneficial, although ABS was the only technology with a statistically significant effect. With the exception of ABS, estimated crash risk reductions were greater for multiple-vehicle crashes. Electronic or roll stability control was associated with a 19% lower crash risk, similar to that of speed governors. Electronic logging devices were associated with large reductions in crash risk. The numbers of other types of systems (e.g., forward collision warning, blind spot warning) were too small to analyze.

4. Discussion

An important, yet unsurprising, finding of the current study is that problems uncovered by inspecting large trucks, especially those serious enough to put the truck out-of-service, predict crash risk. These findings reinforce the importance of conducting such inspections and other enforcement activities. Another important finding is that carriers' recent historical crash rates are predictive of future crash risk, whether considering fatal, injury, or all crashes. Recent legislative activity and research has focused on whether FMCSA should define and remove from consideration non-preventable historical crashes when calculating carriers' safety ratings (Boris & Murray, 2015; Office of the Federal Register, 2016). The current study was not able to identify whether crashes were preventable, but it does provide evidence that considering all crashes is sufficient for predicting carriers' crash risk.

While the current study found vehicle defect violations predict crash risk, it is promising that the overall rate of such violations among inspected vehicles are reported to have declined substantially (CVSA, 2016b). Brake violations have declined because large trucks with airbrake systems (the majority of tractor–trailers and larger single-unit trucks) have been required to have self-adjusting brakes and slack-adjusters since 1994. Unlike in the Jones and Stein (1989) study, steering defect violations were not tabulated in the current study because there were too few to analyze.

Table 3
Distribution of out-of-service inspection violations and associated crash risk estimates.

Type of violation		N (pairs)	Crash/control trucks with violations	Matched-pair odds ratio	95% confidence interval
Brakes[a]	All crashes	137	26/11	3.14	(1.34, 7.36)
	Multiple-vehicle	121	21/8	3.17	(1.26, 7.93)
	Truck striking	50	11/4	4.50	(0.97, 20.83)
	Truck struck	70	10/4	2.50	(0.78, 7.97)
Tires	All crashes	197	27/3	9.00	(2.73, 29.67)
	Multiple-vehicle	157	22/2	11.00	(2.59, 46.78)
	Truck striking	70	7/2	3.50	(0.73, 16.85)
	Truck struck	86	14/0	—	—
Lighting systems	All crashes	197	12/5	2.40	(0.85, 6.81)
	Multiple-vehicle	157	10/3	3.33	(0.92, 12.11)
	Truck striking	70	3/0	—	—
	Truck struck	86	7/3	2.33	(0.60, 9.02)
Any vehicle defect	All crashes	197	77/30	4.62	(2.53, 8.41)
	Multiple-vehicle	157	60/21	5.33	(2.62, 10.87)
	Truck striking	70	28/10	10.00	(2.34, 42.78)
	Truck struck	86	31/11	3.86	(1.68, 8.86)

[a] Includes crash/control pairs where both trucks' brakes were measured

Table 4
Distribution of driver characteristics and associated crash risk estimates.

	N (pairs)	Crash/control trucks	Matched-pair odds ratio	95% confidence interval
Driver age				
<30	195	11/7	2.00	(0.71, 5.64)
30–59	195	139/164	1	
60+	195	45/24	2.51	(1.37, 4.62)
Years of truck driving				
<5	168	17/16	1.09	(0.53, 2.22)
5–9	168	25/23	1.13	(0.58, 2.19)
10+	168	126/129	1	
Annual truck mileage				
<60,000	169	55/41	2.01	(1.10, 3.66)
60,000–99,999	169	48/43	1.46	(0.87, 2.46)
100,000+	169	66/85	1	
Rate of prior moving violations				
1+ per year of driving	142	14/11	1.30	(0.57, 2,96)
<1 per year of driving	142	128/131	1	
Hours-of-service/logbook violations with current inspection				
Out-of-service (vs. not out-of-service)	176	11/8	1.50	(0.53, 4.21)
Any violation (vs. none)	176	22/32	0.63	(0.34, 1.16)
Hours since last main sleep				
<8	169	89/106	0.64	(0.37, 1.09)
8–12	169	56/47	1	
>12	169	24/16	1.19	(0.58, 2.44)
Hours since last stop				
<1	157	55/48	1.36	(0.52, 2.27)
1–5	157	85/100	1	
>5	157	17/9	2.20	(0.92, 5.22)

