Toward Zero Deaths "Safer Vehicles" White Paper: Expanded Truck Section

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Note: The AASHTO-sponsored program, *Toward Zero Deaths: A National Strategy on Highway Safety* (http://safety.transportation.org/activities.aspx) identified and compiled challenges, opportunities, and actions relating to major reductions in the U.S. traffic crash toll. There were ten white papers on various safety areas and initiatives. Below is an expanded version of the heavy truck section from the "Safer Vehicles" white paper by Richard Retting and Ronald R. Knipling.

LARGE TRUCK CRASH COUNTERMEASURES

There are more than half a million registered U.S. trucking companies, and nearly 70 percent of all consumer, commercial, and industrial goods are delivered by trucks. In recent decades, commercial vehicle mileage has increased faster than the population, the economy, and general vehicle mileage. These trends are expected to continue in the decades ahead; the U.S. DOT predicts that truck freight will double by 2035.

The Large Truck Safety Picture

Large trucks are defined as those with gross vehicle weight ratings (GVWR) of greater than 10,000 pounds; 80-90 percent of their crashes involve heavy trucks with GVWRs of greater than 26,000 pounds. The two major large truck configurations are combination-unit trucks (typically tractor-semitrailers) and single-unit trucks (also called straight trucks). Combination-unit trucks (CTs) are typically in long-haul service whereas most single-unit trucks (STs) are short-haul. In 2008, CTs had more than five times the average annual VMT of STs. Greater mileage means greater exposure to crash risk. In 2008, CTs were 25 percent of registered trucks, compiled 63 percent of truck VMT, and were 74 percent of trucks involved in fatal crashes (Craft, 2010).

In all, 4,229 people were killed in 3,733 fatal crashes involving large trucks in 2008. This was 11 percent of the 37,261 total traffic crash fatalities for the year. Truck crash fatalities in 2008 were down 12 percent from 2007 while truck VMT was roughly steady. The number of trucks involved in fatal crashes followed a parallel decline. Thus, from 2007 to 2008 the large truck fatal crash involvement rate also dropped 12 percent, from 2.04 to 1.79 per 100 Million VMT. This was the most impressive single year improvement in a decades-long decline in truck fatal crash rate. Figure 3 shows declines in large truck and passenger vehicle fatal crash rates from 1975 through 2008. Although the rates are converging, the 2008 large truck fatal crash rate was still 23 percent higher than the passenger car rate. Most impressive in Figure 3, however, is the long-term declines in both rates. From its peak in 1979, the large truck fatal crash rate has declined by 68 percent to the 2008 rate.

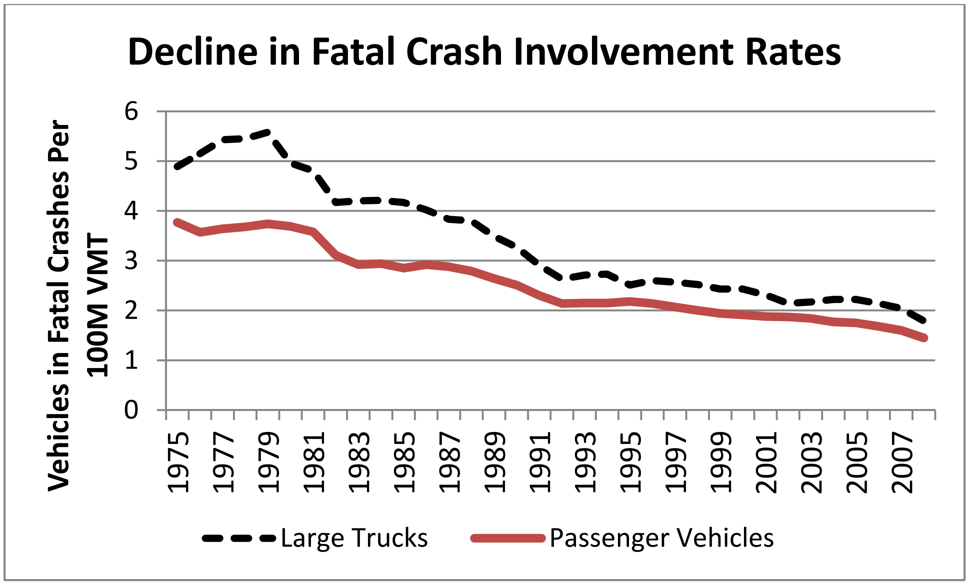

Figure 3. Trends of fatal crash vehicle involvement rates (per 100M VMT) for large trucks and passenger vehicles (cars, vans, and light trucks), 1975 to 2008. **Source: FMCSA (2010)**

Although fatal crash rates are persistently higher for large trucks than for passenger vehicles, the opposite is true for less severe crashes. For example, the 2008 large truck injury crash involvement rate was 71 percent lower than the passenger car rate. One safety advantage trucks have over cars is the fact that a much larger percentage of their mileage is on Interstates and other divided highways with relatively low crash risks.

Truck crashes tend to be more severe than those involving passenger vehicles. In 2008, 1.0 percent of large truck crashes resulted in a fatality, versus 0.5 percent for passenger vehicle crashes. The majority of fatalities and injuries from large truck crashes occur to persons outside the truck. These are mostly occupants of other vehicles, but include pedestrians and bicyclists. Roughly two-thirds of all harm (human and material) in large truck crashes occurs outside the truck (Wang et al., 1999). Of the 4,229 fatalities in 2008 resulting from crashes involving large trucks, 75 percent were occupants of another vehicle, 9 percent were pedestrians or bicyclists, and 16 percent were large truck occupants.

Interstate buses (motor coaches) are also considered to be commercial vehicles and are regulated in similar ways to large trucks. The two primary motor coach operations types are charter and scheduled service (intercity). In 2008 there were 151,000 registered motor coaches and 52 fatalities in their crashes. Though motor coach crashes are highly publicized when there are multiple victims, their overall crash and fatal crash rates are low.

The human and economic cost of large truck crashes is significant. Zaloshnja & Miller (2007) calculated the average comprehensive cost of a police-reported crash involving a large truck to be $91,112 in 2005 dollars. These costs encompass tangible economic human and material consequences, including medical and emergency services, property damage, and lost productivity. They also include the monetized value of pain, suffering, and quality-of-life reduction. An earlier study (Zaloshnja and Miller, 2002) estimated the annual total comprehensive U.S. costs for large truck crashes to be $20 billion annually in 2000 dollars.

Truck drivers make many of the same kinds of driving errors as do light vehicle drivers, but their crashes are less likely to involve extreme unsafe driving acts such as reckless driving and alcohol use (Knipling, 2009). Among all crashes involving a truck and a lighter vehicle, principal fault seems to be more-or-less evenly divided (Council et al., 2003). For more severe crashes, however, principal fault (i.e., the critical driver error or other failure precipitating the crash) shifts strongly toward light vehicle drivers. In the FMCSA/NHTSA Large Truck Crash Causation Study (LTCCS) involving serious injury crashes, trucks were at-fault (assigned the "Critical Reason") in 40 percent of their multi-vehicle crash involvements. This percentage varied greatly depending on crash severity, as follows:

- "B" (non-incapacitating injury): truck 46 percent, other vehicle 54 percent
- "A" (incapacitating injury): truck 37 percent, other vehicle 63 percent
- "K" (fatal injury): truck 23 percent, other vehicle 77 percent.

