Feasibility of Heavy Truck Occupant Protection Measures

Final Report

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16. Abstract

This document presents the results of a study undertaken to explore the feasibility of improving the crash injury outcomes of large truck (GVWR > 10,000lbs) occupants through the use of suitable crash protection systems. Four main tasks were performed as part of this study: (i) A survey of the state of the art in truck occupant protection systems was compiled; (ii) Truck crash data from the US road system was compiled and analyzed; (iii) Truck crash simulation models and occupant injury models were developed; (iv) The potential benefits of various occupant protection countermeasures were quantitatively analyzed.

Analysis of crash data showed that while the majority of truck crashes involve collisions with smaller vehicles, the most serious injuries to truck occupants occur in collisions with either other trucks, or fixed roadside objects. About 744 fatalities and 29,000 non-fatal injuries are suffered by truck occupants annually. 633 fatalities were suffered by truck drivers and 410 of these or almost 2/3^{rds} occurred in single vehicle crashes. Another 94 occurred in two vehicle truck-truck crashes.

A truck crash model was developed using crash test and simulation data available in the literature. An occupant injury model was developed using the MADYMO software package. The results of the computations with and without safety belts was compared with the previously obtained results (from crash data) and the reduction in fatality rates showed good agreement thus providing confidence in the validity of the simulation. The improvement in effectiveness (over safety belt alone) of using both safety belts and airbags was computed again using the truck crash ∇V distribution. The calculations show an estimated reduction of 253 in K and A injuries with the use of both airbags and safety belts, which corresponds to approximately a further 6% (253 out of 4540 annual K and A injuries) reduction over the use of safety belts alone.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kpa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
rnL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	**1.8C + 32**	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

Introduction

Examination of the Trucks Involved in Fatal Accidents (TIFA) and the General Estimates System (GES) databases shows that, over the five-year period from 1995 to 1999, annually about 376,000 large trucks (Gross Vehicle Weight Rating (GVWR) over 10,000 lbs) were involved in traffic crashes on U.S. roads. These crash involvements resulted in considerable loss in terms of deaths, injuries (ranging in severity from incapacitating (A injuries) to complaint of pain (C injuries)), and property damage. Although the lighter vehicles involved in the crashes suffered the most damage, the adverse effects to the truck and its occupants are also significant and bear investigation for the purpose of reducing their severity and costs. Annually, about 744 truck occupants are killed and 29,000 are injured in traffic crashes. Considering just truck drivers, an average of 633 drivers was killed and 24,000 were injured.

This document presents a report of a study to investigate the feasibility of improving post crash truck occupant protection using truck interior countermeasures undertaken in December, 2001, at the University of Michigan Transportation Research Institute (UMTRI) with support (Reference No. CR 19337-425480: UM Sub. To Virginia Tech – DOT Contract No. DTNH 22-00-C-07007) from the National Highway Transport Safety Administration (NHTSA).

1.1. Survey of Truck Occupant Protection Systems

1.1.1. Truck Crash Characteristics

Seiff (1985) identified some of the major characteristics of truck crashes and a follow up study, Seiff (1989) documented the improvements in truck safety both in terms of reduced crash rates (on a per mile traveled basis) and the decreased injuries and fatalities to both car and truck occupants in truck involved crashes.

- Large trucks (weighing over 10,000 lbs) are involved in about 13% of all fatal highway crashes. Only about 18% of these fatalities are truck drivers themselves, 82% of the fatalities were pedestrians or occupants of other vehicles involved in the crash. (1976-1983 data, Seiff (1985))

- About 72% of fatal (occurring both in the truck and in the other vehicle) truck crashes are multi-vehicle crashes, 15% are single vehicle crashes and 8% are trucks hitting pedestrians or cyclists.
- A vast majority (about 70%) of truck occupant fatalities occur in single vehicle crashes. Rollover is involved in 60% of truck occupant fatalities, ejection in around 35%, extrication in about 22%, and 16% of cases involve fires.

Cheng (1996) more recently explored the issue of truck crash characteristics, through in-depth studies of 68 fatal truck crashes. The author stated that the statistical characteristics of these 68 cases closely approximate those of FARS, with the exception of one crash type – that in which the truck strikes a fixed object after rollover. The author's opinion is that the difference in this case results from the fact that FARS consistently underestimates this category of crashes.

From the case studies, fatal truck crashes can be classified into the following categories:

- Head on collisions: These involve collisions between trucks traveling in opposite directions and make up about 22% of fatal multi-vehicle truck crashes. In these cases the collision is usually significantly offset or even a sideswipe. High closing speeds are observed in this crash type which results in significant intrusion into the driver side of each tractor.
- Rear end collisions: These involve a faster moving truck striking the rear of a slower moving or stationary truck, mostly with full contact and constitute about 52% of fatal multi-vehicle truck crashes. Significant damage and intrusion is caused to the cab of the striking tractor due to height mismatch between the striking tractor frame and the struck trailer frame.
- Collisions with fixed objects: These crashes generally involve boulders, buildings, guardrails etc. Significant or total cab destruction can result if the struck object is large such as a bridge pier or building. If smaller obstructions are struck, the severity of the crash usually results from rollover. The author presents FARS (1975-89) data showing that these two crash types (striking fixed objects without and with rollover) constitute respectively 20% and 18% of fatal truck crashes.

