

**Crash Avoidance Potential of
Four Large Truck Technologies**

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Abstract

Objectives: The objective of this paper was to estimate the maximum potential large truck crash reductions in the United States associated with each of four crash avoidance technologies: side view assist, forward collision warning/mitigation, lane departure warning/prevention, and vehicle stability control. Estimates accounted for limitations of current systems.

Methods: Crash records were extracted from the 2004-08 files of the National Automotive Sampling System General Estimates System (NASS GES) and the Fatality Analysis Reporting System (FARS). Crash descriptors such as location of damage on the vehicle, road characteristics, time of day, and precrash maneuvers were reviewed to determine whether the information or action provided by each technology potentially could have prevented the crash.

Results: Of the four technologies, side view assist had the greatest potential for preventing large truck crashes of any severity; the technology is potentially applicable to 39,000 crashes in the United States each year, including 2,000 serious and moderate injury crashes and 79 fatal crashes. Vehicle stability control is another promising technology, with the potential to prevent or mitigate up to 31,000 crashes per year including more serious crashes — up to 7,000 moderate-to-serious injury crashes and 439 fatal crashes per year. Vehicle stability control could prevent or mitigate up to 20 and 11 percent of moderate-to-serious injury and fatal large truck crashes, respectively.

Conclusions: There is great potential effectiveness for truck-based crash avoidance systems. However, it is yet to be determined how drivers will interact with the systems. Actual effectiveness of crash avoidance systems will not be known until sufficient real-world experience has been gained.

Keywords: Crash risk; Active safety; Crash avoidance technology; Large trucks; GES; FARS.

1. Introduction

Large trucks, including single-unit straight trucks and combination tractor trailers, account for a small percentage of registered vehicles but, per unit of travel, are involved in more fatal crashes than other classes of vehicles — 2.0 crashes per 100 million miles traveled in 2007 compared with 1.4 for passenger cars and 1.8 for light trucks (National Highway Traffic Safety Administration (NHTSA), 2008). The higher fatal crash rate is attributable to the size disparity between large trucks and passenger vehicles that puts passenger vehicle occupants at risk when involved in crashes with large trucks. The size disparity is a challenge for highway safety and points to the importance of avoiding large truck crashes altogether. In recent years, crash avoidance has become a large area of focus for truck manufacturers and suppliers as they develop advanced safety technologies for the large truck market. To date, penetration of these technologies into the large truck fleet has been slow but, as more data become available, evidence of safety benefits may provide needed support to motor carriers for deploying the technologies in their fleets. Among many promising safety advancements is the introduction of technologies such as forward collision warning, lane departure warning, side view assist, and vehicle stability control.

Early research on large truck crash avoidance technologies has been promising. In 1999, the US Department of Transportation (USDOT), in cooperation with large truck manufacturers and motor carriers, launched a series of field operational tests to evaluate several advanced safety technologies including lane departure warning, forward collision warning, and vehicle stability control. The field tests yielded early estimates on potential effectiveness of the systems, including a 31-34 percent reduction in the types of driving conflicts that could result in single-vehicle roadway departure crashes or rollovers for trucks equipped with lane departure warning (Orban et al., 2006). Forward collision warning, when bundled with active cruise control and advanced braking, could reduce by 23-28 percent the types of conflicts resulting in rear-end collisions (Batelle, 2007). More recently, USDOT and the University of Michigan Transportation Research Institute used an expert panel, simulation, and field tests combined with fleet crash data to estimate the safety benefits of tractor-trailer stability control and found approximately 42 percent of relevant rollover and loss-of-control crashes could be prevented by electronic stability control (Woodrooffe et al., 2009).

The early USDOT field operational tests each quantified a reduction in societal costs from reduced property-damage-only, injury, and fatal crashes if large trucks were equipped with the studied technologies (Batelle, 2003, 2007; Orban et al., 2006). Despite the benefits, large truck crash avoidance technologies currently are not mandated by the US government, and introducing them requires interest and cooperation from individual motor carriers that must weigh capital investments with competing business priorities such as market competitiveness. Accordingly, the Federal Motor Carrier Safety Administration computed the benefits and costs specific to both small and large motor carriers (Houser et al., 2009; Murray et al., 2009a, 2009b). Initial system costs, including purchase cost, maintenance, and training, were amortized over 5 years and compared with average costs associated with property-damage-only, injury, and fatal crashes. For each system, including roll stability control, forward collision warning, and lane departure warning, both small and large motor carriers could expect a positive return on investment within the 5-year period.

Jermakian (2009) estimated the maximum potential of four crash avoidance technologies for passenger vehicles to reduce crashes using crash records from the 2004-08 files of the National Automotive Sampling System General Estimates System (NASS GES) and Fatality Analysis Reporting System (FARS). Crash types that possibly could have been prevented or mitigated by a crash avoidance system were counted as relevant for that technology. Crashes were considered not applicable if crash circumstances fell outside the limitations of currently available systems. The purpose of the present research was to extend this previous work by estimating the maximum potential crash reductions for large trucks, accounting for capabilities and limitations of currently available systems. It is important to note that the crash avoidance landscape is rapidly changing, and limitations of current systems may not be limitations of future systems. This study builds on previous research by directly comparing multiple crash avoidance technologies using consistent methodology and the most recent data available. The following four technologies were examined: side view assist for intentional lane changing, forward collision warning/mitigation, lane departure warning/prevention, and vehicle stability control.