Although many serious large truck crashes are precipitated by the errors of other drivers, most vehicle-based truck crash countermeasures are designed to improve the safety performance of trucks and/or to intervene to prevent crashes caused by truck driver errors. Motor carriers have the greatest economic incentive to reduce those crashes resulting in high financial liability. Reducing truck-striking rear-end crashes, for example, is a top priority for fleets even though only about 5 percent of truck-light vehicle fatalities result from this crash scenario (Knipling, 2009; Craft, 2010).

The Importance of Large Trucks in Vehicle Technology Advancement

Large truck crashes are important in their own right because of their human and economic consequences – 4,229 fatalities in 2008. Another reason for their importance is the *opportunity* they provide for the advancement of vehicle-based and other safety technologies. Truck fleets are often the ideal testbed for the testing and implementation of advanced countermeasures. This is because of operational setting in which truck driving occurs, and because of the inherently superior economic prospects for safety technologies in the long-haul trucking environment.

Operational setting. Truck driving is supervised. Truck transport occurs within a government regulatory and enforcement regime which prescribes driver, vehicle, and route characteristics. More importantly, successful trucking companies closely monitor and manage their vehicles, drivers, and operations. Thus, they can be ideal testbeds for many safety interventions. Trucks are individually configured at the factory, so they can be built to buyer or researcher specifications. Most retrofit devices are also more easily installed on trucks than on light vehicles. Many large and safety-progressive trucking companies electronically monitor driving using onboard recorders. These onboard recorders can provide rich data on driving, incidents, and vehicle performance. Data can be downloaded at carrier terminals or transmitted wirelessly through mobile communications. There can even be wireless data links to roadside inspection and enforcement. Finally, most fleet drivers are conscientious professionals committed to safety and supportive of potential improvements.

Superior economic prospects. Economic prospects for new safety systems are often inherently superior for long-haul trucks than for lighter vehicles. Ironically, this is because long-haul trucks are inherently *high-risk vehicles*, even though they have lower overall crash rates per VMT than light vehicles, and even though truck drivers generally engage in fewer driving misbehaviors (Knipling, 2009). The elevated crash risk of long-haul trucks comes from the high average severity of truck crashes and trucks' high annual and lifetime mileage exposures.

Average human and economic harm in CT crashes is at least twice those of light vehicle crashes (Zaloshnja and Miller, 2007; Wang et al., 1999). More importantly, CTs have very high annual mileage exposure. In 2008, average VMTs for different vehicle types were 11,432 for light vehicles, 12,362 for STs, and 64,764 for CTs. Plus, trucks have somewhat longer average operational lives than do light vehicles. These factors drive up life cycle crash costs for CTs to levels far above those of other vehicles. One direct comparison (Wang et al., 1999) found CT life cycle costs (all crashes regardless of fault and inclusive of all crash consequences) to be about five times those of STs, light trucks/vans, passenger cars, and motorcycles. The life cycle crash costs of *one* CT were estimated to be about $70,000 in economic loss alone, and $162,000 in comprehensive costs including monetized values of pain, suffering, and quality-of-life reduction.

These same differences in CT, ST, and passenger vehicle crash experience are seen in annual crash fatality statistics. Table 2 shows 2008 fatal crash involvement *rates* (per 100M VMT) and *likelihoods* (per million registered vehicles) for these three vehicle types. The CT fatal crash rate is 1.4 times that of STs and 1.3 times that of passenger vehicles. The big difference, though, is in fatal crash likelihood per one million vehicles. Here, the CT value of 1,253 fatal crash involvements per one million vehicles is 7.2 times that of STs and 7.6 times that of passenger vehicles. For a vehicle-based crash countermeasure that operate continuously, the most-pertinent metric for assessing benefits is the likelihood it will be activated to prevent a crash.

Table 2. 2008 Fatal Crash Involvement Rates and Likelihoods for Three Vehicle Types

Vehicle Type: / Statistic:	CTs	STs	PVs
Fatal Crash Involvement Rate Per 100M VMT	**1.94**	**1.40**	**1.45**
Rate Ratio: CT to Other Vehicle Type		**1.4×**	**1.3×**
Fatal Crash Involvement Likelihood Per Million Vehicles	**1,253**	**173**	**165**
Likelihood Ratio: CT to Other Vehicle Type		**7.2×**	**7.6×**

These statistics show the high relative risks inherent in long-haul CT operations, but also the unique crash prevention *opportunity* associated with improving CT safety. Other factors being equal, a typical safety device installed on a CT and lasting its entire life will have much greater per-unit benefits than the same device installed on other vehicle types. New safety system applications can be cost-beneficial sooner on CTs, and then refined to later be cost-beneficial for other vehicle types. *Total* safety benefits will almost always be greatest for passenger vehicles, but *per-unit* benefits for most similar systems will continue to be greater for CTs. This advantage generally does not apply to STs because their mileage exposures are more like those of passenger vehicles. Thus, for physical, operational, economic, and public safety reasons, CTs can and should be the hosts for the greatest number and variety of vehicle safety systems.

Overview of Truck Safety Systems

Large Truck Crash Countermeasures Addressed

- **Improved Brakes/Shorter Stopping Distances**
- **Electronic Stability Control (ESC)**
- Roll Stability Control (RSC)
- **Forward Collision Warning Systems (FCWS)**
- **Side-Object Detection Systems (SODS)**
- Backing Collision Warning Systems
- **Lane Departure Warning Systems (LDWS)**
- **Onboard Safety Monitoring (OBSM)**
- **Driver Alertness Monitoring**
- Electronic Onboard Recorders (EOBRs)
- Electronic Data Recorders (EDRs)
- Vehicle Condition Monitoring (e.g., Tire Pressure)
- Automated Transmissions
- Speed Limiters
- Truck-Specific Navigation Aids

- Enhanced Trailer Conspicuity
- Enhanced Trailer Rear Lighting/Warnings
- Video Mirrors
- Collision Aggressivity Reductions
- Larger Trucks

Bold = Judged as priorities by the authors.

This section revisits some safety systems described for passenger vehicles, but with a focus on their use with large trucks. It also describes various systems principally or exclusively applicable to trucks. The textbox to the right lists specific countermeasures which will be addressed. Those in **bold** are regarded by the authors as having the greatest life-saving potentials. This judgment is based on the size of the crash problem they address and the degree to which their potential effectiveness and positive cost-benefits have been demonstrated. Systems not shown as priority should not be ignored, however, because they may still be safety- and cost-beneficial. There is no limit to the number of large truck crash countermeasures which could be implemented. Instead, each countermeasure should be evaluated based on its practicality and potential cost-benefits. If a system is truly cost-beneficial and does not interfere with other systems, then there is every reason to promote or even mandate its use. Even a "minor" safety system may be a successful one.