Crashes with rollover can themselves be further distinguished into the following types.

- 90° rollover without subsequent collision: In this case there is minor cab deformation and intrusion.

- 90° rollover with subsequent collision: There may be significant cab damage and intrusion in this case and the collision after the rollover is the most harmful event.
- 180° rollover: In this case the tractor finally rests on its roof. Flat bed trailers are much more likely to experience 180° rollovers than van trailers. There is extensive destruction of the cab in the vertical direction, and the roof may be forced down to the seat level, totally compromising survival space.

Berg (1997) undertook a comprehensive study of truck usage statistics and truck crash figures in Germany from 1970–1995. The paper presented a general overview of crashes involving commercial vehicles, based on a study of 400 crashes. Information about test and simulation studies of commercial vehicle crash testing is also included. The author states that collisions of trucks against the rear of other commercial vehicles are an important but neglected subject of study. These kinds of crashes account for 29% of commercial vehicle crashes in Germany and are very severe to the truck experiencing the frontal impact. There is significant structural incompatibility between the two vehicles in this case leading to high cab deformations even in low speed crashes and a high percentage of severe truck occupant injuries or fatalities.

Overall, a large majority (~70%) of fatal truck crashes involve only a single vehicle – the truck itself. Further, three crash modes or a combination of these, dominate all fatal crashes. These three are (i) rollovers, (ii) collision with fixed objects, and (iii) collision with another vehicle. A significant proportion (55%) of fatal crashes is associated with rollovers. Furthermore whenever rollover appears with combination of other modes, the rollover itself frequently is the most harmful event to the driver.

1.1.2. Causes of Injury to Truck Occupants

While the aforementioned studies investigated the common characteristics of truck crashes, a number of studies considered the issue of the relationship between these characteristics and the injury modes or mechanisms observed in the occupants of the truck.

Neilson (1987) reviewed literature and data relating to heavy truck usage on the European road system. The major causes of injuries observed in truck crashes are ejection from the cab or crushing of the cab structure. The principal crash types in which ejection is observed are frontal impacts (even at low speeds) and rollovers. Ejections through the front windscreen are most common. Significant crush of the cab structure leading to occupant injuries occurs mostly in collisions with other large trucks or with fixed objects such as roadside structures.

Eggleman (1987) studied in detail 136 truck crashes, from both the U.S. and Europe, in which the truck occupant was injured. The study too, noted the importance of ejection and entrapment (cab crush) but added a third cause of injury, namely, impact with the interior components which may occur with or without intrusion due to cab crush. The most common part of the body injured is the head with 55% of all injured occupants suffering head injuries. Injuries to arms and legs are second most common though they are generally not as serious. The author notes that truck cabs offer relatively little protection (compared to passenger automobiles) in the form of energy absorbing crush space and thus are more prone to intrusion or entrapment type injuries.

Seiff (1985) using US crash data identified rollover and ejection (occurring either separately or together) as the cause for the greatest number of truck occupant fatalities. Rollover is involved in 59% of driver fatalities, with ejection found in 34.5%. Driver extrication (indicating crush or entrapment type injuries) was necessary in about 22% of fatal crashes. Fire was involved in 16% of truck driver fatalities. Many of the fatal crashes involve more than one of the previously mentioned injury mechanisms.

Berg (1997) also identified ejection and cab crush as primary factors in driver injury. Of all the ejected occupants 50% were killed and 33% of all occupants that were pinned in the cab were also fatally injured. In comparison only 7% of occupants who were not ejected or pinned suffered fatal injuries.

Of all the interior cab objects causing injury, the steering wheel is the most common, indicating the steering wheel is a target for design improvement efforts. Other conspicuous areas are the dashboard and foot/leg area. The author also mentions that in 2% of the cases the retention system itself was the cause of the injury. Given that very few trucks included in the survey were fitted with seat belts and that the usage of these is also very low, this strongly indicates a need for further improvements in the retention technology.

Ranney (1981) noted some specific patterns in the injury mechanisms relating to interior impacts. Impact with the steering assembly is the most common cause of injury followed by impacts with the instrument panel, doors and windows, and finally windshield and roof. Also impacts with the steering assembly cause the most severe injuries, followed by the relatively infrequent injuries due to the roof.

Injuries to the head are most common, followed by upper extremities and thorax. Injuries to the abdomen and thorax are almost exclusively caused by the steering assembly and are typically the most severe. Heavy trucks differ from the rest of the truck population in that steering assembly impacts result more commonly in chest injuries (as opposed to the head) and can be quite severe.

Grandel (1989) also studied the interior of truck cabs. The goal of this study was to examine exterior and interior cab deformations in truck crashes and their relation to occupant injury. For this purpose data from 100 truck crashes (involving trucks with payload > 3.5 tons) in which occupants were injured were analyzed. The results of the first 33 crash investigations are reported in this paper.

