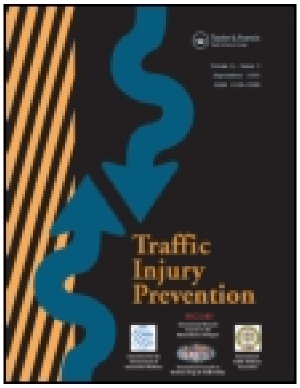

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Potential Benefits of Underride Guards in Large Truck Side Crashes

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Objective: *To evaluate the maximum potential for side underride guards (SUGs) to reduce passenger vehicle occupant fatalities and injuries in crashes with large trucks in the United States.*

Methods: *Examination of the Large Truck Crash Causation Study (LTCCS) identified 206 crash events involving a passenger vehicle impact with the side of a large truck. Each case was evaluated to determine whether the most severe injury sustained by a passenger vehicle occupant was a result of the impact with the side of the truck and whether an SUG could have reduced the injury severity. Data from the 2006–2008 Fatality Analysis Reporting System (FARS) and Trucks Involved in Fatal Accidents (TIFA) survey were used to compare the types of trucks involved in all fatal side impacts with passenger vehicles with the truck types in the LTCCS cases that were studied. FARS and TIFA data also were used to estimate the total annual number of passenger vehicle occupants killed in truck side impacts.*

Results: *In 143 of the 206 cases, the truck side impact produced the most severe injury sustained by a passenger vehicle occupant. In the other cases, no passenger vehicle occupant was injured or the most severe injury was due to an event preceding or following the truck side impact. Forty-nine of these occupants sustained injuries coded as level 3 or higher on the abbreviated injury scale (AIS) or were killed. SUGs could have reduced injury severity in 76 of the 143 cases, including 38 of the 49 cases with an AIS ≥ 3 coded injury or fatality. Semi-trailers were the most common type of impacted truck unit, both overall and when considering only cases where an SUG could have mitigated injury severity. Crashes where the front of the passenger vehicle struck the side of the semi-trailer perpendicularly or obliquely from the oncoming direction were less common overall than side-to-side and oblique/same direction crashes but more often produced an AIS ≥ 3 injury or fatality. The distribution of truck types in the LTCCS sample was similar to that in the FARS and TIFA data. Overall, around 1600 passenger vehicle occupants were killed in 2-vehicle truck side impact crashes during 2006–2008, or 22 percent of all passenger vehicle occupants who died in 2-vehicle crashes with large trucks.*

Conclusions: *Structural incompatibility was a common factor in LTCCS crashes between passenger vehicles and the sides of large trucks. SUGs could have reduced injury risk in around three fourths of the crashes that produced an AIS ≥ 3 injury or fatality. Most of these crashes involved semi-trailers. However, the necessary strength and location of these SUGs present technical challenges that need to be addressed.*

Keywords Large truck crashes; Side underride guards; Occupant fatalities; Compatibility

INTRODUCTION

Twenty-three percent of passenger vehicle occupants killed in 2-vehicle crashes during 2000–2009 were in collisions with large trucks, despite the fact that large trucks accounted for less than 10 percent of all vehicle miles traveled during this period (Federal Highway Administration 2011; Insurance Institute for Highway Safety, unpublished data, 2011). The greater ride height of large trucks is one of the factors contributing to their overrepresentation in fatal crashes with passenger vehicles, and Federal Motor Vehicle Safety Standards (FMVSS) 223 and 224 outline requirements for underride guards on the rears of large trucks in the United States. However, there are no guard requirements for the sides or fronts of large trucks in the United States. European Union regulations require guards on the fronts, sides, and rears of trucks, but the side guards are much weaker and are intended only to protect pedestrians and bicyclists (United Nations Economic Commission for Europe 1988).

Blower et al. (2001) estimated that the fronts, sides, and rears of large trucks were involved in 59, 22, and 12 percent, respectively, of passenger vehicle occupant fatalities in 2-vehicle crashes with large trucks during 1996–1998, with the remainder classified as other or unknown. The authors reported that the distribution shifted to 34, 40, and 17 percent, respectively, for the fronts, sides, and rears of large trucks when considering occupants sustaining an incapacitating injury, as coded by

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police. They could not estimate how many of these fatalities and injuries were the result of underride but concluded that the substantial proportion from truck side impacts suggested that "design changes to reduce [side] underride seem like a necessary first step" (p. 11).