The implementation paths and prospects for truck safety systems are often fundamentally different than those of both passenger vehicle systems and non-vehicle-based systems. Trucking companies are much more likely to base their safety purchases on prospective monetary cost-benefits than are passenger vehicle owners. In addition, the Federal government generally mandates more vehicle safety systems for trucks than for passenger vehicles because more systems are applicable and because their public benefits per unit cost are more easily demonstrated.

Toward Zero Deaths focuses on fatality reduction, but a more pertinent measure of success for most truck safety systems is *Return on Investment* (ROI) per dollar spent. ROI incorporates device cost into its equation, putting "large" and "small" countermeasures on a common scale. Crash reduction in ROI calculation incorporates all harm, including human fatalities, injuries, and property damage. ROI can also incorporate *non-safety* benefits of systems, which may be considerable for truck devices. For many safety systems, concurrent benefits in efficiency, fuel-economy, and/or sustainability may rival or exceed safety benefits. ROI brings these considerations into play and portrays promising onboard safety systems to buyers as attractive business investments.

Truck Braking, Handling, & Stability

Heavy truck brakes are inherently problematic because of the large size of trucks and the fact that most truck travel is at highway speeds. Loaded CT stopping distances are currently about 60 percent greater than those of a car. Truck stability during braking or other maneuvers is a concern because of trucks' and trailers' relatively high centers of gravity and because articulated vehicles (i.e., tractor semi-trailers) are subject to jackknifes. Fortunately, there have been truck dramatic improvements in brake system capabilities and reliability in past decades (Freund et al., 2006; Perrin et al., 2007). Continuing and future improvements include faster initiation of braking and greater vehicle stability during braking through electronic control (Silvani et al., 2009). Brakes no longer have the single task of decelerating the vehicle; rather, they are seen as an integral part of Vehicle Stability Systems (VSS), as will be discussed below.

Improved conventional truck brakes (drum brakes) and new designs, such as disc and hybrid drum-disc brake configurations are improving truck stopping distances considerably (Perrin et al., 2007). Based on this potential, NHTSA has mandated truck stopping distance decreases of about 30 percent for new trucks, beginning in 2011. This will greatly reduce truck-car differences in stopping distance. Air disc brakes, such as shown in Figure 4, have potential advantages over drum brakes, including less needs for adjustment, more precise control and modulation by drivers, far less susceptibility to brake fade due to heat buildup, easier maintenance, and better vehicle stability during hard stopping. Stability benefits are achieved by a more uniform distribution of braking force across multiple wheels.

Figure 4. Truck Air Disc Brake. **Courtesy Bendix Corporation.**

In the LTCCS, one-third of large trucks braked prior to impact in their crashes (Knipling and Bocanegra, 2008). Theoretically, improved brakes would have some benefit in almost all of these crashes, usually by reducing impact force and sometimes by preventing the crash altogether. NHTSA estimates the annual reductions from its new truck brake performance standard to be 227 fatalities, 300 injuries, and more than $169 million in property damage costs. Accordingly, improved brakes are designated in this report as a priority safety technology. Unlike other priority truck safety technologies to be discussed, full penetration of this one (over time as the fleet turns over) is ensured by the NHTSA rule.

One of the most effective and revolutionary vehicle technologies for trucks, and all vehicles, is *electronic stability control* (ESC). NHTSA has mandated ESC for light vehicles and is considering a similar mandate for heavy trucks. Based on a review of crash data, Jermakian (2010b) has estimated that ESC systems on large trucks can prevent or mitigate 31,000 crashes resulting in 439 fatalities (about 11 percent of truck-related fatalities). Woodroofe et al. (2009) examined LTCCS CT loss-of-control crashes and other crash databases to judge probably ESC effectiveness and estimate national benefits from full penetration of the U.S. CT fleet. They estimated crash and human harm reductions to be 4,700 crashes, 126 fatalities, and 5,900 injuries. Economic losses avoided in 2007 dollars would be $1.74 Billion. A study limited to STs and buses (da Silva et al., 2009) estimated target crash population sizes (not crashes prevented) for these commercial vehicle types. Their estimate was 2,200 annual ST crashes (1.5 percent of the total) and 1,000 bus crashes (1 percent of the total). Although there is a wide discrepancy between the Jermakian estimate and the combined estimates of the other two authors, there is no doubt that ESC is a priority technology for large truck crash reduction.

Compared to ESC, truck Roll Stability Control (RSC) is a relatively simple crash avoidance technology. RSC monitors lateral forces within a vehicle (i.e., centrifugal forces in a curve), combines it with vehicle data (e.g., center-of-gravity height), and predicts imminent rollover risk. When excessive lateral forces are detected, RSC automatically slows the truck, usually by depowering the throttle. This rapid intervention alleviates rollover risk. RSC also flashes a driver visual display and sounds an auditory alarm indicating that the system has activated. RSCs are also onboard monitors. They record lateral forces and provide a computer record of events for post-trip review. FMCSA (2009) estimated the costs RSCs for CTs to be $440 to $866 per vehicle, and the five-year return-on-investment (ROI) to be $1.66 to $9.36 per dollar spent. As part of the same study cited above for ESC, Woodroofe et al. (2009) estimated full-penetration RSC CT crash reductions to be 3,500 crashes, 106 fatalities, 4,400 injuries, and $1.46 Billion in economic losses. This implies potential RSC benefits are 75 percent or more of ESC benefits. Others view ESC as a far superior technology. Bendix Corporation, a major ESC/RSC supplier, views RSC as having a crash reduction potential which is significant but far below that of ESC. That’s because ESC acts to prevent and mitigate both directional instability (yawing) and roll instability, whereas RSC is limited to the latter (Bendix, 2010). Because ESC’s capabilities encompass and exceed those of RSC, RSC is not designated as a priority technology in this white paper. It would certainly be one, however, if ESC were not available.

Collision Warning Systems

Forward Collision Warning Systems (FCWS)

As discussed previously under passenger vehicles, FCW systems monitor the roadway in front of the vehicle and warn of rapid closing with a vehicle ahead, or other collision risks. Adaptive

Cruise Control (ACC) is a natural partner to FCW because the same sensor readings can be inputs to throttle controls to maintain steady highway following distances. ACC also reduces driver workload, an important concern in long-haul driving operations. A new NHTSA assessment of ACC (Silvani et al., 2009) estimates that full deployment of ACC on large trucks would prevent up to 320 fatalities annually.

FCWSs principally target rear-end crashes. Truck-striking rear-end crashes were 14 percent of serious truck crash involvements in the LTCCS (Knipling and Bocanegra, 2008). These crashes are probably also the biggest source of crash liability claims against trucking companies because the truck driver is almost always considered at-fault and because the vast majority of human harm occurs inside “innocent” struck vehicles (Knipling, 2009). Trucking companies should be highly motivated to prevent these crashes, and FCWSs are a perfectly tailored solution. FMCSA (2009) estimated FCWS costs to be about $1,600 per unit and five-year ROIs to be $1.33 to $7.22 per dollar spent. Jermakian (2010b) has estimated that FCWSs on large trucks could prevent or mitigate 31,000 crashes and 115 fatal crashes (about three percent of truck-related fatal crashes). Because of FCWSs’ proven effectiveness and the harm their target crashes cause to the motoring public, FCWS is designated here as a priority technology.