- Truck/Truck crashes play the largest role in occupant injury. Car/Truck crashes are also found to be dangerous for truck passengers because the impact can lead to dangerously unstable driving conditions that cause overturning or secondary impacts. Single vehicle crashes like overturning did not lead to above-average injuries. Also, for truck/truck crashes, head on collisions were not as dangerous as rear-end collisions, which caused more fatalities and serious injuries (to the occupant of the truck that strikes the rear of the other vehicle) due to the strength and stiffness mismatch between truck cabs (relatively soft) and rear structures (stiff).
- Cab deformation: Even relatively minor deformations of the cab exterior (less than 20 cm) can cause serious or fatal injuries occur, but only as a result of truck occupants being ejected from the cab. Deeper deformations (between 20 and 40 cm) cause serious injuries often and fatalities less often. Deep deformations (above 40 cm) often cause serious injuries and fatalities.
- Interior impacts: The steering assembly most often causes injury to drivers. The steering wheel/steering column often comes up together with the foot/leg area causing serious injuries especially to the legs and chest. Interior components that suffer damage (like pillars) do not generally cause injury, whereas parts like the steering column that do not deform cause much

greater injury, because the deformation acts as an energy dissipation mechanism to soften the impact of the occupant against the component.

1.1.3. Truck Occupant Crash Protection Countermeasures

The subject of interior crash protection has received significantly more attention for automobiles than for commercial vehicles. The experience gained from these studies forms a good foundation for designing improved truck occupant protection systems and will be briefly surveyed here, before focusing on the literature relating to heavy trucks.

Hobbs (1980) provides an in-depth analysis of injury patterns and mechanisms for car occupants. Gabler (1991) studied the safety performance of cars with respect to interior head impacts using sled tests with Free Motion Head Form (FMH) dummies. The study concluded that even as little as 1 inch of padding on the interior surfaces most involved in head impacts can reduce the head injury criterion (HIC) by as much as half. Scott (1995) studied car-truck collisions and the improvements in injury outcomes possible through the use of interior countermeasures. Hollowell (1996) presents results from car crash tests against both other cars and deformable or moving barriers. The principal conclusion of the study is that airbags prevent serious head or chest injuries in all but the most severe crashes, but that lower extremity injuries are more common and require improvements in protection systems. Digges (1998) studied rollover crashes and demonstrated that seat belts are the single most effective countermeasure in preventing injury (by preventing ejection and reducing interior impacts) in such crashes.

Occupant protection systems can be distinguished into systems that require the occupant to actively adopt their use, such as wearing seat belts or helmets etc., and those that are inherently present in the vehicle such as airbags, energy absorbing steering columns, padding of interior structures etc. These are sometimes referred to as active and passive systems respectively. Active systems (especially safety belts) have the disadvantage that use of the system is not always assured, thus often rendering them ineffective. Evans (1989) compared the effectiveness of the two most popular passive and active safety measures in passenger automobiles, namely air bags and seat belts. Seat belts reduce the risk of fatality by preventing ejection of the occupant and reducing the severity of impacts with interior objects, while air bags reduce the chance of injury due to impacts with interior components primarily in frontal collisions. Based on crash data, the author has calculated that seat belts are 77±6% effective in reducing occupant fatality. Air bags alone (without the use of seat belts) are 18±4% effective in reducing occupant fatality. Combined use of seat belts and air bags is estimated to provide an added 5% reduction in fatalities over the use of seat belts alone.

Seiff (1985 and 1989) presented an analysis of methods for reducing the injury toll of truck crashes, both through crash prevention and the use of post crash occupant protection countermeasures.

- The most important aspect in preventing injury to truck occupants is seat belts. Seat belt use in heavy trucks increased from 6% in 1982 to about 33% in 1987. The author suggests that improvements in seat belt design other restraint systems are the most important area for study.
- Protection from post crash fire.
- Cab interiors free from sharp and hard objects, improved design of steering wheel rim and column.
- Improved cab design providing crash space and means of escape after crash.

Clarke (1994) and De Coo (1994) deal respectively with U.S. and European efforts to improve truck occupant protection. Both studies used detailed analysis of truck crashes combined with crash testing to estimate the achievable improvements in truck occupant injury outcomes. De Coo (1994) concluded that a 60% reduction in injury measures is possible through the use of seat belts alone and a further 21% reduction is possible with the addition of airbags.

Clarke (1994) analyzed crash data from 182 case summaries of fatal heavy truck crashes from a 1990 NTSB study to develop computational crash simulations and representative crash pulses to research occupant dynamics, and truck cab interior crashworthiness.

Analysis of crash data revealed 3 principal types of crashes; rollover, collision with fixed object, and collision with other trucks. In the majority of the collision cases the principal impact was frontal. Fatal head on collisions with other trucks or with fixed objects are usually characterized by high closing speeds. Fatalities caused by collision with the rear end of another truck occur over a wide range of speeds and involve occupant compartment intrusion due to the cab of the striking truck, contacting the frame of the struck truck. Rollovers occurred in nearly 50% of the sample of cases studied. 180° rollovers were generally not survivable due to crush of the occupant compartment. 90° rollovers usually allow sufficient survivable space. Approximately 22% of the analyzed crashes were judged to have sufficient occupant survival space.

There is considerable agreement among all studies of truck interior safety that occupant restraint systems are the most effective measure in reducing injury severity and fatality rates. Cheng (1996a and 1996b) used crash reconstruction and simulation studies to analyze the effectiveness of occupant restraint systems. Three cases of seatbelt usage were investigated, a three-point seat belt, a lap belt, and an unrestrained occupant. In rear-end collisions the shoulder belt was shown to be effective in limiting forward excursion of the upper body and limiting head impact with the steering wheel and the roof. In rollover crashes the seat belt was less effective in preventing impacts with the roof. As expected lap belted and unrestrained occupants suffered higher impact forces.