This recommendation contrasts with 2 other analyses. In developing its rear underride guard regulation, the National Highway Traffic Safety Administration (1991) stated that "side underride countermeasures have been determined not to be cost-effective" (p. 15). The agency reported an average of 61 passenger vehicle occupant fatalities each year during 1982–1989 resulting from underride with the side of a large truck, or about 2 percent of fatalities in crashes with large trucks. Padmanaban et al. (2008) conducted a similar study using 1994–2005 data and reported an average of 78 annual fatalities in side underride crashes with combination trucks. This represented 3 percent of all fatalities in crashes with combination trucks and 20 percent of those that were truck side impacts.

Both the National Highway Traffic Safety Administration (1991) and Padmanaban et al. (2008) based their estimates on underride codes in the Fatality Analysis Reporting System (FARS), which has been shown to drastically underreport the incidence of underride. In fact, the authors of the latter study identified cases from the National Automotive Sampling System–Crashworthiness Data System (NASS-CDS) where the NASS investigator reported underride of a combination truck and matched these cases with crashes in FARS. FARS indicated underride in just 5 of the 32 matches. Despite this, no adjustment was made to the annual fatality estimates calculated from FARS underride codes. Braver et al. (1997) found a similar discrepancy between underride codes in FARS and NASS-CDS. In another study, Braver et al. (1998) reviewed on-scene photographs and police reports of 107 fatal crashes and found that 50 produced underride extending into the passenger compartment, but the FARS codes indicated just 6 cases of underride. Finally, a review of rear truck crashes in the Large Truck Crash Causation Study (LTCCS) found that 23 of 28 fatalities involved underride into the passenger compartment compared with just 8 instances of FARS-reported underride for these cases (Brumbelow and Blanar 2010).

The current study used a detailed LTCCS case review process to evaluate the potential for side underride guards (SUGs) to reduce passenger vehicle occupant fatalities and injuries in crashes with large trucks. Though previous research has utilized the detailed measurements and photographs of passenger vehicles in NASS-CDS to verify underride codes in NASS-CDS and FARS, the lack of corresponding information for large truck crash partners precludes a full analysis of the vehicles' structural interaction. In many cases, NASS-CDS does not even report the type of truck or trailer involved in the crash. LTCCS contains the detailed truck information and postcrash photographs necessary for this research.

METHODS

The LTCCS is a sample of 1070 crashes that occurred during 2001–2003 (Toth et al. 2003). A qualifying crash involved at least one truck with a gross vehicle weight rating (GVWR) of more than 4536 kg and resulted in a fatality, incapacitating injury, or nonincapacitating but evident injury (K, A, or B on the KABCOU scale, where C represents possible injury, O no injury, and U unknown). A crash researcher and state truck inspector were involved in data collection for each case. Gathered data came from official reports, site investigations, vehicle inspections, and interviews with those involved in the crash, witnesses, motor carrier representatives, and family and friends of involved occupants. Approximately 1000 variables were gathered for each crash, including detailed truck and trailer measurements, information on other vehicles in the crash, occupant injuries, and crash circumstances. Photographs of the vehicles also were recorded. An effort was made to collect much of the data and photographs at the crash scene. Brumbelow and Blanar (2010) used the LTCCS to evaluate FMVSS 223 and 224 in rear truck crashes. The current study used a similar case review process to investigate crashes between passenger vehicles and the sides of large trucks. A large truck was defined as any truck with a GVWR of more than 4536 kg. Passenger vehicles included cars, vans, sport utility vehicles (SUVs), and pickups with GVWRs less than 4536 kg.

Of the 2777 LTCCS events (EVENT, defined by LTCCS as any contact between 2 vehicles or a vehicle and other object), those selected for initial review were impacts between a passenger vehicle and large truck that had not been previously determined by Brumbelow and Blanar (2010) to be rear impacts and for which the truck's coded general area of damage (GAD) was not "front." The GAD codes for the remaining impacts were "back-rear of tractor," "left side," "right side," "undercarriage," and "front of cargo area." The photographs and crash summary were used to confirm that the impact was to the side of the truck and that the involved vehicles were a large truck and passenger vehicle. If either of the studied vehicles rolled over prior to the impact between them, the case was excluded. For all cases, sufficient photographic documentation of both vehicles was required to evaluate the interaction between the passenger vehicle impact point and truck side.