Crash counts are estimates of the maximum potential applicability of current technologies. Although these estimates account for relevant crash types and known limitations of current crash avoidance systems, they do not account for potential reductions in effectiveness due to driver interactions

with the systems. That is, the estimates provide the total number of crashes that may be prevented or mitigated if the systems were 100 percent effective in alerting drivers and drivers had the appropriate response 100 percent of the time. Actual effects depend on how drivers accept the technologies and respond to the information provided by the systems and/or the actions taken by the systems. Not all drivers will react appropriately. Drivers may be overwhelmed or annoyed by the warnings, particularly if vehicles are equipped with multiple technologies, allowing for potential simultaneous warnings. If drivers find the systems annoying, they may disable the systems, rendering them ineffective. However, unlike passenger vehicles, motor carriers installing the technologies may require drivers to use the systems and prevent the systems from being disabled. The ultimate effect of the technologies also depends on whether the systems fundamentally alter the driving task or driver behavior.

2. Methods

Data were extracted from two national crash databases maintained by the NHTSA. NASS GES contains information from annual probability samples of police-reported crashes in the United States. Approximately 57,000 crashes are sampled each year. When each case is weighted by the inverse of its selection probability, the yearly sample is representative of about 6 million crashes nationwide (NHTSA, 2008). FARS is an annual census of crashes that occur on public roads and result in the death of a vehicle occupant or other involved party within 30 days of the crash.

All medium and heavy large truck records in the 2004-08 NASS GES and FARS files (GES body style codes 64, 66, 78 and FARS body style codes 61, 62, 63, 64, 66, 71, 72, 78) were merged with the corresponding crash records. Records in GES were weighted by their case weights to produce national estimates. Crashes in GES with maximum injury severity coded as incapacitating (A) or nonincapacitating (B) were classified as severe or moderate injury crashes. To account for missing data in the crash files, imputed data were used whenever available in the GES files.

The first step was to assign each crash to one of nine general crash types: changing lanes, angle, front-to-rear, single-vehicle, head-on, other front-to-front, sideswipe same direction, sideswipe opposite direction, and other. Classification was hierarchical, so any crash with characteristics of more than one category was assigned to the earliest category in the list. For instance, changing lanes took precedence

over all other categories. This categorization implied no meaning other than providing a useful starting point for identifying relevant crashes for each technology.

A lane-changing crash was defined as one where a large truck struck another vehicle while intentionally changing lanes, merging, or turning. This was based on the precrash vehicle movement variables in GES and FARS. The MANEUV_I variable in GES has codes 1=going straight, 2=decelerating in traffic lane, 3=accelerating in traffic lane, 4=starting in traffic lane, 5=stopped in traffic lane, 6=passing or overtaking another vehicle, 7=disabled or parked in travel lane, 8=leaving a parked position, 9=entering a parked position, 10=turning right, 11=turning left, 12=making U-turn, 13=backing up, 14=negotiating a curve, 15=changing lanes, 16=merging, 17=corrective action to a previous critical event, 97=other. The VEH_MAN variable in FARS has codes 1=going straight, 2=slowing or stopping in traffic lane, 3=starting in traffic lane, 4=stopped in traffic lane, 5=passing or overtaking another vehicle, 6=leaving a parked position, 7=parked, 8=entering a parked position, 9=controlled avoidance maneuver, 10,11,12=turning right, 13=turning left, 14=making U-turn, 15=backing up, 16=changing lanes or merging, 17=negotiating a curve, 98=other.

In both files, NHTSA defines crash types using a manner of collision variable. The MANCOL_I variable in GES has codes 0=not a collision with a motor vehicle in transport (i.e., single-vehicle), 1=rear-end, 2=head-on, 3=rear-to-rear, 4=angle, 5=sideswipe same direction, 6=sideswipe opposite direction. In addition, the accident type (ACC_TYPE) variable specifies of how each vehicle was configured in the crash. Codes range from 0 to 98 and allow for a finer breakdown of manner of collision. So, for example, records with manner of collision coded as head-on were classified as head-on only if accident type also was specifically coded as head-on (i.e., values of 50-53). Otherwise, records were classified as other front-to-front collisions.

The MAN_COLL variable in FARS has codes 0=not a collision with a motor vehicle in transport (i.e., single-vehicle), 1=front-to-rear (includes rear-end), 2=front-to-front (includes head-on), 3=front-to-side same direction, 4=front-to-side opposite direction, 5=front-to-side right angle (includes broadside), 6=front-to-side angle (direction not specified), 7=sideswipe same direction, 8=sideswipe opposite direction, 9=rear-to-side, 10=rear-to-rear, and 11=other.