Kubaik (1997) presented a detailed dynamic testing based analysis of the effectiveness of a three point seat belt coupled with an air bag in heavy trucks. Tests were conducted using a High Impulse Generator (HYGE) slide on a 50th percentile male dummy. Four scenarios were considered: exclusive use of seat belt, exclusive use of air bag, use of airbag and seat belt and unrestrained occupant. Since the maximum number of injuries and fatalities are observed for unrestrained occupants, the data collected for those were treated as a baseline (100%) and all other observations were normalized with it. Tests were conducted twice for each scenario to avoid variations in dynamic testing.

The results obtained are summarized in Table 1. The author presents the following discussion of the test results:

	Seat belt/Airbag	Airbag	Seat Belt	Unrestrained
Head injury Criteria (HIC)	83.7	94.1	148.4	100.0
3 ms Resultant Chest Acceleration	72.5	70.8	81.2	100.0

Chest Deflection	96.1	97.6	87.4	100.0
Chest Viscous Injury	76.7	84.9	68.3	100.0
Positive Neck Shear	25.2	91.0	814.2	100.0
Negative Neck Shear	43.1	54.3	41.7	100.0
Neck Tension	64.1	67.3	137.8	100.0
Neck Compression	1.0	84.2	2.6	100.0
Neck Flexion	23.9	68.5	335.3	100.0
Neck Extension	30.7	51.3	27.5	100.0
Right Femur Load	35.5	87.8	52.7	100.0
Left Femur Load	65.1	111.1	80.4	100.0

Table 1. Comparison of Occupant Restraint System Effectiveness

- Unrestrained Occupants: Excessive displacement of the lower extremities occurred resulting in high femur loads. Also, the occupant's chest contacted the steering wheel causing the column tilt mechanism to rotate forward, allowing the dummy's head, right shoulder and right forearm to break through the 0.25-inch polycarbonate windshield, causing maximum injuries and ejection.
- Seat Belt only: The seat belt restrained the occupant's torso and lower extremities, lowering chest accelerations and femur loads, but allowed forward displacement of the head to continue, resulting in increased moment about the neck. Also the occupant's head contacted the steering wheel hub. This resulted in high HIC, positive neck shear, and neck tension and neck flexion injuries.
- Seat Belt and Air bag: Simultaneous use of both components limited occupant's forward excursion and reduced the occupant injury level to a minimum.
- Air Bag only: Air bags protected the head and the upper torso, reducing, HIC, chest accelerations and neck loads, with the exception of neck compression due to the mass of the

body pushing into the bag. It also allowed for greater forward chest and lower extremities displacement resulting in high femur loads.

Simon (2001) studied the potential benefit of 100% use of seatbelts using an in-depth study of 403 truck crashes in France. The author also surveyed ten earlier studies on effectiveness of seatbelts.

	Crashes	Fatalities	Seriously Injured	Slightly Injured	Unhurt	Total Involved
Car to Truck	190	0	0	8	199	207
Truck to Truck	49	9	12	25	46	92
Truck with Obstacles	43	5	5	25	12	47
Truck in rollover	121	10	12	72	39	133
Total	403	24	29	130	296	479

Table 2. Distribution of Casualties in Trucks with a Breakdown by Truck Crash Types in France

In order to evaluate the correlation between crash violence and injury level the author defined factors such as EES (Equivalent Energy Speed), Delta V, and crash speed. These factors take into account all the relevant details such as crash speeds, type of crash, and deformation of vehicle etc. Formulae for the evaluation of these factors are given in the paper. The author tried to find a correlation between EES and injury level suffered.

Three main types of injury causation mechanisms are identified: (i) Intrusion: where an external object or the crushed cab frame causes injury to the passenger (ii) Projection: where the body of the passenger impacts an object or surface within the cab and (iii) Ejection.

Simon (2001) described the effect of using seat belts in each of these injury mechanism cases:

- Intrusion: For front to rear impact, seat belts can prevent or reduce injury to the upper portion (chest or head) of the body, but has no impact on the lower portion (legs, abdomen). For a belted person, the intrusion has to be in line with the person for injury to occur. For rollovers, the use of seat belts prevents injury as long as the roof crush is not directly above the occupant. The seat belt would be effective in all other cases.
- Projection: Projection is the most common form of injury and according to the author use of seat belts would reduce or prevent injury in all cases. In cases of minor injury, the injury can be avoided altogether and in case of severe crashes having high value of ESS, the injury can be reduced in all cases.
- Ejection: The author states that ejection is the most dangerous mechanism, which is most common in rollover cases. The author distinguishes two types of rollovers, counter-clockwise and clockwise. The counter-clockwise is the more dangerous of the two as the driver is closer to the ground. Seat belts again provide the most practical means of preventing ejection and reducing injury.

Simon (2001) used statistical models and formulae to predict injury to belted drivers with ESS being the critical factor determining risk of injury. All these models suggest a lesser risk of injury in all cases for a belted driver over small to medium values of ESS. Based on these results, the author concluded that use of seat belts will avoid fatalities in about 1/3rd cases and also avoid serious injury in 1/3rd of cases. Most of these gains are in crashes between trucks, in rollover or frontal impacts or in frontal impacts with fixed objects. Potential effectiveness is mostly due to the reduction of projection or ejection of the occupant.