Some broad differences between the side impact cases and the rear impacts previously studied required adaptations to the review process. For example, the passenger cars involved in the truck rear impacts rarely had another crash event, but those in the side impacts often struck other vehicles, fixed objects, or even the same truck multiple times. To account for this, it was necessary to determine which impact was most likely to have produced the most severe injury to any occupant in the passenger vehicle as measured on the Abbreviated Injury Scale (VMAIS). When this event was an impact other than the event of interest with the side of the truck, the interaction with the truck was still studied but the fact that the VMAIS came from a different event was accounted for when evaluating the potential effect of SUGs. Though the presence of multiple-event crashes was a potential source of error in estimating the number of cases in which SUGs could reduce injury severity, the vehicle dynamics and damage patterns usually indicated that the passenger vehicle experienced one major crash event and one or more events that

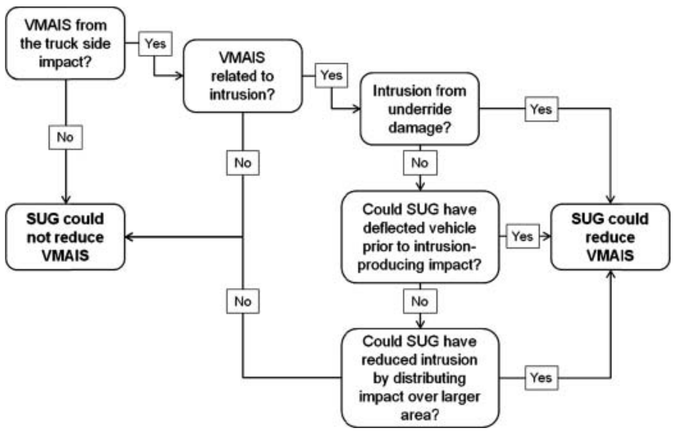

Figure 1 Flowchart for determining whether an SUG could reduce VMAIS.

were much less severe and unlikely to have caused injury. This was especially true in crashes that resulted in an AIS ≥ 3 injury. When there did appear to be more than one crash event of substantial severity, the seat position of the injured occupant and the location of the injury were used to evaluate which event was most likely to have produced the VMAIS. However, in some cases no judgment could be made and it was assumed that an SUG could not have reduced the VMAIS.

Some LTCCS cases contained multiple relevant events when different passenger vehicles contacted the side of a single truck or when a single passenger vehicle contacted the sides of 2 different trucks. All such events were included in the analyses. However, in cases where one passenger vehicle contacted the side of the same truck multiple times, only the most severe impact was analyzed.

Underride occurrence and severity were determined using the categories established by Braver et al. (1998). The presence of underride meant that the extent of damage in one of the 3 vertical regions defined by the collision deformation classification (CDC) was greater than the extent in the region directly below it. The CDC defines the vertical regions as (1) the greenhouse, which includes all vehicle structure above the belt line; (2) the middle region between the belt line and the top of the frame/bumper; and (3) the low region with all structure below the height of the top of the frame (Society of Automotive Engineers 1980). The categories of none, negligible, slight, moderate, severe, and catastrophic were used to describe the underride severity.

There were cases where the passenger vehicle did not sustain damage meeting the definition of underride but where an SUG still could have reduced the crash severity. Most commonly this occurred when a portion of the passenger vehicle passed under the side of a trailer before running into the front or rear surface of the truck's or trailer's wheels. In these cases, the side structure of the trailer may not have produced underride damage, but an SUG could have created an oblique impact, deflecting the vehicle away and preventing the more severe wheel contact. Figure 1 illustrates the process used to identify cases where an SUG could have been expected to reduce the VMAIS. As stated above, the first step was to exclude cases where the VMAIS appeared to result from an impact other than the one with the side of the truck. Then it was necessary to determine which VMAIS injuries likely were related to occupant compartment intrusion sustained during the truck side impact. When this intrusion was the result of underride damage, it was assumed that an SUG would be helpful in mitigating the severity of the VMAIS. When the intrusion was not related to underride, an SUG was still expected to lower the VMAIS if it could have substantially reduced the intrusion severity either by deflecting the passenger vehicle away from the truck or by spreading the forces of the impact over more of the passenger vehicle's structure. Though it is conceivable that SUGs could have affected some injuries not related to intrusion or injuries occurring in impacts subsequent to the truck side impacts, these possibilities were not explored.