Crash avoidance and mitigation technologies continue to be introduced into the fleet, and some have been mandated by the federal government. ABS has been required on new tractors beginning in 1997 and on new trailers, single-unit trucks, and buses beginning in 1998. This could have introduced a bias in that the ABS comparison inherently compared newer trucks with older ones. As of August 2017, tractor–trailers and buses will be required to have ESC. NHTSA estimates that ESC will prevent 40–56% of untripped rollovers and 14% of loss-of-control crashes (Wang, 2011). In 2016, FMCSA issued a final rule mandating the use of ELDs for compliance with hours-of-service rules, and NHTSA proposed a change to the regulation governing rear underride guards that would strengthen them and extend the rule to single-unit trucks. NHTSA has announced its intention to begin rulemaking on mandating speed limiters on large trucks, and it has granted a petition to begin rulemaking on requiring front crash prevention technologies.

The finding that the use of a short-haul exemption is associated with substantially increased crash risk is unexpected. While it is reasonable to believe short-haul drivers spend more time on non-interstate roads, which have higher crash rates than interstate highways, the current study sampled controls at the same sites as crashes. So the finding cannot be explained by simple roadway exposure differences. Use of the short-haul exemption among study trucks was associated with other risk factors identified in the current study, in particular driving fewer annual miles and being owner-operators. There may be other related factors unobserved in the current study. It also is possible that carriers assign less safe drivers to more local operations, that long-haul drivers who temporarily take on local jobs disrupt their regular sleep schedules, or that older or more poorly maintained trucks are used in local operations. One study based on focus groups of truck drivers suggested fatigue may be a major factor for short-haul drivers, but the study was unable to determine if fatigue was a bigger factor for short-haul drivers compared with long-haul drivers (FMCSA, 2001).

The current study collected data on drivers' logbooks, but this information was unavailable in many cases. This primarily was due to the use of short-haul exemption and ELDs. In many cases, drivers with ELDs were unable to provide the officer with a printout of 7 days of data, even though this is required by federal regulations. Thus, officers

Table 6
Distribution of characteristics of crash-involved study trucks by short-haul exemption.

	No short-haul exemption		Short-haul exemption	
	N	Percent	N	Percent
Truck type				
Single-unit truck	6	4	13	27
Combination-unit truck	131	96	35	73
Day of week				
Weekday	123	90	45	94
Weekend	14	10	3	6
Type of road				
Interstate highway	76	55	5	10
Non-interstate road	61	45	43	90
Crash type				
Single-vehicle crash	25	18	9	19
Multiple-vehicle crash	111	81	39	81
Driver age				
<30	5	4	6	12
30–59	98	72	32	67
60+	33	24	10	21
Owner-operator				
Carrier has 1 power unit vs. 2+	4	3	7	15
Carrier employs only 1 driver vs. 2+	4	3	8	17
Annual truck mileage				
<60,000	24	18	29	60
60,000–99,999	35	26	7	15
100,000+	59	43	6	12

Table 5
Distribution of carrier crash risk factors and associated crash risk estimates.

	N (pairs)	Crash/control trucks	Matched-pair odds ratio	95% confidence interval
Owner-operator (two available definitions)				
Carrier has one power unit	194	11/10	1.11	(0.45, 2.73)
Carrier employs only one driver	194	12/8	1.57	(0.61, 4.05)
10+ percent of inspections resulted in out-of-service violation				
Driver violations	192	19/15	1.31	(0.64, 2.69)
Vehicle violations	192	139/136	1.08	(0.69, 1.69)
Carrier crashes within past 24 months				
At least 100 crashes per 1000 power units	193	88/65	1.72	(1.11, 2.66)
At least 100 injury crashes per 1000 power units	193	28/10	3.25	(1.47, 7.18)
At least 10 fatal crashes per 1000 power units	193	43/5	10.50	(3.77, 29.28)
Driver operating under short-haul exemption	184	48/25	4.83	(2.01, 11.64)

Table 7
Distribution of safety technologies on truck and associated crash risk estimates.

	Multiple-vehicle crashes				All crashes			
	N (pairs)	Crash/control trucks	Matched-pair odds ratio	95% confidence interval	N (pairs)	Crash/control trucks	Matched-pair odds ratio	95% confidence interval
Electronic/roll stability control	76	17/23	0.65	(0.30, 1.38)	97	23/27	0.81	(0.43, 1.53)
Electronic logging device	135	28/41	0.58	(0.32, 1.04)	170	41/54	0.66	(0.40, 1.09)
ABS on power unit	145	122/132	0.47	(0.21, 1.05)	179	149/166	0.35	(0.16, 0.74)
ABS on trailer	107	83/87	0.77	(0.37, 1.57)	134	103/109	0.73	(0.38, 1.38)
Speed governor	127	103/108	0.72	(0.35, 1.47)	157	127/131	0.83	(0.45, 1.52)

were able to determine if there were logbook or hours-of-service violations, but driving hours could not be calculated. This may be remedied in future studies by the ELD mandate, which standardizes reporting requirements because ELDs currently are configured in a variety of ways.