	Unhurt	Intrusion	Projection	Ejection	Other	Total
Car to Truck	199	1	5	0	2	207
Truck to Truck	46	25	19	1	1	92

Truck with Obstacles	12	10	17	5	3	47
Truck in rollover	39	9	71	13	1	133
Total	296	45	112	19	7	479

Table 3. Injury Causation Mechanisms for Each Crash Type

Type	Belt Use	Unhurt	Slightly Injured	Seriously Injured	Killed	Total
Car to Truck	None	199	8	0	0	207
	Belted	204	3	0	0	207
Truck to Truck	None	46	25	12	9	92
	Belted	60	15	11	6	92
Truck with Obstacles	None	12	25	5	5	47
	Belted	30	11	3	3	47
Truck in roll-over	None	39	72	12	10	133
	Belted	93	33	2	4	133

Table 4. MAIS Distribution Without and With Seat Belt for Each Crash Type

	Belt Use	Unhurt	Slightly Injured	Seriously Injured	Fatally Injured	Total
Intrusion	None	0	16	15	14	45
	Belted	2	16	16	11	45
Projection	None	0	102	8	2	112
	Belted	7 5	36	0	1	112

Ejection	None	0	5	6	8	19
	Belted	11	6	1	1	19

Table 5. Expected Gains with Belt for Each Injury Causation Mechanism

Simon (2001) indicated that in only one out of 479 cases would the chances of injury increase if the occupant were wearing a seatbelt. The author noted the low usage of seat belts in Europe, with reported usage among truck drivers in France being as low as 1.5%.

1.1.4. Current Research

A number of studies address current efforts and the future directions that these efforts are likely to take to achieve improved heavy truck crashworthiness and occupant protection.

Rossow (1995) discusses post crash safety measures. Rollover and ejection present the most serious risks for truck occupants. Seat belts offer the most protection against those. Barrier crash testing at 30mph has shown that the use of advanced restraint systems may make survivable many crashes previously thought to be unsurvivable. The advances in restraint systems likely to provide the greatest benefits are belt and seat pretensioning and use of airbags. The use of new seat integrated belt systems that prevent movement of shoulder belts relative to the suspended seat, a major source of irritation for many truck drivers, may improve the usage rates of seat belt systems.

In rollover type crashes the lack of survival space is the major cause of fatalities, and cab structural crashworthiness becomes an important issue. The author estimates that 27% of rollover crashes are survivable with the use of restraints whereas about 42% are unsurvivable, and the remaining cases may be survivable with improvements in cab structural strength. The majority of the unsurvivable crashes are 180^{o} rollovers in which cab deforms in the vertical direction to the belt line and severely compromises the survival space. 90^{o} rollovers are much less severe and more survivable. For unrestrained occupants, most of whom are ejected through the doors or windshield, the author discusses the FMVSS 206 regulations covering door latches and hinges and the FMVSS 212 windshield mounting and retention requirements.

Sicher (2000) documents a study that is particularly relevant to the current effort. This paper describes an effort to improve occupant crash protection for army truck occupants by using off the shelf technology available in commercial and passenger cars and trucks.

The restraint system developed for the High Mobility Multipurpose Wheeled Vehicle (HMMWV), a light tactical combat truck used by the army had the following characteristics:

- A strong head restraint for rear end crashes.
- A modern 3-point symmetrical seat belt mounted directly on the seat.
- Seat belt forces are applied at optimal positions on the occupant
- Reduced slack through use of pretensioners
- Improved lateral restraint larger side bolsters, supplemental shoulder belt, and improved seat geometry.
- Anti-submarining seat bottom that was strong enough to withstand drop testing.
- Optimal seat belt geometry and rate dependent foam.

All this technology was modular and was essentially off the shelf, i.e. available in commercial restraint systems. The system was tested using drop tower vertical testing.

Desfontaines (2001) discusses a comprehensive study of truck safety, coordinated by the European Centre for Studying Safety and Analyzing Risks (CEESAR), involving partners with unique expertise. These include universities, research labs, truck manufacturers, truck operators etc. The study emphasizes quickly integrating improvements into current practice by involving users in the entire system.

One of the important components of this study is a quality database of large truck crashes, to form the basis for assessing the efficacy of implemented safety improvement measures and to direct future studies in choosing technologies.

Another component is the High Safety Concept Vehicle (HSV), a sort of ‘laboratory on wheels’ concept truck developed by Volvo with partnership of all its major component suppliers. The truck contains all the state of the art active and passive safety measures that may be used in heavy trucks in the near or distant future. This concept will help in choosing the most efficient technology improvements that can be integrated into commercial products.

Desfontaines (2001) also describes a systematic analysis method used to assess the efficacy of each new technology using statistical information.