The LTCCS contains case weights intended to make the data nationally representative, but concerns have been raised that the weights do not account for potential biases in the sample (Blower and Green 2009). The current study was based on a subsample of LTCCS cases and includes some investigated in a pilot segment that were not assigned weighting factors. Also unweighted were cases where a passenger vehicle struck a large truck parked off the roadway or where investigators determined that there were no crash-related injuries. These cases were retained for study because they provided insight into the underride problem. For these reasons, LTCCS weighting factors were not used.

LTCCS crashes resulting in a fatality were matched to corresponding crashes in FARS using a combination of the first 10 characters of the vehicle identification numbers supplied in LTCCS and the crash year, month, and time of day. This was done to compare the FARS underride coding with the results from the LTCCS case review. In addition, 2006–2008 data from FARS and the supplemental Trucks Involved in Fatal Accidents (TIFA) survey conducted by the University of Michigan Transportation Research Institute were analyzed (Jarossi et al. 2011). This was done to provide an updated estimate of the number of fatalities in truck side crashes and to compare the distribution of truck types in the reviewed LTCCS cases with the larger and more recent sample of fatal side crashes. As noted by Blower et al. (2001), the FARS-coded clock point description of the impact location is not as meaningful for large trucks as for light vehicles, so a combination of the impact location and the TIFA "accident type" variable was used to define truck side impact crashes. Only 2-vehicle crashes where the passenger vehicle's most harmful event was an impact with the other vehicle were included.

RESULTS

There were 206 LTCCS events involving an impact between a passenger vehicle and the side of a large truck that could be studied. Some of the LTCCS cases contained multiple passenger vehicles contacting the side of a truck or a single passenger vehicle contacting the sides of multiple trucks; the total number of events came from 195 LTCCS cases and involved 204 passenger vehicles and 197 trucks. Many of the passenger vehicles had crash

Table I Underride severity and potential benefit of SUG for LTCCS truck side impacts

	VMAIS not from truck impact	VMAIS from truck impact; Could SUG reduce VMAIS?		
		Yes	No	Total
No/negligible underride	44	11[a]	34	89
Slight/moderate underride	13	5	21	39
Severe/catastrophic underride	6	60	12	78
Total	63	76	67	206

[a]Includes one case where underride severity could not be determined.

Table II Passenger vehicle occupant fatalities in 2-vehicle crashes by truck contact location, 2006–2008 TIFA

	Front	Side	Rear	Unknown[a]	Total
Fatalities	4141	1468	953	603	7165
Percentage of total fatalities	58	20	13	8	
Percentage excluding unknowns	63	22	15		

[a]Includes cases where the truck's most harmful event was not a collision with the other vehicle.

events other than the event of interest with the side of the truck, and these other events often appeared to be the likely source of the most severe injury sustained by any occupant of the vehicle (VMAIS). Of the 206 truck side impacts studied, 143 appeared to be the source of the VMAIS. For the remainder, the crash event likely producing the VMAIS either preceded the truck side impact (19 cases), was subsequent to the truck side impact (24), or could not be determined (7). In addition, there were 13 passenger vehicles in which all of the occupants were uninjured and inclusion in the LTCCS was due to an injury in another vehicle.

In 94 of the 143 instances where the VMAIS resulted from the truck side impact, the most severe injury was minor or moderate (1 or 2 on the AIS scale), 24 were VMAIS ≥ 3 but nonfatal, and the remaining 25 produced at least one fatality. Using vehicle photographs, scene diagrams, and case narratives, it was determined that SUGs could have reduced the VMAIS severity in 76 of the 143 cases, including 16 of the VMAIS ≥ 3 nonfatal crashes and 22 of the cases with a fatality. The association between underride severity and the potential for SUGs to reduce the VMAIS is listed in Table I.

Comparisons With FARS/TIFA

Overall, 2006–2008 FARS contained 7250 passenger vehicle occupant fatalities in 2-vehicle crashes with large trucks where the most harmful event was coded as an impact with another vehicle. This is 27 percent fewer than the number of passenger vehicle occupant fatalities in all crashes involving a large truck, but it is not possible to link crash partners in cases with more than 2 vehicles. TIFA contained associated records for 99 percent of the 2-vehicle crashes. After excluding unknowns, the fronts, sides, and rears of large trucks were involved in 63, 22, and 15 percent of the crashes, respectively (Table II). This indicates that approximately 530 passenger vehicle occupants died, on average, each year during 2006–2008 in 2-vehicle crashes in which the passenger vehicle struck the side of a large truck.