The data were collected during a period of declining crash rates such that it took longer than anticipated to build an adequate sample of crash/control pairs, and limits on time and resources meant that a larger sample of crash/control pairs could not be obtained. This limited the statistical power and the ability to disaggregate the data by various factors such as short-haul exemption and road type. Another limitation was that controls were sampled up to 2 months after their corresponding crashes, during which time conditions such as weather or traffic density could have changed. Since much of the information analyzed came from CVSA level 1 inspections, the crash sample was necessarily skewed toward crashes that are more likely to involve such inspections – usually more serious crashes. This, as well as other inclusion criteria, makes it difficult to compare to overall crash populations in other databases, but the study sample still represents an important subset of truck crashes. Moreover, serious crashes are of most concern from a safety perspective and the crashes toward which most safety countermeasures are directed. Also, violations resulting from crash damage could not be excluded reliably. Finally, while evaluating carriers' historical crash rates on a per-VMT basis would be preferable to a per-power-unit basis, only the latter data were available on the SAFER website. This analysis was not intended to provide an exhaustive comparison of carrier's relative safety but rather to examine carrier characteristics that may predict crash risk.

Despite these limitations, the current study represents one of the few carefully controlled studies of risk factors of large truck crashes in the United States. There is opportunity for further research to target specific aspects of the crash risks identified in the present study. It will be particularly important to conduct controlled studies of the effects of crash prevention technologies on crash risk.

Acknowledgements

The authors gratefully acknowledge the hard work and professionalism of the North Carolina State Highway Patrol's Motor Carrier Enforcement division, command staff, and Troops B, C, D, E, F, and H. Without their support and hard work, this study would not have been possible. We also acknowledge the Federal Motor Carrier Safety Administration, particularly Ralph Craft, for its assistance in obtaining data. The website of carrier safety information maintained by the agency was particularly helpful. Bo Lan, of the University of North Carolina, helped maintain the data and perform some initial analyses. This study was supported by the Insurance Institute for Highway Safety.

References

Blower, D. (1998). *The relative contribution of truck drivers and passenger car drivers to two-vehicle, truck-car traffic crashes. Publication no. UMTRI-98-25.* Ann Arbor, MI: University of Michigan Transportation Research Institute.

Blower, D., Green, P. E., & Matteson, A. (2010). Condition of trucks and truck crash involvement: Evidence from the large truck crash causation study. *Transportation Research Record*, *2194*, 21–28.

Boris, C., & Murray, D. (2015). *Assessing the impact of non-preventable crashes on CSA scores.* Arlington, VA: American Transportation Research Institute.

Brumbelow, M. L. (2012). Potential benefits of underride guards in large truck side crashes. *Traffic Injury Prevention*, *13*, 592–599.

Brumbelow, M. L., & Blanar, L. (2010). Evaluation of U.S. rear underride guard regulation for large trucks using real-world crashes. *Stapp Car Crash Journal*, *54*, 119-113.

Commercial Vehicle Safety Alliance (2016a). *Inspections; All inspection levels.* (Greenbelt, MD. Available: http://cvsa.org/inspections/inspections/all-inspection-levels).

Commercial Vehicle Safety Alliance (2016b). *Commercial Vehicle Safety Alliance releases 2015 International Roadcheck results.* (Greenbelt, MD. Accessed: Sep 27, 2016. Available: http://www. prweb.com/releases/2015/Roadcheck/prweb12974997.htm).

Council, F. M., Harkey, D. L., Khattak, A. J., & Mohamedshah, Y. M. (2003). Examination of fault, unsafe driving acts, and total harm in car-truck collisions. *Transportation Research Record*, *1830*, 63–71.

Federal Motor Carrier Safety Administration (2001). *Impact of local/short-haul operations on driver fatigue: Field study. Report no. FMCSA-MCRT-01-006.* Washington, DC: U.S. Department of Transportation.

Federal Motor Carrier Safety Administration (2006). *Report to Congress on the Large Truck Crash Causation Study. Report no. MC-R/MC-RRA.* Washington, DC: U.S. Department of Transportation.