- The CEESAR database of large truck crashes is used for an in-depth study of all the relevant crash cases and to determine injury causing mechanisms and relevant countermeasures.
- For each technology, a sample of relevant crashes is chosen.
- Crash reconstructions are carried out (using PC Crash software) to better understand the causes and effects of each crash.
- The next step (often the most difficult) is to quantify the effect each technology has on reducing the physical parameters of the crash (such as crash energy etc.).
- The crashes are again reconstructed to account for the protective effect of the new technology.
- The results obtained from the reconstructions are used to evaluate the effectiveness of each new technology in avoiding crashes or reducing injury.
- A more conventional substitute method that relies on accumulated experience and observations concerning crashes and their consequences (injuries caused, etc.), is also used in parallel to estimate improvements.

Sukegawa (2001) describes experimental research done in truck driver protection in Japan. 'The Guidelines for Frontal Crash Test of Heavy Duty Trucks' have been formulated in Japan, and all trucks are tested to meet these specifications. These trucks are equipped with safety features such as: three point seat belt (with pretensioner) for driver as well as occupant, side-door beams, impact absorbing steering wheel and column, airbags, softer instrument panels and a secure survival space

The paper further discusses areas in which research is being done to protect truck drivers. One of these is the type of chest and abdomen injury suffered by truck drivers that are often fatal or serious. These injuries are unique to truck drivers because of the size and position of the steering wheel. Research is being done to develop new evaluation techniques for chest and abdomen injuries. One of the concerns is the accuracy of the chest displacement meters used. The meters are used only on one chest rib and the measurements are accurate only when the steering wheel impacts that particular rib, whereas they are quite inaccurate if the wheel impacts other ribs. Sukegawa (2001) has shown that much more accurate readings can be obtained if stress measurements are obtained from multiple numbers of ribs of the dummy. The author suggested more accurate injury criterion, including those to soft tissue (called Viscous Criteria (VC)), and stated that there are a large number of cases in which the driver is trapped inside the cab and an emergency rescue team is called to extricate the driver from the cab as soon as possible. The author suggested measures such as improved cab construction customized for better rescue performance, with improved and standardized door frame designs so that rescue teams can easily open the cab door, improved front panels and instrument panels that offer more survival space and are easier for rescue teams to manipulate.

Carra (2001) discussed a data collection measure initiated by NHTSA. This is the 'Large Truck Crash Causation Study' (LTCCS). Its goal is to determine the factors associated with large truck crashes, to develop countermeasures to reduce the probability of large truck crashes and to reduce the severity that do occur. The study is limited to crashes that involve at least one large truck and at least one fatality or serious injury. Data are being collected using the NASS (National Automotive Sampling System) CDS (Crashworthiness Data System). Cases in the study are sampled from 24 NASS CDS sites around the country. In addition to very detailed data on the circumstances of each crash, the LTCCS data includes information on driver injury similar to the NASS CDS file. Data collection began in the Spring of 2001; preliminary analysis will begin in the Fall of 2003

1.2. Summary

Truck occupant protection systems have thus far received less attention than automobile passenger protection systems, but a number of recent studies are beginning to fill the gap in this area of vehicle crashworthiness research. These studies of motion of the occupant due to the crash accelerations and forces and the geometry of the truck cab cover a wide range of issues, including truck crash characteristics, occupant injury modes and mechanisms and most importantly occupant protection countermeasures.

A number of recent studies that take a comprehensive look at the truck occupant safety issue are also currently underway. Some of these studies include a comprehensive data collection effort in the United States supported by the National Highway Traffic Safety Administration (NHTSA); the High Safety Vehicle (HSV) project in Europe involving partnership between several different users of truck transport including government bodies, research organizations, and commercial truck manufacturers and operators; and the Japan Automobile Manufacturers Associations efforts to improve truck crashworthiness. The results of these studies will be available in the near future and should provide much insight into the design of safer trucks.

2. Crash Data Analysis

2.1. Introduction

Publicly available crash data were surveyed to identify the major factors associated with truck driver injury. There has been relatively little focus on the crashworthiness of trucks or injury mechanisms for truck drivers in traffic accidents. Accordingly, the crash data available on truck driver injuries do not provide much detail on the nature of the injuries or how they were sustained. While the NASS CDS supplies detailed information on injuries to passenger vehicle occupants, (e.g., type of injury, body region, and vehicle contact point), there is no comparable data for truck occupants. The Large Truck Crash Causation Study, conducted by FMCSA and NHTSA, will include NASS-like injury detail for truck occupants, but those data will not be available for analysis until the Fall of 2004.

2.2. Data Analysis

For the purposes of the present study, crash data from two sources were analyzed: the Trucks Involved in Fatal Accidents (TIFA) study from the Center for National Truck Statistics at the University of Michigan Transportation Research Institute, and the General Estimates System (GES) file compiled by the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration. The TIFA file surveys all medium and heavy trucks (GVWR > 10,000 lbs) involved in fatal crashes in the United States. Candidate truck cases are identified from NHTSA's Fatality Analysis Reporting System (FARS) file, police reports are acquired for each crash, and UMTRI researchers survey drivers, owners, operators, and other knowledgeable parties about each truck. For some years of data, some limited sampling was done to reduce the number of cases processed. The result is a near-census file that provides the most accurate identification available of large trucks involved in fatal crashes. The TIFA survey collects a detailed description of each truck involved, as well as data on the truck operator and a variable on the truck's role in the crash modeled on a similar variable in the GES file.

The General Estimates System (GES) file is a complementary dataset to the NASS CDS file mentioned above. GES is a nationally representative sample of police-reported traffic crashes. It includes all motor vehicles involved in traffic crashes, not just large trucks. GES data are coded from police reports selected through a complex sampling system.