Matching FARS cases were identified for 25 of the 26 fatal LTCCS crashes (there was a fatality in 1 of the 7 crashes where the VMAIS-producing event could not be determined). Based on the LTCCS case reviews, the underride was considered moderate in one case and severe or catastrophic in 22 others, with 20 involving the front or rear of the passenger vehicle and 3 involving the side. LTCCS codes indicated underride in 11 of the 25 cases. FARS codes indicated the presence of underride in 3 cases, unknown underride in one, and no underride for the remaining 21.

The distribution of side-impacted truck types in LTCCS was similar to that in 2006–2008 TIFA. Crashes with straight (non-articulated) trucks accounted for 21 percent of the LTCCS sample and 20 percent in TIFA, with the remainder involving tractor-trailers or tractors without trailers. The types of straight truck and trailer units are shown in Figure 2. In TIFA it is not possible to determine which units were contacted for combination trucks, so all trailer types are shown for the tractor-trailers in LTCCS even if the analysis revealed that the main side loading was to the tractor. For straight trucks, too few were pulling trailers to make meaningful comparisons, so only the truck units are compared.

Figure 3 shows the part of the truck where the main loading occurred in the LTCCS cases. Semi-trailers accounted for almost half of the events, truck-tractors around one third, and the cab and cargo portions of straight trucks made up most of the remainder. Trailer impacts also resulted in the VMAIS more commonly than impacts with the other types of truck units, and they accounted for three fourths of the cases where an SUG could be expected to reduce the VMAIS. The type of truck unit is not shown in Figure 3 for 10 impacts: 4 with trailers being pulled by a straight truck, 2 with tractor-trailers where loading from both truck units appeared to be of similar severity, and 2 involving mobile homes that were being transported.

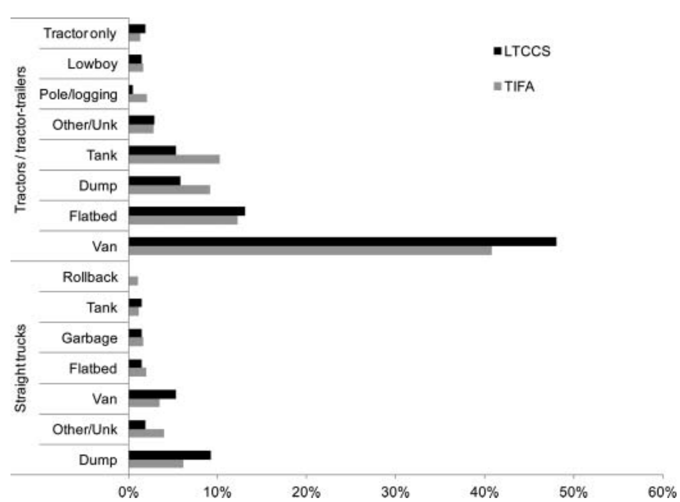

Figure 2 Distribution of side-impacted truck types in LTCCS and 2006–2008 TIFA.

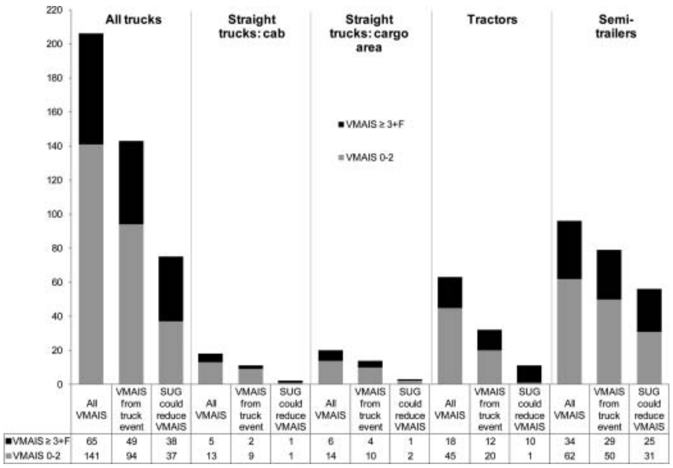

Figure 3 Involved truck unit and potential benefit of an SUG.