After crashes were classified according to the nine general crash types, they were further separated into nonrelevant and potentially relevant crash types for each of the four crash avoidance technologies. For example, a crash caused by a driver who intentionally changes lanes probably would not be prevented by a lane departure warning system, but may be prevented by a side view assist system. Crashes involving more than two vehicles were classified as nonrelevant in every case because of an inability to clearly define the sequence of events. Once relevant crash types were defined for a given technology, the effects on relevant crash counts of the limitations of systems currently on the market were estimated. Crashes that occurred during inclement weather (e.g., rain, snow) were identified as nonrelevant for all technologies using cameras, radar, or LIDAR (Light Detection And Ranging) sensors. These sensors may not be reliable in poor weather conditions because precipitation can either obscure objects from view of cameras or interfere with reflected radar/LIDAR signals. Crashes that occurred during inclement weather were identified using the atmospheric condition (WEATHER, WEATHER1-2) variables in GES and FARS.

Crashes that involved preimpact braking were identified using the corrective action (P_CRASH3) variable in GES and avoidance maneuver (AVOID) variable in FARS. Crashes that occurred while negotiating a curve were identified using the precrash vehicle movement (MANEUV_I, VEH_MAN) variables in GES and FARS. Crashes that involved speeding were identified using the speed related (SPEEDREL) and violations charged (VLTN_I) variables in GES and driver related factors (DR_CF1-4) and violations charged (VIOLCHG1-3) variables in FARS. Crashes involving loss of control were identified using precrash critical event (P_CRASH2), precrash vehicle control (PCRASH4), and accident type (ACC_TYPE) variables in GES and driver related factors (DR_CF1-4) variable in FARS.

3. Results

There were 42,678 crash records in the 2004-08 NASS GES files that involved at least one large truck. When sampling weights were applied, these records represented approximately 1,920,000 crashes nationwide. There were 20,757 fatal crashes in the 2004-08 FARS files that involved at least one large truck. Thus for the 5-year study period, there was an average of approximately 384,000 crashes per year involving large trucks, of which 4,151 were fatal. Average annual counts for all large trucks for each of the nine general crash types are summarized in Table 1A.

(Table 1A inserted here)

For the 5-year study period, an average of approximately 134,000 crashes annually involved straight trucks, of which 1,213 were fatal. Average annual counts for straight trucks for each of the nine general crash types are summarized in Table 1B.

(Table 1B inserted here)

For the 5-year study period, an average of approximately 179,000 crashes annually involved combination tractor-trailers, of which 3,000 were fatal. Average annual counts for straight trucks for each of the nine general crash types are summarized in Table 1C. All tables stratified by truck type exclude crashes coded in GES or FARS with unknown truck type (GES body style code 78 and FARS body style codes 71, 72, 78). As a result, the total crash counts in Tables 1B and 1C may not sum to the total crash counts in Table 1A.

(Table 1C inserted here)

3.1. *Side view assist systems*

Side view assist systems use cameras or radar sensors to monitor areas to the side of a truck and alert the driver of vehicles in the side blind zones. This technology has the potential to prevent certain crashes involving two vehicles traveling in the same direction where a large truck intentionally changes lanes. Beginning with all large truck crashes that involved intentional lane changes (Table 1A), crashes were subsequently deemed nonrelevant if the crash circumstances would not be addressed by side view assist systems, leaving only certain types of angle, front-to-rear, and sideswipe same direction crashes as potentially relevant (Table 2). For the remaining crash types, system limitations might further reduce the number of applicable crashes (e.g., side view assist systems use sensors that may be unreliable in inclement weather). Taking system limitations into consideration, relevant crashes accounted for 41 percent of lane-changing crashes, or approximately 39,000 crashes per year (Table 2). Such crashes are characterized by a vehicle approaching from behind, so relatively few involve moderate-to-serious injury (2,000) or death (79).

(Table 2 inserted here)

3.2. *Forward collision warning/mitigation systems*

Forward collision warning/mitigation systems use cameras, radar, or LIDAR sensors to monitor the area in front of a truck and alert the driver of a potential collision with a vehicle or object. Some systems require the driver to take action, whereas other systems, if driver action is not taken, may autonomously brake or steer the truck to reduce crash severity or avoid a crash altogether. Most current systems use radar or LIDAR for range assessment and therefore only can detect objects with reflective surfaces. Also, due to limitations associated with identifying the nature of objects reflecting radar or LIDAR signals, most current systems are designed primarily to address front-to-rear crashes with leading vehicles in traffic.

This technology has the potential to prevent certain crashes involving two vehicles traveling in the same direction, where a large truck strikes the rear of the vehicle ahead. Therefore, relevant crashes were a portion of all front-to-rear crashes (Table 1). Crashes were classified by considering the following variables: relation to roadway (REL_RWY in GES, REL_ROAD in FARS), first harmful event (EVENT1_I in GES, HARM_EV in FARS), number of vehicles (VEH_INVL in GES, VE_FORMS in FARS), driver related factors (DR_CF1-4 in FARS), critical event (P_CRASH2 in GES), and avoidance maneuver (DRMAN_AV in GES, AVOID in FARS).