A set of analytical data files was developed for the present analysis. While the GES file provides the best estimates of traffic crashes nationally overall, it is known to underestimate the number of crashes involving a fatality. Accordingly, in this study, all counts of fatalities and injuries in fatal traffic accidents are taken from the TIFA file, while statistics on non-fatal crashes were determined from the GES file. The combination of TIFA and GES data provides the most accurate coverage of truck crash involvements covering all crash severities: fatal, injury, and property damage only.

Five years of crash data were combined in this analysis. Combining multiple years of crash data improves the accuracy of the analysis, particularly when considering a relatively narrow subset of the crash population, such as truck driver injury. Traffic crashes are subject to random annual fluctuations; combining several years aids in damping out the random noise and revealing underlying relationships. In addition, the GES file is a sample file, and therefore frequencies estimated from the file have an associated sampling error. Combining several years of data helps to reduce the error.

The tables show average annual frequencies or percentages for the five years of data used. Estimates taken from the TIFA file are shown exactly, since the TIFA file is virtually a census and provides the most accurate data available on fatal crashes involving trucks. Frequency estimates from the GES file are rounded to the nearest thousand, to reflect the sampling error associated with the estimates derived from GES. All totals and percentages are calculated before the rounding is done.

In this study, all medium and heavy trucks are included as large trucks. Large trucks are defined as all trucks with a gross vehicle weight rating (GVWR) of 10,001 pounds or more. This is the conventional GVWR threshold for trucks. Basically, it includes all trucks with at least two axles and six tires.

The purpose of this analysis is to identify crash events associated with the risk of serious injuries, here defined as fatal or A (incapacitating) injuries. Specific crash types are identified that pose a significantly higher probability of injury to the truck driver. Specific crash events that increase truck driver injury risk are also determined. The level of analysis is fairly high, since the desired detail on injury mechanisms—body regions injured, interior contact points and the like—

simply is not available. It is not possible to determine injury mechanisms in the available accident data.

The findings here reinforce and update results from previous research reviewed above. Serious truck driver injury is associated with collisions with massive objects, either fixed objects such as bridge abutments or embankments or other large trucks or the ground, as in a rollover. Most truck crash involvements with another vehicle pose relatively low risk of serious injury to the truck driver because the other vehicle is typically a passenger vehicle that is much smaller than the truck. Single-vehicle crashes, in which the truck either rolls over or strikes a massive fixed object, and crashes involving another truck account for the majority of serious injuries to the truck driver. Single-vehicle crashes and two-vehicle, truck-truck crashes account for about 75% of all truck driver fatalities and A injuries, though they are only 26% of all truck crash involvements. Moreover, three specific events—rollover, fire, and ejection—are found in almost two thirds of serious truck driver injuries, regardless of crash type.

	Person location		
	Truck occupant	Not in truck	Total
Fatalities	744	4,741	5,485
Injuries	29,000	95,000	124,000
	Row percentages		
Fatalities	13.6	86.4	100.0
Injuries	23.5	76.5	100.0
Total	23.1	76.9	100.0
Source: 1995-1999 TIFA and GES			

Table 6. Average Annual Injuries and Fatalities in Truck-Involved Crashes, 1995-1999

An average of approximately 376,000 trucks is involved in traffic crashes every year. In these crashes, on average 5,485 persons are fatally injured and another 124,000 persons receive some sort of injury (Table 6). As would be expected, most fatalities and injuries are suffered by occupants of passenger cars, light vehicles, or "non-motorists" such as pedestrians and bicyclists, rather than by truck occupants. **Error! Reference source not found.** The table shows the average annual toll from traffic accidents involving trucks, separately for truck occupants and non-truck occupants. In this table, non-truck occupants include non-motorists, as well as drivers and passengers in automobiles, vans, and other light vehicles.

Of the almost 5,500 people who are fatally injured each year; truck occupants account for 744, or about 13.6% of the fatalities. Approximately 124,000 people are injured to some degree, 29,000 of whom (23.5%) are truck occupants. While truck drivers and other occupants are "underrepresented" among the injured in crashes involving trucks, 30,000 annual casualties is a significant problem. The toll in deaths and injuries contribute to making truck driver one of the most dangerous occupations in the U.S

Injury severity	N	%
Fatal	633	0.2
A injury	4,000	1.1
B injury	8,000	2.1
C injury	12,000	3.2
Injured, severity unknown	2,000	0.5
No injury	333,000	88.6
Unknown	19,000	5.1
Total	376,000	100.0
Source: 1995-1999 TIFA and GES		

Table 7. Average Annual Injuries to Truck Drivers, 1995-1999

Table 7 shows average annual injuries to truck drivers, not all truck occupants. Since relatively few trucks have passengers, the driver of the truck will be the focus of the analysis from this point forward. About 633 truck drivers were fatally injured annually between 1995 and 1999. An additional 4,000 drivers suffered A injuries, 8,000 received B injuries, and 12,000 drivers had C injuries. There were an estimated 2,000 drivers with injuries of unknown severity, for a total of almost 27,000 truck drivers injured in traffic crashes annually.