Semi-Trailer Crashes

There were 5 crash configurations for the semi-trailer side impacts (Table III). The most common was a side-to-side impact with both vehicles initially traveling in the same direction. These typically resulted from one of the vehicles moving into the other vehicle's lane due to unintentional drifting or failure to recognize that the adjacent lane was occupied. The second configuration also involved both vehicles initially traveling in the same direction, but loading had an oblique component usually due to a loss of control of one vehicle prior to the impact. Perpendicular front-to-side crashes were the third most common configuration. Most of these occurred at controlled intersections, but some trucks were struck as they made a U-turn or after a loss of control left them perpendicular to the direction of travel. The fourth configuration typically occurred when the passenger vehicle crossed a centerline or median into oncoming traffic, producing an oblique frontal impact with the side of the truck. The final, least common, configuration involved impacts between the side of the trailer and the rear of the passenger vehicle. Three of the 7 such cases occurred when the truck was approaching the passenger vehicle from behind, lost control, and the trailer jackknifed prior to impact.

With the exception of the rear-to-side configuration, there was an inverse relationship between the frequency of each configuration and the proportion of those events that resulted in a serious injury or fatality (VMAIS $\geq$ 3+F). Only 3 of the 33 side-to-side crashes resulted in a VMAIS $\geq$ 3+F injury to an occupant of the passenger vehicle, whereas 8 of the 12 oblique/opposite crashes produced such an injury. Of the 28 crashes where a VMAIS $\geq$ 3+F injury did result from the trailer side impact, the improved compatibility offered by an SUG would have been expected to reduce the injury severity in all but 3 cases.

The location on the trailer where the SUGs would need to be located also was considered. For the 25 cases where a VMAIS $\geq$ 3+F injury could have been mitigated by a SUG, the necessary placement of the guard likely would have overlapped the forward most location of the rear sliding axles in 8 cases. In another case, the SUG would have needed to be located so far forward that it may have affected the articulation of the truck. In a tenth case, an SUG may have affected the operation of a bottom dump trailer.

Truck-Tractor Crashes

After semi-trailers, truck-tractors were the second most commonly impacted type of truck unit, accounting for 63 of the 206 events. More than half of the events were side-to-side impacts (Table IV). In most of these, the VMAIS was due to a preceding or subsequent event, and injuries that did result from the truck side impact were not serious (AIS 1 or 2). Around one fourth of the truck-tractor crashes were front-to-side impacts, and in most the VMAIS was due to the truck impact. The remaining truck-tractor events were a mix of oblique/same direction, oblique/opposite direction, and rear-to-side crashes.

Table III Crash configurations for semi-trailer side crashes

	Side to side	Oblique same direction	Front to side	Oblique opp. direction	Rear to side	Total
All VMAIS						
All impacts	33	25	19	12	7	96
VMAIS from unknown event/no injury	4	—	1	1	1	7
VMAIS from preceding event	5	1	—	—	1	7
VMAIS from subsequent event	3	1	—	—	—	4
VMAIS from truck event	21	23	18	11	5	78
SUG could reduce VMAIS	12	19	12	11	2	56
VMAIS $\geq$ 3+F						
All impacts	7	7	9	8	3	34
VMAIS from preceding event	3	—	—	—	1	4
VMAIS from subsequent event	1	1	—	—	—	2
VMAIS from truck event	3	6	9	8	2	28
SUG could reduce VMAIS	3	6	7	8	1	25
SUG could reduce VMAIS $\geq$ 3+F, by required guard location						
Between truck and trailer wheels	2	3	4	5	1	15
Overlapping trailer wheels	1	3	3	1	—	8
Other possibly impractical location	—	—	—	2	—	2

Table IV Crash configurations for tractor side crashes

	Side to side	Oblique same direction	Front to side	Oblique opposite direction	Rear to side	Total
All VMAIS						
All impacts	34	8	14	5	2	63
VMAIS from unknown event/no injury	5	1	2	—	—	8
VMAIS from preceding event	6	1	1	—	—	8
VMAIS from subsequent event	15	—	—	—	—	15
VMAIS from truck event	8	6	11	5	2	32
SUG could reduce VMAIS	—	1	4	5	1	11
VMAIS ≥ 3+F						
All impacts	4	2	6	5	1	18
VMAIS from preceding event	2	1	1	—	—	4
VMAIS from subsequent event	2	—	—	—	—	2
VMAIS from truck event	—	1	5	5	1	12
SUG could reduce VMAIS	—	1	3	5	1	10
SUG could reduce VMAIS ≥ 3+F, by required guard location						
Between first and second axles	—	—	2	5	1	8
Forward of 1st axle	—	1	1	—	—	2