Beginning with all front-to rear large truck crashes (Table 1), crashes were deemed nonrelevant if the crash circumstances would not be addressed by forward collision/mitigation systems (Table 3). Collisions off roadways were classified as nonrelevant for two reasons: (1) detection of objects may be unreliable given the environment and possible erratic path of the vehicle, and (2) a driver who has departed the roadway and roadside may not be in sufficient control of the vehicle to respond to warnings. Collisions preceded by the successful avoidance of an object in the vehicle's path also were classified as nonrelevant. The erratic path of a truck in the midst of an avoidance maneuver seems likely to hinder the detection of obstacles. These types of avoidance maneuvers also may be prompted by forward collision warnings. Collisions preceded by vehicle mechanical problems or road defects also were classified as nonrelevant. Such vehicle or road problems may make it difficult for the driver to take appropriate action to avoid the crash.

If a driver recognizes the threat of collision and initiates braking, then the warning/mitigation system may be unnecessary. For this reason, crashes with evidence of braking by the striking vehicle were classified as possibly relevant. Estimates of relevant crash counts were calculated both with and without evidence of braking. Thus a range of estimates for crashes relevant to forward collision warning/mitigation systems were presented.

Relevant crash types accounted for 31-37 percent of large truck front-to-rear crashes (Table 1A), or approximately 26,000-31,000 crashes per year (Table 3). Of these, 2,000-3,000 involved nonfatal injuries and 98-115 involved fatal injuries. In approximately 83 percent of these crashes, the driver did not brake to prevent the crash.

(Table 3 inserted here)

3.3. Lane departure warning/prevention systems

Lane departure warning systems use cameras to track vehicle position within the lane, alerting a driver if the truck is in danger of inadvertently straying across lane markings. This technology is probably not relevant to intentional lane-changing, angle, or front-to-rear crashes (Table 1A). It is, however, relevant to the other crash types including single-vehicle, head-on, and sideswipe crashes, if the truck inadvertently drifted out of the lane. Beginning with each of these crash types (Table 1A), crashes subsequently were deemed nonrelevant if the crash circumstances would not be addressed by lane departure warning systems (Tables 4A-B). Maneuvers that successfully avoided an obstacle in the truck's path were not classified as intentional lane changes, but they were not inadvertent either. Crashes involving such maneuvers were deemed nonrelevant to lane departure warning/prevention technology. Collisions preceded by vehicle mechanical problems or road defects also were classified as nonrelevant. Such vehicle or road problems may make it difficult for a driver to take appropriate action to avoid the crash. Crashes caused by non-large trucks straying across lane markings were deemed nonrelevant because the focus of the analysis was large truck warning systems. Finally, single-vehicle run-off-road crashes on interstates were not relevant because most interstates have edge-line rumble strips that alert drivers to unintentional lane departures, making lane departure warning systems redundant.

Given current system limitations, single-vehicle, head-on, and sideswipe crashes were assumed nonrelevant if the speed limit was below 40 mph or there was snow on the roadway. Current lane departure warning systems do not operate under a speed threshold of approximately 40 mph and will not provide reliable warnings if lane markers are absent, as is common on roads with speed limits below 40 mph, or obscured by snow on the roadway or heavy precipitation.

Single-vehicle crashes occurring on the roadway typically were animal/object strikes or noncollision events such as a rollover or jackknife. These crashes were classified as nonrelevant because the truck did not inadvertently stray from the travel lane. Single-vehicle crashes were categorized as loss of control if the driver lost control of the truck due to environmental conditions, overcorrecting, or reckless driving. These also were considered nonrelevant.

A lane departure warning may be too late to be effective if a driver is speeding. For this reason, crashes with evidence of speeding were classified as possibly relevant. Tables 4A-4B include estimates of relevant crash counts both with and without evidence of speeding. Thus each table provides a range of estimates for crashes relevant to lane departure warning/prevention systems.

Relevant crash types accounted for 3 percent of large truck single-driver crashes (Table 1A), or approximately 3,000 crashes per year (Table 4A). Of these, approximately 1,000 involved nonfatal injuries and 48-60 involved fatal injuries.

(Table 4A inserted here)

Relevant crash types accounted for 10 percent of large truck head-on, sideswipe same direction, and sideswipe opposite direction crashes (Table 1A), or approximately 6,000-7,000 crashes per year (Table 4B). Of these, approximately 1,000 involved nonfatal injuries and 179-187 involved fatal injuries.

(Table 4B inserted here)

Combining Tables 4A and 4B, approximately 9,000-10,000 large truck crashes annually were relevant to lane departure warning/prevention systems. Of these, 1,000 involved nonfatal injuries and 227-247 involved fatal injuries.

3.4. Vehicle stability control systems

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. For large trucks, there are two

main types: roll stability control (RSC) and electronic stability control (ESC). RSC intervenes when lateral acceleration on the truck and/or trailer puts the truck at risk of rollover. ESC incorporates roll stability with directional stability to prevent understeer or oversteer conditions that could result in loss-of-control crashes. ESC requires additional sensors but also provides more sophisticated interventions, potentially allowing for earlier detection and intervention in a wider range of crash scenarios.

Single-vehicle crashes involving rollover were considered relevant for RSC systems. These crashes accounted for 12 percent of large truck single-vehicle crashes (Table 1A), or approximately 13,000 crashes per year (Table 5).

(Table 5 inserted here)

For full ESC, relevant crashes were defined as single-vehicle crashes involving reported loss of control prior to the crash or occurrence of a jackknife. Relevant crash types accounted for an additional 10,000 large truck single-vehicle crashes for a total of 10 percent of the crashes in Table 1A, or approximately 23,000 crashes per year (Table 5).