Side-Object Detection Systems (SODS)

Another priority technology for large trucks is side object detection to prevent lane change/ merge crashes. Side Object Detection Systems (SODS) detect objects to the side of the truck. They provide auditory warnings drivers when a side objects are detected. They function as supplements to truck mirrors to aid lane changes, especially those to the right. About three-quarters of truck side impacts following a lane change/merge occur when the truck is moving to the right. This reflects the limitations of truck mirrors and the large blind areas on the right sides of tractor-semitrailers.

Compared to passenger vehicles, large trucks are highly overinvolved in lane change/merge (LC/M) crashes. In one five-year study, combination-unit trucks (CTs) accounted for 2 percent of all motor vehicle crash involvements, but were 8.5 percent of the at fault vehicles in LC/M crashes (Wang et al., 1999). About 25,000 police-reported crashes involving a lane changing/merging truck occur annually. IIHS (Jermakian, 2010b) has estimated that 79 truck-involved fatal crashes could be prevented annually by universal use of SODS, which they termed “Side View Assist Systems.” Video mirrors, to be discussed later, are another countermeasure to LC/M crashes.

Backing Collision Warning Systems

Backing Collision Warning Systems, usually termed Rear-Object Detection Systems (RODS) for large trucks, use proximity sensors to detect rear-field objects and warn drivers of their presence (NHTSA, 2006). Less than one percent of serious crashes in the LTCCS involved trucks backing, but a much higher percentage of minor police-reported truck crashes and unreported crashes involve backing maneuvers. These crashes are an annoyance to trucking companies as they often result in vehicle downtime or customer (shipper and receiver) complaints and restitution claims. Although RODS proximity sensors function effectively (Garrott et al., 2007), video mirrors, discussed below, probably have greater future potential as aids to safe and precise truck backing.

Lane Departure Warning Systems (LDWS)

As discussed earlier under cross-cutting systems, Lane Departure Warning Systems (LDWS) warn drivers that they are beginning to drift of out of their lane. They function like an in-vehicle rumble strip. Note that LDWSs do not address loss-of-control-related lane departures following directional instability. They also do not prevent rollovers due to excessive speed on curves or similar dynamic mishaps. A product guide available on FMCSA's website lists six LDWS vendors, and states current prices to be in the $1,000 to $2,000 range. Figure 5 shows a functional schematic of a truck LDWS marketed by Iteris, Inc.

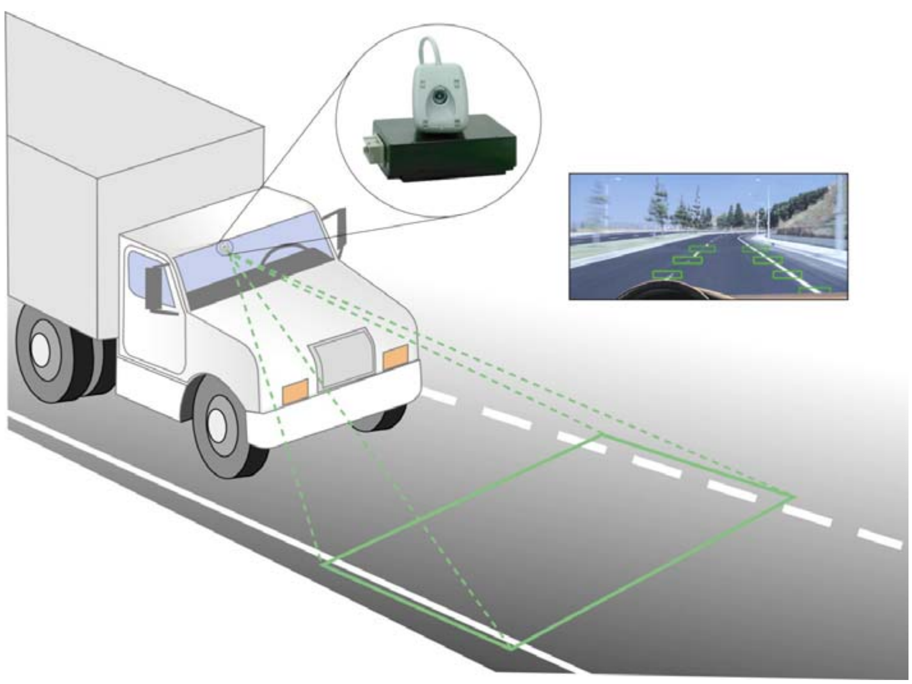

Figure 5. Functional schematic of lane departure warning system. **Courtesy: Iteris, Inc.**

LDWSs are most applicable to ”drift” lane departures due to driver inattention, drowsiness, or other impairment. In the case of drowsiness, deterioration of performance usually begins well before actual lane breaks. In this case, LDWSs are potentially capable of providing corrective feedback to drivers well before they are imminent danger. Yet most current systems base driver feedback only on imminent or actual lane breaks. The provision of LDWS feedback to drivers during their early, incipient performance deterioration is an application which should receive greater R&D attention.

FMCSA (2009) has estimated LDWS costs to be about $800 per vehicle and five-year ROIs to be $1.37 to $6.55 per dollar spent. Jermakian (2010b) has estimated that LDWS on large trucks could prevent or mitigate 10,000 crashes and 247 fatal crashes (about seven percent of truck-related fatal crashes). Because of their high mileage exposures, CTs’ lifetime likelihood of involvement in lane departure crashes is approximately three times that of passenger vehicles. Because of the high CT potential for involvement in these crashes and the high potential that LDWSs have to prevent them, LDWS is designated here as a priority technology.

Integrated Vehicle-Based Safety System (IVBSS)

As described under passenger vehicles, the U.S. DOT-funded Integrated Vehicle-Based Safety System (IVBSS) initiative is designing and testing orchestrated, multi-element collision warning systems. IVBSS has been developed, configured, and field tested on 16 passenger vehicles and 10 CTs (Sayer and Flanigan, 2010). As illustrated in Figure 6, the current IVBSS suite includes three countermeasures, all designated in this report as priorities for large trucks:

- Forward Collision Warning (FCW)
- Lane Change/Merge Warning (also known as Side Object Detection Systems or SODS)
- Lateral Drift Warning (also known as Lane Departure Warning Systems or LDWS).