Overall, equipping truck-tractors with SUGs may have reduced the VMAIS in 11 of the 32 cases where the injury was due to the truck impact. Considering only VMAIS $\geq$ 3+F injuries from the truck loading, 10 of 12 could have been mitigated with SUGs. Most of these were oblique/opposite direction or front-to-side crashes. In 2 cases where an SUG could have been helpful, the truck was struck between the front wheel and the front corner of the tractor, so a guard would have needed to fill this space. In the other 8 cases, a guard between the first and second axles could have improved the structural interaction between the vehicles.

DISCUSSION

Analysis of 2006–2008 TIFA data indicates that around 22 percent of passenger vehicle occupant fatalities in 2-vehicle large truck crashes involve the side of the truck. This is consistent with the results of Blower et al. (2001) using 1996–1998 TIFA data. Blower et al. also used the General Estimates System to look at crashes resulting in nonfatal injuries and found that more occupants sustained incapacitating injuries from crashes with sides of trucks than with the fronts. Based on the LTCCS sample, fitting the sides of semi-trailers with underride guards could reduce the injury severity of around half of the crashes where a serious or fatal injury resulted from an impact with the side of a large truck. If SUGs also were installed on truck tractors, three fourths of the crashes with serious or fatal injuries from truck loading could be addressed.

In reality, however, it would be difficult to achieve the full potential injury reduction for a few reasons. First, for maximum effectiveness these SUGs would need to extend outboard of the wheels for trailers with sliding axles, or trailers would need to be redesigned without sliding axles. Both of these options present technical challenges. Second, the analyses were conducted under the assumption that there would be minimal relative displacement between an SUG and the truck structure that loaded the passenger vehicle in these crashes. This level of strength likely would require a guard and support system of substantial mass, especially in the front-to-side and oblique/opposite direction crashes. As listed in Table III, these configurations accounted for the majority of the crashes producing serious injury where a SUG could have been beneficial. Though much more common overall, the side-to-side and oblique/same direction configurations accounted for fewer of the serious injuries.

Kumar et al. (2009) designed and tested a guard system that prevented underride of a small car striking a stationary van semi-trailer at 56 km/h and a 45 degree angle (Figure 4). The guard spanned the side of the trailer between the landing gear and the forward position of the sliding axles, had a ground clearance of 51 cm, and weighed 435 kg (S. Kumar, email communication, February 2012). Others have suggested that the best approach requires redesigning trailers with lower decks or frames as opposed to attaching dedicated guard systems (Gugler et al. 2010). One example of this strategy was the Krone Safe Liner (Figure 5), previously available in Europe (Schenck 2000; Wüst 1999). The practical implications of converting the U.S. trailer fleet to such designs or of fitting trailers with strong guard systems should be evaluated in light of the potential benefits, but this is beyond the scope of the current study. However, some of the issues discussed by others considering the implementation of side guards to protect pedestrians and bicyclists are relevant, including the effect on maximum payload, aerodynamics, brake cooling, access to underbody equipment for inspection or repair, break-over angle, and the collection of snow, ice, and mud (National Research Council Canada 2010).

A third potential limitation of SUG effectiveness is that though guards could have prevented the specific injuries observed in these cases due to passenger compartment intrusion, they would not have transformed every crash into a low-severity event. Some occupants still could have sustained other injuries due to a lack of restraint use, high deceleration levels, or other factors. Finally, it is possible that strong SUGs could create

Figure 4 SUG designed and tested by Kumar et al. (2009).

more glance-off crashes and that serious injury could still occur in events subsequent to the truck impact. Twelve percent of the VMAIS injuries in the current study were the result of an event subsequent to the truck impact. Roughly half of these events involved other passenger vehicles or fixed objects offering a more distributed reaction surface than the side of a typical semi-trailer, but other factors (e.g., relative direction of travel, rotation of the subject vehicle between events, restraint system effectiveness in multiple impacts) complicate the understanding of how SUGs could affect these crashes.