Vehicle stability controls systems also may be relevant to some multiple-vehicle crashes. Similar to all other technologies, relevant multiple-vehicle crashes were limited to those involving two vehicles due to an inability to clearly define the sequence of events. Two-vehicle crashes were considered relevant to stability control systems if a rollover or jackknife was the first harmful event or the truck experienced loss of control prior to the crash. There were 8,000 two-vehicle crashes relevant to stability control systems. Of these, 2,000 involved nonfatal injuries and 59 involved fatal injuries. Combining two-vehicle crashes with relevant single-vehicle crashes (Table 5), approximately 31,000 large truck crashes annually were relevant to stability control systems. Of these, 7,000 involved nonfatal injuries and 439 involved fatal injuries.

3.5. Combined effect

There was some degree of overlap in the relevant crashes of Tables 2-5. As a final step, crashes were identified that were potentially relevant to any of the four technologies without redundancies. A combination of all four technologies could prevent or mitigate (without double counting) up to 107,000 crashes each year, including 12,000 nonfatal injury crashes and 835 fatal crashes (Table 6).

(Table 6 inserted here)

3.6. *Straight truck crashes*

Results presented in Tables 2-6 include both straight trucks and combination tractor trailers. For the 5-year study period, an average of approximately 134,000 crashes annually involved straight trucks, of which 1,213 were fatal. A combination of all four technologies could prevent or mitigate (without double counting) up to 38,000 straight truck crashes each year, including 4,000 nonfatal injury crashes and 235 fatal crashes (Table 7).

(Table 7 inserted here)

3.7. *Combination tractor-trailer crashes*

For the 5-year study period, an average of approximately 179,000 crashes annually involved combination tractor-trailers, of which 3,000 were fatal. A combination of all four technologies could prevent or mitigate (without double counting) up to 57,000 tractor-trailer crashes each year, including 7,000 nonfatal injury crashes and 599 fatal crashes (Table 8).

(Table 8 inserted here)

4. **Discussion**

More than one-quarter of the nearly 400,000 police-reported large truck crashes each year are potentially relevant to at least one of four crash avoidance technologies: side view assist, forward collision warning/mitigation, lane departure warning/prevention, or vehicle stability control. Side view assist has the greatest potential to prevent or mitigate crashes of any severity, potentially preventing or mitigating up to 39,000 crashes, or 10 percent, of the 384,000 police-reported large truck crashes each year. These crashes involve vehicles traveling in the same direction, and relatively few involve moderate-to-serious injury or fatality. Vehicle stability control is another promising technology, with the potential to prevent or mitigate up to 31,000 crashes each year including more serious crashes — up to 7,000 moderate-to-serious injury crashes and 439 fatal crashes per year. Vehicle stability control could prevent or mitigate up to 20 and 11 percent of moderate-to-serious injury crashes and fatal crashes, respectively.

Vehicle stability control for large trucks is offered as either RSC or full ESC, which incorporates roll control with directional control. ESC is more expensive, and this may cause motor carriers to forego the system in favor of less expensive RSC. However, ESC systems are more sophisticated in their

sensing and interventions and, therefore, may address a broader range of crash scenarios. RSC alone is applicable to 41 percent, or 13,000, of the crashes that would be applicable to a full ESC system. However, due to the large number of fatal and injury crashes involving rollover, RSC potentially can prevent or mitigate a large proportion of more serious crashes — 65 and 76 percent, respectively — that are applicable to ESC. The fact that RSC-relevant crashes constitute a large fraction of serious ESC-relevant crashes should not be construed to mean that RSC is a better value because the effectiveness of either system's ability to prevent crashes is unknown. It is possible that ESC may prevent rollovers, like those preceded by loss of control events, that RSC cannot. Both RSC and ESC address unstable vehicle dynamics, which are complex events that may be difficult to identify using datasets such as FARS and GES, making the true contributions of RSC versus ESC difficult to estimate and outside the scope of this study.

Straight trucks are involved in more than 40 percent of police-reported large truck crashes and almost 30 percent of fatal crashes. Despite the prevalence of straight truck crashes, some important safety regulations for large trucks exclude or exempt straight trucks. Crash avoidance technologies have the potential to prevent or mitigate crashes involving both truck categories, including as many as 38,000 and 57,000 police-reported crashes and 235 and 599 fatal crashes per year for straight trucks and combination tractor-trailers, respectively. Straight trucks and combination tractor-trailers vary in both use patterns and vehicle dynamics, resulting in different types of crashes. Straight trucks are involved in proportionally more front-to-rear crashes, whereas tractor-trailers are involved in more lane-changing and sideswipe same direction crashes. Despite this difference, both truck types would benefit from the same crash avoidance technologies, even though the systems with the greatest potential for saving lives are not exactly the same as those with the greatest potential for preventing the most crashes. Side view assist, forward collision warning, and vehicle stability control each are potentially applicable to 8-9 percent of the 134,000 police-reported straight truck crashes each year and 8-12 percent of the 179,000 combination tractor-trailer crashes. Vehicle stability control has the largest potential of the four technologies to prevent or mitigate the most serious crashes involving either straight trucks or combination tractor-trailers — 10 percent of fatal tractor-trailer crashes and 11 percent of fatal crashes

involving straight trucks. Lane departure warning addresses another 6 percent of fatal crashes involving both truck types.