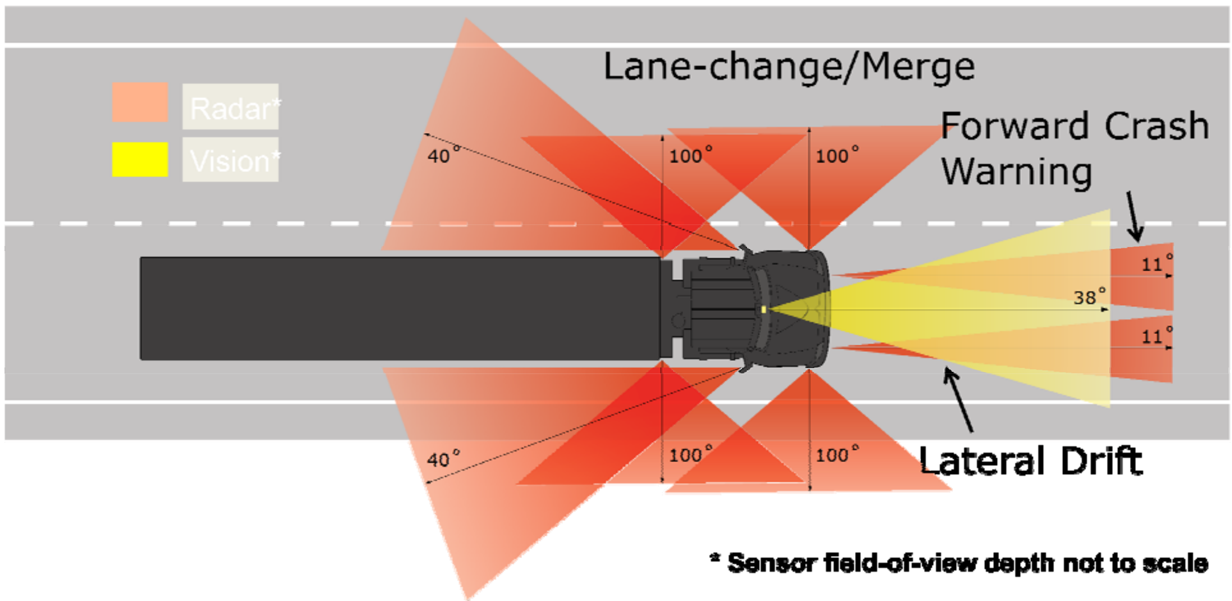

Figure 6. IVBSS truck safety system. **Source: Sayer and Flanigan, 2010.**

About 60 percent of all large truck crashes are potentially addressable by the IVBSS instrumentation suite. Field test results indicate that these three systems can be successfully integrated. Eighteen truck drivers using the IVBSS have generally found it to be helpful to safe driving, and would recommend it to others. Annoyance from excessive alarms remains as a concern, however (Sayer and Flanigan, 2010).

Driver Behavior & Alertness Monitoring

Onboard Safety Monitoring (OBSM)

A fundamental difference between commercial driving and non-commercial driving is the fact that commercial driving is, or should be, *managed driving*. Management includes employee performance monitoring. In the case of driving, performance monitoring can and should include direct monitoring of driving behaviors.

Onboard Safety Monitoring (OBSM) is continuous measurement and recording of safety-related driving behaviors like speed, acceleration, and braking force. Potentially, OBSM can involve any safety-related driving parameter measurable in a vehicle. Vehicle speed and speed and hard braking applications are two frequently measured parameters. Almost all advanced collision warning systems, including FCWS, LDWS, and SODS can also function as monitors. They can provide real-time warnings and also post-trip summary feedback to both drivers and safety managers.

Truck and bus fleet managers regularly track their drivers' on-road events, including crashes, incidents, and violations. Yet, even though the technology is available, relatively few use OBSM to track the *source safety behaviors* that create these negative outcomes. Outcome tracking is necessary, but consider these OBSM advantages from Knipling (2009):

- OBSM documents specific driver behaviors causing crashes, incidents, and violations.
- Drivers can receive proactive corrective feedback before a crash, incident, or violation occurs.
- Evaluations and feedback are objective, timely, and frequent.
- Drivers can receive positive feedback and rewards for their successes.
- Driving behavior benchmarks can be set so drivers know where they stand in relation to carrier norms and expectations.
- Rewards and recognition can be individualized but also structured to reinforce group achievements, thereby fostering *esprit-de-corps*.
- OBSM can replace time-consuming ride-along driving observations, and it is more indicative of true behavior because no observer is present.
- OBSM can obtain a 100% sample of behavior.

No national estimates of the potential benefits of OBSM are available, in part because OBSM is not simply a vehicle-based technology. Rather, it is a carrier safety management initiative employing technology. One OBSM test in Israel (Toledo et al., 2008) used green (good), yellow (questionable), and red (bad) visual displays to give commercial drivers feedback on their driving safety. Drivers could see their performance indicators in real-time while driving and via a secure web link after driving. Driving risk was assessed based on vehicle speeds, lateral accelerations (e.g., on curves), and longitudinal accelerations (e.g., hard braking). In a testing involving 191 service drivers, feedback was provided without any adverse or other tangible consequences for drivers. Providing feedback alone, with no other consequences, resulted in a 33% mean reduction in risky driving behaviors for these drivers. Clearly, OBSM will be at the center of future safety improvements in commercial motor vehicle transport. Fatality reductions in the hundreds, or even one thousand or more, could be possible because of the pervasive driving behavior changes possible through correctly managed OBSM.

A simpler variation of OBSM involves capturing videos of critical events occurring during driving. A typical system has two cameras at the middle top of the windshield. One captures the vehicle forward view and looks back at the driver to see the driver's face and record driver reactions. The system has an audio recorder and records a continuous video/audio loop. An accelerometer detects excessive lateral, longitudinal, or vertical forces, and prompts the device to save 10 seconds of data from before and after the triggering event. Managers or drivers themselves can then review events to see what went wrong. Hickman et al. (2009) field tested a video capturing device with 50 commercial drivers in operational service. After a no-feedback baseline period, the system was fully activated. Drivers and their managers reviewed and reconstructed triggered events as a performance improvement exercise. Event rates in two fleets decreased by 37 and 52 percent, respectively, during the intervention period. If such interventions can be conducted in a positive manner with sufficient rewards and positive feedback to drivers to ensure acceptance, there is every reason to believe that decreases in event rates can translate directly to decreases in at-fault crashes.

Alertness Monitoring

Another emerging technology, not yet widely implemented, is driver *alertness monitoring*. As described earlier, alertness monitoring can be based on driver lane-keeping as indicated by LDWS sensors, by eyelid droop (PERCLOS), or by both measures combined into a single optimized assessment. Alertness monitoring is potentially a much stronger countermeasure to commercial driver fatigue than Electronic Onboard Recorders (EOBRs, discussed below) because it would measure drowsiness and impaired performance directly as opposed to measuring driving time, which is only weakly associated with driver alertness (Knipling, 2009). Someday, even government regulation of commercial driver alertness and fatigue may be based on direct alertness monitoring of drivers rather than the current Hours-of-Service logging regimen.