Federal Motor Carrier Safety Administration (2012). *Company snapshot; Safety and Fitness Electronic Records (SAFER) System.* Washington, DC: U.S. Department of Transportation (Available: https://safer.fmcsa.dot.gov/companysnapshot.aspx).

Hanowski, R. J., Wierwille, W. W., Garness, S. A., & Dingus, T. A. (2000). Impact of local/short haul operations on driver fatigue. *Final report. Report no. DOT-MC-00-203.* Washington, DC: Federal Motor Carrier Safety Administration.

Insurance Institute for Highway Safety (2016). *Fatality facts: Large trucks, 2015.* (Arlington, VA: Available: http://www.iihs.org/iihs/topics/t/large-trucks/fatalityfacts/large-trucks).

Jones, I. S., & Stein, H. S. (1989). Defective equipment and tractor–trailer crash involvement. *Accident Analysis and Prevention*, *21*, 469–481.

Knipling, R. R., & Shelton, T. T. (1999). Problem size assessment: Large truck crashes related primarily to driver fatigue. *Proceedings of the Second International Large Truck Safety Symposium* (pp. 3–12). Knoxville, TN: University of Tennessee Transportation Center.

Kostyniuk, L. P., Streff, F. M., & Zakrajsek, J. (2002). *Identifying unsafe driver actions that lead to fatal car-truck crashes.* Washington, DC: AAA Foundation for Traffic Safety.

McCartt, A. T., Rohrbaugh, J. W., Hammer, M. C., & Fuller, S. Z. (2000). Factors associated with falling asleep at the wheel among long-distance truck drivers. *Accident Analysis and Prevention*, *32*, 493–504.

National Transportation Safety Board (1990). *Safety study: Fatigue, alcohol, other drugs, and medical factors in fatal-to-the-driver heavy truck crashes. Report no. NTSB/SS-90/02.* Washington, DC: U.S. Department of Transportation.

Office of the Federal Register (2016). *Federal Motor Carrier Safety Administration, request for public comment, docket no. FMCSA-2014-0177; crash preventability program. Federal Register, vol. 81, no. 133.* (pp. 45210–45213). Washington, DC: National Archives and Records Administration, 45210–45213.

Stein, H. S., & Jones, I. S. (1988). Crash involvement of large trucks by configuration: A case-control study. *American Journal of Public Health*, *78*, 491–498.

Wang, J. S. (2011). *Effectiveness of stability control systems for truck tractors. Report no. DOT HS-811-437.* Washington, DC: National Highway Traffic Safety Administration.

Eric R. Teoh is a senior statistician at the Insurance Institute for Highway Safety. Since joining the Institute in 2006, Mr. Teoh has conducted numerous studies quantifying the state of highway safety and identifying ways to improve it. His research has focused on motorcycles, young drivers, large trucks and passenger vehicle safety. Mr. Teoh holds a master's degree in mathematics from the University of Alabama at Birmingham, where he also earned his bachelor's degree.

Daniel L. Carter is an engineering research associate at the UNC Highway Safety Research Center. He conducts research in the areas of countermeasure evaluation, pedestrian safety, safety data, and professional training. Much of his work focuses on using crash, roadway, and traffic volume data from state and local agencies to conduct research on these topics. He also works to disseminate the research knowledge through his management of the FHWA Crash Modification Factors Clearinghouse and the development of related training materials. Mr. Carter obtained his bachelor's and master's degrees in civil engineering from North Carolina State University and holds a Professional Engineer license in North Carolina.

Sarah Smith, an engineering research associate at the UNC Highway Safety Research Center since 2008, serves as a project engineer for projects for the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration, the National Cooperative Highway Research Program and the North Carolina Department of Transportation (NCDOT). Her research experience includes the areas of roadway and safety data, countermeasure evaluation, and pedestrian safety. She assists in handling data collection and analysis for many types of highway safety studies. Prior to her employment at HSRC, Ms. Smith worked for the Insurance Institute for Highway Safety (IIHS) for six years. At IIHS, Ms. Smith's assignments included high speed vehicle crash testing, low speed rear impact crash testing, data analysis, assessment of vehicle ratings, and reporting of test findings and results. Ms. Smith earned her bachelor of science degree in mechanical engineering from the University of Virginia in 2003.

Anne T. McCartt retired in May 2016 as Senior Vice President, Research, from the Insurance Institute for Highway Safety. She has published approximately 200 papers and technical reports on a wide variety of topics. She received a B.A. from Duke University and a Ph.D. from the Rockefeller College of Public Affairs and Policy, State University of New York (SUNY) at Albany.