The crash counts listed in Tables 2-8 provide the maximum potential or applicability of each technology. However, based on the USDOT field operational tests of early systems, actual reductions in crashes likely will be much smaller. The effectiveness of early forward collision warning systems in reducing conflicts or crashes has been estimated at 23-28 percent (Batelle, 2007). When these estimates are applied to the maximum potential crash reductions, a more realistic expectation is a reduction of 7,000-9,000 large truck front-to-rear crashes annually rather than the 26,000-31,000 estimated above. For vehicle stability control, an estimated effectiveness of 42 percent (Woodrooffe et al., 2009) for tractor-trailers would result in a reduction of 7,000 tractor-trailer crashes annually compared with the 18,000 potentially applicable crashes.

Crash avoidance technologies are becoming increasingly available on large truck models as either factory installed options or aftermarket additions, and they continue to become more sophisticated. Some forward collision warning systems, after flashing an indicator light and/or sounding an alarm to warn the driver of an imminent collision, initiate automatic braking. System improvements will not add to the list of potentially relevant crashes, but they could increase the percentage of such crashes that actually will be prevented. Many of the limitations of currently available systems may not be limitations of future systems (e.g., they may function more reliably in inclement weather). New forward collision warning systems may use multiple sensors and advanced algorithms to more precisely identify and characterize a broader range of potential hazards such as stationary objects or pedestrians.

Each of the four crash avoidance technologies studied shows potential for reducing large truck crashes. This would have safety benefits for motor carriers and all road users. However, there are several challenges to equipping large trucks with crash avoidance features. The average life span of large trucks is relatively long. So even under ideal circumstances, this may result in significant lag in fleet penetration. The technologies for large trucks currently are not mandated in the United States. Early adopters tend to be larger and more safety conscious motor carriers, despite evidence of positive return on investment (Houser et al., 2009; Murray et al., 2009a, 2009b). Large trucks are a substantial investment. Even though advanced technologies are only a fraction of the cost of a truck, equipping them

requires additional capital investment that may put motor carriers, particularly smaller carriers, at a competitive disadvantage. Some tractor manufacturers are supporting the use of ESC by offering it as a standard feature on all new tractors. Such actions from manufacturers are promising, but encouraging motor carriers to adopt these technologies without a government mandate may require broader, more creative incentives such as tax credits.

Encouraging carriers to equip their fleets with crash avoidance technologies is the first step. Once equipped, however, it is not known how carriers will implement the technologies, train their drivers, monitor drivers' use of the systems, and assess the technologies' effects on driving performance and crashes. Motor carriers carry responsibilities beyond the initial purchase of equipment. They must maintain the equipment, establishing training programs, and set guidelines and rules for the technologies' use. It also is not known how drivers will interact with the systems. Surveys of drivers of early forward collision and lane departure warning systems and roll stability advisor indicated that, in general, drivers view the systems positively and prefer to drive trucks equipped with the systems (Batelle, 2003, 2007; Orban et al., 2006). Many drivers reported that, despite some nuisance warnings, the systems reduced workload and improved driving through increased alertness, lane-keeping ability, and following distance. Nuisance warnings or unnecessary alerts may cause drivers to mistrust the systems and either ignore them or turn them off. Unlike passenger vehicles, however, motor carriers can mandate and monitor drivers' use of the technologies. On the other hand, it is possible that drivers with too much faith in the systems may be less observant or drive more aggressively, pointing to the importance of monitoring use. Driver interaction with crash avoidance systems is the subject of ongoing field, test track, and simulator studies. Researchers are determining the best way to warn drivers of dangerous situations and assist in correcting errors. It is important to consider that large truck drivers may interact differently with crash avoidance systems compared with passenger vehicle drivers, pointing to the need for designing and evaluating systems and interfaces specific to the large truck environment (Campbell et al., 2007). With all of the many considerations, the true test of the effectiveness of these systems will not be known until sufficient numbers are on the road gaining real-world experience.

The current study has several limitations. Estimates were based on two databases, NASS GES and FARS. Both databases rely on police-reported data, which may include some degree of

misclassification of key variables that may affect the applicability of crashes within a given category. The databases may not contain sufficient detail on vehicle, driver, or environmental conditions to determine true applicability of the technologies. Current lane departure warning systems rely on lane markings to determine vehicle position within the lane. There is no information with sufficient detail in the NASS GES and FARS data sets to determine whether lane markings are present. So it was necessary to assume that lane markings are present on roads with speed limits of 40 mph and higher to determine applicability of lane departure warning systems. Warning systems require actions from drivers, but driver impairments such as distraction, alcohol use, medical issues, and drowsiness were not considered. A warning system might alert a distracted driver to an impending crash, but the reaction of an impaired driver to such a system is not well understood and beyond the scope of the study. Finally, capabilities of crash avoidance technologies vary from system to system. Although attempts were made to account for the majority of systems currently available, some systems may have capabilities beyond those described or limitations not well characterized.