Alertness monitoring has special relevance to commercial driving, but perhaps not for the reasons many people would assume. Commercial drivers' per-VMT rate of involvement in fatigue-related related crashes is probably no greater than that of non-commercial drivers. In the LTCCS, for example, eight of every nine car-truck asleep-at-the-wheel crashes were due to the *car* driver falling asleep (Knipling, 2009). In the LTCCS, about 4 percent of all serious large truck crashes were attributable to truck driver asleep-at-the-wheel. FMCSA has attributed 7.25 percent of fatal crashes to fatigue, in part by adding related inattention crashes. That percentage would translate to about 270 large truck fatal asleep-at-the-wheel crashes annually. A rough estimate of the number preventable through driver alertness monitoring is 100.

The special relevance of alertness monitoring to commercial driving is primarily due to crash *likelihood* and *severity* differences between trucks and cars, as discussed early in this section. Long-haul trucks (i.e., CTs) are driven far more miles than cars, and their crashes are much more severe. One study (Knipling, 1998) estimated CT life cycle fatigue-related crash costs to be ten times those of passenger vehicles and more than 20 times those of STs, which are primarily short-haul, day-use vehicles. Further, alertness monitoring benefits for truck safety might not be limited to the prevention of known asleep-at-the-wheel crashes. As a group, commercial drivers are among the unhealthiest of Americans. Alertness monitoring and other OBSM systems might help motivate drivers to change their driving styles and even their lifestyles in holistic ways resulting in more pervasive benefits. This concept is discussed in the textbox below. Finally, alertness monitoring may someday be encouraged as a regulatory alternative to conventional

HOS rules and logs. Which would be better, monitoring commercial driver hours or directly monitoring their alertness and driving performance?

What's Your Driving Average?

Every baseball player knows his or her batting average, and whether it is good or bad. Sports provide precise quantitative feedback to players on their performance. There are official or unofficial benchmarks for quality performance, such as a par score in golf. Do you know the same thing about your driving? Probably not. Most drivers, even high-risk drivers, think they are better than average drivers. It's call the *self-assessment bias*. It's easy for people to have this bias because they do not receive objective feedback on their driving, and there are no quantitative benchmarks for driving proficiency. Crash and violation histories are the best metrics we have, but they are unreliable because they are rare events affected by chance and confounded by differences in risk exposure. It's easy to invent excuses to dismiss their significance. Baseball and other sports, in contrast, have many quantitative performance metrics. Players know their scores.

This situation may gradually change over the coming decades. OBSM systems will give commercial drivers numeric feedback on their driving behavior. OBSMs are also being used with teenagers to help them (and their parents!) assess and improve teen driving. ”Alertometers” will tell drivers their alertness scores, hopefully using a standardized, easy-to-understand scale. If you had such information about your own alertness while driving, how would you use it? Would repeated low alertness scores motivate you to get more sleep and otherwise change your lifestyle? A core principle of psychology is that feedback facilitates performance. Will objective feedback to drivers from onboard monitoring systems enable and motivate them to change?

Electronic Onboard Monitors (EOBRs)

EOBRs monitor commercial driver Hours-of-Service (HOS) compliance by maintaining a readable electronic time record of vehicle movement. Truck drivers are currently permitted 11 hours of driving during a daily 14-hour maximum tour-of-duty. EOBRs cannot track non-driving work time, but they do track vehicle motion and thereby effectively deter drivers from driving excessive hours. EOBRs are used voluntarily by some fleets but are currently required only for those commercial fleets with the worst histories of HOS non-compliance. FMCSA is considering extending the EOBR requirement to a larger percentage of non-compliant carriers.

EOBRs are assumed by the public and many government officials to be effective countermeasures against commercial driver fatigue and asleep-at-the-wheel crashes. This assumption may be questioned, however. A number of researchers do *not* consider hours of driving, the principal EOBR recording metric, to be among the most important determinants of driver alertness on a daily basis (Hanowski et al., 2008; Knipling, 2009; Wylie et al., 1996). Instead, the four principal alertness determinants are amount of sleep, time awake (with alertness typically dropping after 16 hours awake), time-of-day (reflecting circadian rhythms), and individual differences in fatigue susceptibility (Knipling, 2009). The first two of these are only indirectly addressed by EOBRs and HOS rules, and the last two are not addressed at all.

Ironically, the biggest benefits of EOBRs may not be from driver fatigue reduction, but rather from more efficient operations and safety management. Because EOBRs automate driver log-keeping, they save drivers time, streamline records and compliance management, and provide for better safety oversight of drivers through quicker identification of non-compliant drivers. Shackelford and Murray (2006) found EOBR benefits to include improved fuel consumption monitoring and fuel tax compliance, quicker tabulation of driver mileage and loads, easier tracking of vehicle and engine wear, real-time vehicle location monitoring, better communications and dispatching, and even improved driver morale.

Electronic Data Recorders (EDRs)

As described under passenger vehicles, Electronic Data Recorders (EDRs) record vehicle speed, accelerations, brake applications, and other dynamic parameters of interest in crash reconstruction. EDR data can be critical in crash investigation and litigation. The trucking industry generally holds the view that the same EDR-related laws and court rules should apply to equally to all vehicle types.

Vehicle Monitoring & Automated Functions

Mechanical maintenance deficiencies are common in large trucks. In the LTCCS, 40 percent of crash-involved trucks had some vehicle-related deficiency or malfunction, although these were the proximal cause (the “Critical Reason”) for only about four percent of crashes (excluding cargo shifts, which were another two percent). Numerous automatic vehicle condition monitoring technologies are now available to reduce this source of crash risk. These can provide continuous monitoring and feedback to drivers, recordings to EDRs and, potentially, to roadside inspectors through wireless transmission. Such monitoring can potentially include brake adjustment and condition (the most common vehicle-based problem in inspections and crashes), tires, lighting, vehicle weight, and other vehicle faults. In addition to vehicle condition monitoring, automated functions can extend to the task of driving (e.g., automated truck transmissions), to vehicle speeds, and to trip navigation.

Tire Pressure Monitors

In the LTCCS, about 1 percent of at-fault truck crashes were caused primarily by tire failure. Poor tire condition is the second most common vehicle source (behind brakes) of violations in truck roadside inspections. The most common cause of tire failure is underinflated tires. Underinflated tires become overheated and experience excessive flexing of their sidewalls. This can raise fleet tire replacement costs by more than 10 percent annually and reduce fuel economy by increasing rolling resistance (Freund et al., 2006). An FMCSA safety technology product guide, available on its website, describes various types of tire pressure monitoring systems available from nearly 20 vendors. The safety benefits come from reduced incidence of tire failures. These devices also save pre-trip inspection time, improving operational efficiency. Part of the "equation" for assessing large truck safety systems is their *non-safety* benefits. Time pressure monitors are an excellent example.