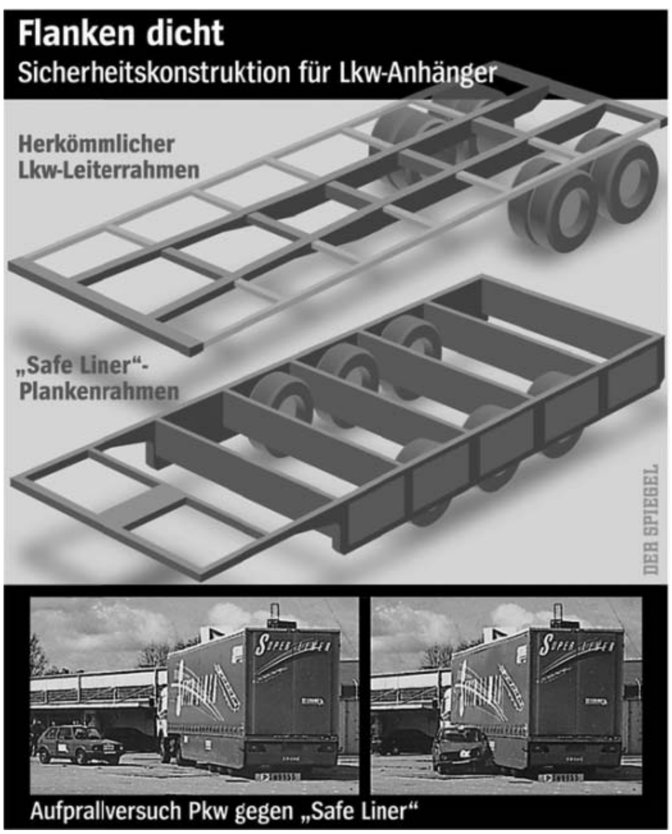

Figure 5 Krone Safe Liner compared to conventional design (Der Spiegel 22/1999).

Despite these unknowns, strong SUGs still would have a beneficial effect for many passenger vehicle occupants involved in large truck crashes. Consumer and regulatory test programs have resulted in passenger vehicles that have the structural capacity to interact with rigid objects while maintaining the integrity of the occupant compartment in frontal crashes at speeds of at least 56 to 64 km/h. In addition, improvements in structures and restraint systems have increased the ability of vehicles to protect their occupants when struck in the side by other passenger vehicles (Teoh and Lund, 2011). Based on the LTCCS sample, this crashworthiness is not utilized in the majority of truck side crashes producing serious injuries or fatalities; 38 of the 49 impacts producing serious or fatal injury could have been less severe if the truck had been equipped with a SUG. Active safety technologies such as lane departure or forward collision warning could help to prevent some of these crashes, including those where a SUG would not be helpful, and could reduce the severity of others, thus also reducing the level of guard strength necessary to prevent underride. However, it may be decades before most vehicles on the road are equipped with these systems (Insurance Institute for Highway Safety 2012), and their effectiveness in crashes with large trucks is not yet known. Finally, though guards likely would create more glance-off truck impacts with subsequent crash events, it is not possible to estimate how often these events would increase the overall injury risk relative to contacting the side of a truck without a guard.

Previous studies have found that FARS codes underreport underride relative to NASS-CDS (Braver et al. 1997; Padmanaban et al. 2008) and relative to photograph-based case reviews (Braver et al. 1998; Brumbelow and Blanar 2010). The current analysis further demonstrates that estimating the incidence of truck underride using FARS data is problematic. Only 3 of 22 fatal crashes with severe or catastrophic truck side underride based on the case review were coded as having side underride in FARS. The extent of the underreporting in FARS may partly be due to state crash reporting practices. Among the 17 states with at least 500 fatal 2-vehicle crashes involving a passenger vehicle and a large truck in 2000–2009 FARS, reported underride rates ranged from 0 percent (South Carolina) to 21 percent (Ohio).

CONCLUSIONS

Detailed LTCCS case reviews demonstrate that structural incompatibility is a common factor in injury-producing crashes between passenger vehicles and the sides of large trucks. Side underride guards could have reduced the injury risk in around half of all crashes where the most severe injury came from the truck side impact. Maximum potential reductions would be proportionally greater for crashes resulting in serious or fatal injury; up to three fourths could have been mitigated by a side underride guard. Most of the benefits for the crashes in the

LTCCS sample would have been obtained from guards fitted to semi-trailers, but technical challenges such as the strength and positioning of guards must be overcome. To the extent that comparisons could be made between the LTCCS sample and national fatal crash databases, they support the relevance of the current analyses to all fatal truck side crashes.

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