Acknowledgment

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Table 1A

Average annual crashes involving large trucks during 2004-08*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Lane-changing/merging/turning	97,000	6,000	444
Angle (without lane-changing)	35,000	6,000	783
Front-to-rear (without lane-changing)	84,000	9,000	681
Single-vehicle (without lane-changing)	102,000	8,000	850
Front-to-front head-on (without lane-changing)	3,000	1,000	492
Front-to-front other (without lane-changing)	1,000	<1,000	126
Sideswipe same direction (without lane-changing)	48,000	3,000	203
Sideswipe opposite direction (without lane-changing)	13,000	3,000	522
Other (e.g., rear-to-rear, end-swipe, unknown)	<1,000	<1,000	48
	384,000	37,000	4,151

*Columns may not sum to total due to rounding

Table 1B

Average annual crashes involving straight trucks during 2004-08*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Lane-changing/merging/turning	30,000	2,000	141
Angle (without lane-changing)	18,000	3,000	256
Front-to-rear (without lane-changing)	37,000	4,000	169
Single-vehicle (without lane-changing)	28,000	3,000	272
Front-to-front head-on (without lane-changing)	1,000	<1,000	162
Front-to-front other (without lane-changing)	1,000	<1,000	23
Sideswipe same direction (without lane-changing)	14,000	1,000	44
Sideswipe opposite direction (without lane-changing)	5,000	1,000	134
Other (e.g., rear-to-rear, end-swipe, unknown)	<1,000	<1,000	11
	134,000	14,000	1,212

*Columns may not sum to total due to rounding

Table 1C

Average annual crashes involving combination tractor-trailers during 2004-08*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Lane-changing/merging/turning	54,000	4,000	290
Angle (without lane-changing)	14,000	3,000	524
Front-to-rear (without lane-changing)	36,000	5,000	511
Single-vehicle (without lane-changing)	40,000	5,000	573
Front-to-front head-on (without lane-changing)	1,000	<1,000	328
Front-to-front other (without lane-changing)	1,000	<1,000	103
Sideswipe same direction (without lane-changing)	28,000	2,000	161
Sideswipe opposite direction (without lane-changing)	6,000	2,000	388
Other (e.g., rear-to-rear, end-swipe, unknown)	<1,000	<1,000	36
	179,000	21,000	2,914

*Columns may not sum to total due to rounding

Table 2

Annual intentional lane-change large truck crashes relevant to side view assist systems*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
All intentional lane-change crashes	97,000	6,000	445
Nonrelevant crash circumstances			
Single-vehicle	17,000	1,000	111
More than two vehicles	2,000	<1,000	44
Front-to-front	<1,000	<1,000	35
Angle, different travel directions	32,000	2,000	106
Front-to-rear, striking	2,000	<1,000	11
Sideswipe opposite direction	<1,000	<1,000	52
(Subtotal nonrelevant crashes)	(54,000)	(4,000)	(359)
Crashes not addressed by current system limitations			
Angle, same travel direction, inclement	2,000		0
Angle, unknown travel direction, inclement	<1,000		0
Front-to-rear, struck, inclement	<1,000		4
Sideswipe same direction, inclement	2,000		2
Other, inclement	<1,000		1
(Subtotal system limitations)	(4,000)	(<1,000)	(7)
Crashes relevant to current systems			
Angle, same travel direction, clear	17,000	1,000	1
Angle, unknown travel direction, clear	<1,000	<1,000	1
Front-to-rear, struck, clear	2,000	<1,000	33
Sideswipe same direction, clear	20,000	1,000	39
Other, clear	<1,000	<1,000	5
Total relevant	39,000	2,000	79
Percent of intentional lane-change crashes	41%	35%	18%
Percent of annual large truck crashes	10%	6%	2%

*Columns may not sum to total due to rounding; percentages calculated using unrounded numbers

Table 3

Annual front-rear large truck crashes relevant to forward collision warning systems*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
All front-to-rear crashes	84,000	9,000	681
Nonrelevant crash circumstances			
Off roadway	<1,000	<1,000	33
More than two vehicles	13,000	2,000	210
Vehicle/road defect	<1,000	<1,000	2
Avoidance maneuver	<1,000	<1,000	48
Struck by non-large truck	35,000	3,000	262
(Subtotal nonrelevant crashes)	(49,000)	(6,000)	(555)
Crashes not addressed by current system limitations			
Front-to-rear, other, with braking, inclement	1,000		3
Front-to-rear, other, without braking, inclement	3,000		8
(Subtotal system limitations)	(4,000)	(<1,000)	(11)
Crashes possibly relevant or relevant to current systems			
Possibly relevant			
Front-to-rear, other, with braking, clear	5,000	1,000	17
Relevant			
Front-to-rear, other, without braking, clear	26,000	2,000	98
Total relevant	31,000	3,000	115
Percent of front-to-rear crashes	37%	29%	17%
Percent of annual large truck crashes	8%	7%	3%

*Columns may not sum to total due to rounding; percentages calculated using unrounded numbers