Automated Transmissions

In cars, automatic transmissions are regarded as a convenience, not a safety feature. In large trucks, however, making gear-shifting easier can facilitate safety by reducing driver workload. "Work" refers primarily to the *mental* tasks of driving – perceiving, distinguishing crash threats, deciding, executing responses. Truck driving has a physical element as well, since manual shifting requires double-clutching, a more difficult and tiring task than shifting gears in a car. Because they reduce workload, automated transmissions can contribute to truck driving safety. The adjective "automated" rather than "automatic" is used because these transmissions are not fully automatic like those of a car. Schneider National, one of the nation's largest truckload carriers, conducted an experiment in which a group of new drivers was trained and equipped with automated transmission vehicles while a control group used standard gears. New drivers using automated transmissions had a 26 percent lower first-year crash rate than controls. They also completed their training sooner on average, and had a 35 percent higher one-year retention rate with the company (Knipling, 2009).

Speed Limiters

Speed limiters were addressed previously under cross-cutting issues. As noted, speed limiters are already common on large trucks, though they not yet considered standard equipment. In European Union countries they are required on all heavy vehicles. In the U.S., NHTSA and FMCSA have proposed federal regulations for speed limiting heavy trucks, and the matter is under rulemaking consideration. The proposal would likely require that new trucks' electronic control modules be programmed to limit top powered speeds to some set point. This would be an easy and low-cost engine modification. More difficult would be ensuring that they are tamper-resistant.

Much of the trucking industry favors mandatory speed limiters on large trucks. The American Trucking Associations (ATA) and other organizations have petitioned NHTSA and FMCSA to require speed limiters with a set point of 68 mph on new heavy trucks (ATA, 2006). Reduced crashes are the primary rationale, but other reasons include lower fuel and maintenance costs, reduced emissions, and longer tire life.

One should realize that speed limiters will not prevent most truck crashes arising from excessive speed. Most instances of "excessive speed" occur on lower speed roads and at speeds below 68 mph. Moreover, speed limiters would not slow the downhill speeds of trucks. In support of its petition, however, ATA (2006) cited an analysis of 2001-2005 FARS data on truck speeding-related crashes. In 20% of the speeding-related fatal crashes where the truck's speed was recorded, that recorded speed exceeded 68 mph. Many of these crashes would be prevented or reduced by speed limiters.

Intelligent speed adaptation was also discussed earlier. This is a system which would use GPS navigation technology to "know" the speed limit or a recommended maximum speed for a road, or section of road. Carsten et al. (2008) fabricated and tested an intelligent speed adaptation system on a medium delivery truck. Although the system functioned as designed and excessive speeds for road conditions were reduced, driver acceptance was low and the system was considered distracting. This is a concept with promise, but one needing more refinement.

Truck-Specific Navigation Aids for Risk Avoidance

Proper use of Global Position System (GPS) navigation aids by commercial drivers can significantly reduce exposure to risk and, therefore, crash rates. Truck-specific navigation aids can provide both trip planning and in-vehicle GPS-synchronized directions customized to truck transport. GPS devices can steer drivers clear of roads where truck traffic and/or hazardous cargo is restricted or prohibited. They can warn drivers of low clearance underpasses (e.g., bridges with less than 14 feet of vertical clearance, the national standard for local roads and collectors) or other hazardous locations. If systems are frequently updated, they can route drivers around construction zones, where crash risks far exceed those on normal roads. Thirteen percent of truck crashes in the LTCCS occurred in work zones, versus less than one percent of truck driving exposure. Simply routing trucks away from undivided roadways and from those with high traffic densities can reduce crash risk considerably. Truck instrumented vehicle studies permit the comparison of incidents (e.g., hard-braking events) to exposure (random samples of driving) to determine relative risk (odds ratios) of various road types and conditions. Here are some examples of risk odds ratios relevant to smart routing of trucks:

- Construction zones vs. normal roads: 8.5 (relative odds of incident vs. controls)
- Undivided vs. divided roads: 5.3

- Dense traffic vs. moderate-to-light traffic: 5.9.

Truck-specific road information is needed, however. Many trucking companies warn their drivers not to use generic (i.e., passenger vehicle) GPS units because they do not contain information on truck-specific restrictions or hazards.

Visibility & Conspicuity

Truck Conspicuity & Enhanced Lighting/Signalling

You wouldn't think that something as large as a truck would be hard to see, but many nighttime collisions between cars and trucks involve a car striking an unseen truck. Fortunately, this problem has been reduced by a Federal requirement for improved retroreflective tape on the sides and backs of truck trailers produced after 1997. These enhancements were found to reduce crashes into the sides or backs of trailers by 29 percent (Perrin et al., 2007).

Trucks and trailers are also required to meet standards for conspicuity lighting, including tail lights, brake lights, signal lights, and marker lights. In 2008, there were nearly 600 fatal crashes in which another vehicle struck a large truck in the rear (Craft, 2010). FMCSA is testing new trailer rear conspicuity enhancements which would a) further enlarge reflective surfaces to include an octagonal stop sign-like display, and b) provide radar-triggered visual and even auditory warnings. The effort is comparing the warning effectiveness of various configurations, and will field test top designs (FMCSA, 2010). Truck-struck rear-end crashes are a sizable safety problem, but truck-based technologies addressing these crashes are not sufficiently advanced to warrant their being designated as priority countermeasures. More likely, FCWSs on vehicles which might strike trucks will be more effective in reducing these crashes.

Video Mirrors

As noted earlier, combination-unit trucks (CTs) are strongly overinvolved in lane change/merge (LC/M) crashes, especially those involving left-to-right lane changes. Over a vehicle lifetime, average CT crash costs from LC/M crashes are more than ten times those of light vehicles (Wang et al., 1999).   The overinvolvement of CTs in these crashes is related primarily to poor visibility around trucks. Improvements have been made in conventional mirror design and coverage (e.g., convex mirrors, supplemental spot mirrors), but mirrors cannot possibly provide a truck driver full visibility around his or her truck.

Video cameras with in-cab displays can provide the same visual functionality as conventional mirrors, along with many enhancements. Cameras can be mounted on the sides of tractors and on the sides and backs of trailers, with dedicated video monitors for each in the cab. Although these are cameras, not mirrors, a natural name for them is "video mirrors." The advantage of video mirrors is that the driver can see whatever the cameras see. Cameras can be placed almost anywhere, so there are no inherent blind areas. Cameras mounted on the back of a trailer can provide a precise, close-up perspective during backing.

The key safety issue for video mirrors is not whether they can provide visual information, but rather whether drivers can use them without making *negative transfer errors*; that is, errors made in switching from one type of device to a different one. A series of tests (Wierwille et al., 2007) has shown that truck drivers can generally make more precise vehicle maneuvers using video mirrors compared to conventional ones. Not only do video mirrors reduce blind spots – they also make it easier for truck drivers to judge distances from other vehicles and objects during close maneuvers. In a backing test, drivers backed their tractor-semi-trailers as close as possible to a loading dock without bumping it. Their average of 47" from the dock using conventional side mirrors was reduced to 10" using video mirror mounted on the back of the trailer.

Collision Aggressivity Reductions & Occupant Protection

Most harm in crashes involving large trucks is suffered by the occupants of other vehicles. Of the 4,229 truck-related fatalities in 2008, more than 3,151 (75 percent) were other vehicle occupants. A CT with an 80,000 lb. GVWR has 15-30 times the mass of a light vehicle. The laws of physics dictate that collisions between two bodies of such unequal mass will result in more abrupt speed changes and resulting damage to the smaller object. This characteristic of larger vehicles in relation to smaller ones is termed *collision aggressivity*. Other design features contributing to truck collision aggressivity are the height and stiffness of truck and trailer bodies. Prospects for reducing truck collision aggressivity are limited compared to the dramatic potential for *preventing* crashes using the various technologies described in this white paper. One relatively simple approach would be to lower truck bumpers to improve vertical compatibility with smaller vehicles. Freund et al. (2006) discuss the potential use of hyperelastics, such as specially formulated polyurethanes, in the construction of truck bodies. In modeling studies of crash barriers, these materials have been shown to reduce force in forward impacts by as much as 65 percent. They could be used for specific truck body structures like rear underride guards. Given the size of trucks, any external modifications to their bodies are likely to be more expensive than similar changes to a car body. Their attractiveness from a cost-benefit perspective may be problematic.

Of the 4,229 truck-related fatalities in 2008, 675 occurred to truck drivers and other truck occupants. Many of these truck occupant fatalities were in rollovers. Bahouth et al. (2007) have noted that rollovers constitute just 4 percent of large truck crash involvements but account for 36 percent of truck driver fatalities. Many truck drivers killed in rollovers are unbelted, and many are ejected. Average injuries to unbelted drivers in rollovers (and in truck crashes in general) are more than twice as severe as those to belted drivers. According, a priority for truck occupant protection is ensuring safety belt use. Current Federal Motor Vehicle Safety Standards (FMVSSs) for passenger vehicles require a visual and auditory belt use reminder system, but no such requirement exists for trucks. Bahouth et al. (2007) concluded that such systems would be effective with truck occupants, just as they are in cars.

Air bags reduce car driver fatalities by 30% in frontal impacts. What about air bags for heavy trucks? Although no manufacturers currently offer truck air bags, Volvo and others are developing and testing them. In a high-speed truck forward impact with a fixed object, an air bag would likely have a similar life-saving effectiveness to that seen in cars. Crashes with such abrupt speed changes are less common in trucks than in cars, however. In a typical large truck collision with a car, an air bag would make little difference and might not even deploy because the impact deceleration of the truck is relatively small. Thus, while safety belts are equally important in trucks and cars, air bags have relatively less potential benefits in trucks. They may still be seen in trucks in future years, especially if their costs decrease.

Larger Trucks?

Across the entire transportation system, society seeks the highest performance for the lowest economic, environmental, and human cost. In the present context, one may ask whether the profile of truck configurations on our roadways could be shifted to result in higher freight productivity at lower cost, including the human cost associated with truck crashes. Higher productivity vehicles (HPVs) are those with GVWRs of more than 80,000 lbs., the maximum size of standard tractor-semitrailers. U.S. restrictions on truck size and weight have been frozen for nearly two decades, but many observers are now asking whether geographic and roadway restrictions on HPVs should be liberalized. At the June 2009 *International Conference on Efficient, Safe, and Sustainable Truck Transportation Systems for the Future* in Ann Arbor, Michigan (website: *www.magictrucks.org*), speakers from around the world described potential benefits from more widespread use of HPVs. The most compelling HPV rationale is reduction of fuel consumption and associated carbon emissions, primarily because HPVs can haul the same cargo weight or volume in fewer trips.

The same concept could apply to safety. Although the motoring public reflexively fears larger trucks, there is a safety rationale for expanded HPV use, in addition to the environmental and economic rationales. One may extrapolate from a comparison between conventional STs and CTs. The two main truck types have roughly the same total crash costs per mile traveled (Wang et al., 1999). Since CTs carry far more freight, they are far safer than STs in terms of crash harm per ton-mile. In regard to HPVs, an Australian study (Moore, 2007) found their crash rate per freight ton-mile to be less than one-half that of regular combination-unit trucks. Two Canadian studies (Montufar et al., 2007; Tardif and Barton, 2006) compared HPV safety to that of conventional CTs and other configurations. Both concluded that LCVs offer both productivity and safety benefits if their operations are closely and intelligently controlled. On the other hand, Zaloshnja and Miller (2007) found HPV crashes to be more severe than those of CTs or STs. A definitive safety assessment would determine total crash harm per ton-mile for different truck configurations as well as other, similar metrics (TRB, 2010). It is hoped that society can make a rational judgment on future HPV use as opposed to an emotional one based on reflex.

Realizing Truck Safety Technology's Potential

There appears to be an ever-increasing carrier in interest in, and acceptance of, truck onboard safety technologies. Nevertheless, carriers want assurance of their safety rationales, likely outcomes based on real-world data, prospective ROIs, operational requirements (e.g., installation, maintenance, and training), data processing requirements, and driver acceptance (Houser et al., 2007). Bottom-line ROI is perhaps the single most important measure of truck safety system potential, because the decision to buy truck safety devices is usually an economic one. Providing detailed, current, and valid information to carriers on system ROI prospects is one important strategy for increasing technology sales. Industry has strong data privacy, security, and litigation concerns associated with onboard technologies which record vehicle status and driver actions. These concerns must be addressed. The textbox above, adapted from Knipling (2009) outlines a systems approach to assessing safety technologies and ensuring their success in the rigors of trucking. System developers and vendors should anticipate these concerns and design these elements into their products to ensure their successful deployment.

A Systems Approach to Truck Safety Technologies

An onboard truck safety technology must:

- Be truly **applicable** to the crash problem.
- Be **usable** by drivers and **acceptable** to them.
- Be **durable** and **reliable**.
- Be **maintainable** by carriers.
- Be **compatible** with legal, institutional, and cultural factors (e.g., does not create increased liability).
- Actually result in:
  - Driving **behavior change**.
  - Crash **problem reduction** (number and/or severity).
- If possible, provide **efficiency**, **fuel-economy**, **sustainability**, and/or **fleet management** benefits in addition to safety benefits.
- Be **affordable**.
- Be **marketable**.

A system is a chain: ***all*** *links must be strong!*

Apart from scientific, engineering, and operational challenges, there are economic obstacles to greater deployment of truck safety technologies. The industry's most innovative and successful companies have sufficient capital and cash flow to finance purchases of vehicle safety technologies. But that's not true of most companies, where tight profit margins are the rule.

Two-thirds of the harm in truck crashes is outside the vehicle, experienced by other motorists or road users (Wang et al., 1999). The motoring public would benefit substantially from any improvement in truck safety. Accordingly, various safety organizations are calling for tax incentives to promote carrier purchase of advanced safety technologies. The *Commercial Motor Vehicle Advanced Safety Technology Act* is a bill before Congress calling for a 50 percent tax credit for the purchase of selected proven onboard technologies. Covered technologies would be include collision warning systems, lane departure warning systems, vehicle stability systems (e.g., ESC), and brake stroke monitoring systems. Thousands of lives would be saved and tens of thousands of injuries prevented if more trucks were equipped with these systems. Congress should strongly consider providing this safety benefit to industry and to the motoring public.

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