Table 4A

Annual single-vehicle large truck crashes relevant to lane departure warning systems*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
All single-vehicle crashes	102,000	8,000	850
Nonrelevant crash circumstances			
On roadway	33,000	3,000	382
Run off road, vehicle/road defect	2,000	1,000	8
Run off road, avoidance maneuver	53,000	3,000	121
Run off road, loss of control	2,000	<1,000	17
Run off road, on interstate highway	1,000	<1,000	63
(Subtotal nonrelevant crashes)	(92,000)	(7,000)	(591)
Crashes not addressed by current system limitations			
Speed limit < 40 mph	6,000		186
Snow on roadway	<1,000		4
Other, speeding, inclement	<1,000		2
Other, without speeding, inclement	<1,000		7
(Subtotal system limitations)	(7,000)	(<1,000)	(199)
Crashes possibly relevant or relevant to current systems			
Possibly relevant			
Other, speeding, clear	<1,000	<1,000	12
Relevant			
Other, without speeding, clear	3,000	<1,000	48
Total relevant	3,000	1,000	60
Percent of single-vehicle crashes	3%	8%	7%
Percent of annual large truck crashes	1%	2%	1%

*Columns may not sum to total due to rounding; percentages calculated using unrounded numbers

Table 4B

Annual head-on, sideswipe same direction, and sideswipe opposite direction large truck crashes relevant to lane departure warning systems*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
All head-on crashes	3,000	1,000	492
All sideswipe same direction crashes	48,000	3,000	203
All sideswipe opposite direction crashes	13,000	3,000	522
(Total)	(64,000)	(7,000)	(1,218)
Nonrelevant crash circumstances			
More than two vehicles	4,000	1,000	233
Vehicle/road defect	2,000	<1,000	9
Avoidance maneuver	1,000	<1,000	339
Non-truck out of lane	46,000	5,000	399
(Subtotal nonrelevant crashes)	(53,000)	(6,000)	(980)
Crashes not addressed by current system limitations			
Speed limit < 40 mph	3,000		18
Snow on roadway	<1,000		6
Other, speeding, inclement	<1,000		5
Other, without speeding, inclement	1,000		22
(Subtotal system limitations)	(5,000)	(<1,000)	(51)
Crashes possibly relevant or relevant to current systems			
Possibly relevant			
Other, speeding (possibly relevant)	<1,000		8
Relevant			
Other, without speeding (relevant)	6,000		179
Total relevant	7,000	1,000	187
Percent of head-on and sideswipe crashes	4%	7%	15%
Percent of annual large truck crashes	2%	1%	4%

*Columns may not sum to total due to rounding; percentages calculated using unrounded numbers

Table 5

Average annual single-vehicle large truck crashes relevant to stability control systems*

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
All single-vehicle crashes**	119,000	9,000	967
Nonrelevant crash circumstances			
Non-rollover, non-loss of control	96,000	3,000	587
(Subtotal nonrelevant crashes)	(96,000)	(3,000)	(587)
Crashes relevant to current roll stability control systems			
Rollover, vehicle/road defect	1,000	<1,000	8
Rollover, avoidance maneuver	7,000	2,000	98
Rollover, negotiating a curve	2,000	1,000	84
Rollover, lane change or turn	1,000	<1,000	6
Other rollover	2,000	1,000	134
(Subtotal relevant to RSC)	(13,000)	(5,000)	(330)
Crashes additionally relevant to current electronic stability control systems			
Loss of control, vehicle/road defect	2,000	<1,000	4
Other loss of control	5,000	<1,000	21
Loss of control, jackknife	3,000	<1,000	25
(Subtotal additionally relevant to ESC)	(10,000)	(1,000)	(50)
Total relevant	23,000	6,000	380
Percent of single-vehicle crashes	19%	62%	39%
Percent of annual large truck crashes	6%	15%	9%

*Columns may not sum to total due to rounding; percentages calculated using unrounded numbers

**All crashes involving only one vehicle, including lane-change crashes

Table 6

Annual large truck crashes that potentially could be prevented or mitigated by four technologies

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Side view assist	39,000	2,000	79
Forward collision warning	31,000	3,000	115
Lane departure warning	10,000	1,000	247
Roll stability control	13,000	5,000	335
Electronic stability control	31,000	7,000	439
Total unique crashes	107,000	12,000	835
Percent of annual large truck crashes	28%	34%	20%

Table 7

Annual straight truck crashes that potentially could be prevented or mitigated by four technologies

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Side view assist	13,000	1,000	21
Forward collision warning	12,000	1,000	22
Lane departure warning	3,000	<1,000	67
Roll stability control	4,000	2,000	108
Electronic stability control	11,000	2,000	135
Total unique crashes	38,000	4,000	235
Percent of annual straight truck crashes	28%	32%	19%

Table 8

Annual combination tractor-trailer crashes that potentially could be prevented or mitigated by four technologies

Crash type	All crashes	Nonfatal injury crashes (A or B)	Fatal crashes
Side view assist	22,000	1,000	55
Forward collision warning	14,000	2,000	95
Lane departure warning	6,000	1,000	181
Roll stability control	8,000	3,000	222
Electronic stability control	18,000	4,000	295
Total unique crashes	57,000	7,000	599
Percent of annual tractor-trailer crashes	32%	36%	21%