Given the disparity in size, geometry, and structural stiffness between trucks and the other vehicles on the road, it is not surprising that injury risk to the truck driver is higher in crash types that do not include cars. Truck driver injury most often occurs when the truck strikes something relatively massive, either a roadside feature or the ground in a single vehicle crash, or another truck. Of the 633 annual driver fatalities, 410 or almost two-thirds occurred in single-vehicle crashes. Another 94 occurred in two-vehicle truck-truck crashes. There are about ten times more truck-car crashes than truck-truck crashes, but truck-truck crashes accounted for about half again as many truck driver fatalities, 94 to 65, as truck-car crashes.

Single-vehicle crashes account for about 19% of crashes but 64% of truck driver injuries. There is an annual average of about 73,000 single-vehicle crashes, of which roughly 2,400 involve a fatal or A injury to the driver, and 23,000 some other injury. With rounding to the nearest 1,000 to account for the sampling error from the GES estimates, most of the cells would show zeros if frequencies were included. (See Table 8).

Safety belts are widely understood to be the most effective injury prevention device available, but there are almost no data available on their use in the truck driver population, and data on safety belt use in crashes are likely biased. NHTSA in 1982 and again in 1991 monitored safety belt use at four weigh stations. About 6.3% of truck drivers were observed to use safety belts in 1982, and the observed proportion increased to about 56% in 1991. But other than those observations, no estimates of belt use could be found.

Safety belt use coded in the crash data is likely to be biased, and the likely bias exaggerates estimates of effectiveness. Other than fatally- and seriously-injured drivers, for whom police officers can observe safety belt use directly, most belt use in crash data is self-reported. Given the increased emphasis on safety belt use, including laws mandating use in some jurisdictions and some trucking companies requiring them, it is likely that safety belt use is increasing. But it is also likely that drivers claim to have used a safety belt even if they did not, for the same reasons. Since belt use is self-reported for drivers with minor or no injuries, misreporting tends to over-report belt use for the uninjured, thus biasing upwards estimates of belt effectiveness.

	Crash Type				
Driver Injury	Single Vehicle	Truck-truck	Truck-car	> Two vehicles	Total
Fatal	410	94	65	63	633
A injury	2,000	0*	1,000	0*	4,000
B injury	4,000	1,000	2,000	1,000	8,000
C injury	5,000	1,000	5,000	1,000	12,000
No injury	58,000	21,000	229,000	24,000	333,000
Unknown	3,000	1,000	13,000	1,000	19,000
Total	73,000	25,000	250,000	28,000	376,000
	Column percentages				
Fatal	0.6	0.4	0.0	0.2	0.2
A injury	3.4	1.5	0.3	1.0	1.0
B injury	6.1	4.1	0.7	2.3	2.1
C injury	6.3	4.6	2.1	4.7	3.3
No injury	79.6	85.2	91.5	87.0	88.4
Unknown	4.0	4.1	5.3	4.8	5.0
Total	100.0	100.0	100.0	100.0	100.0

*Estimated fewer than 500

Source: 1995-1999 TIFA and GES

Table 8. Average Annual Injuries to Truck Drivers by Crash Type, 1995-1999

However, it is clear that belt use nearly eliminates ejection, a major risk factor in serious injury. Table 9 shows ejection for restrained and unrestrained drivers who suffered fatal or A injuries. Among the unrestrained, almost 23% were totally or partially ejected. In contrast, only 3.3% of restrained seriously-injured drivers were partially ejected, and 0.1% were coded as totally ejected. In the case of belted ejected drivers, the cab of the truck was probably so heavily damaged that the seat was ejected along with the driver.

The ejection path is coded for truck drivers involved in fatal crashes. The ejection path provides important clues to cab structures that could be strengthened to keep the driver in the vehicle. Since virtually all ejected drivers suffer either fatal or A injuries, keeping the driver in the cab is an important first step. Unfortunately, the ejection path is not known for about 75% of ejected drivers. This is not surprising given the source of the data, but it warrants caution in interpreting the data. Of ejections where the ejection point is known, 34% of ejected truck drivers went out the windshield, and 30.7% were ejected through the side door. Among the partially ejected, 41.2% went through the side window, probably on the driver's side. Only 15.8% of the totally ejected went out the side window. Clearly windshield retention and side doors remain targets for truck driver injury reduction.

	Unrestrained	Restrained
None	76.6	96.4
Partial	20.1	3.3
Complete	2.8	0.3
Unknown	0.5	0.1
Total	100.0	100.0
Source: 1995-1999 TIFA and GES		

Table 9. Ejection by Restraint Use, Truck Drivers with Fatal or A injuries1995-1999

Overall, ejection increases the probability of driver fatality by almost 286 times, the risk of a fatal or A injury by 68.8 times, and the risk of a fatal, A or B injury by 28.5 times. Fire increases the risk of a truck driver fatality by 67.2 times, compared with the risk where no fire occurred. And rollover increases the risk of a driver fatality by almost 26 times, compared with no rollover.

Rollover, fire, and ejection are all strongly associated with truck driver injury. Over half (54.6%) of fatally injured truck drivers were involved in a rollover, as were 59.8% of drivers with A injuries. In contrast, only 2.2% of uninjured drivers rolled over. Only 0.2% of all truck drivers were ejected, but 31.5% of fatally injured drivers were ejected, and 6.5% of drivers with A injuries were ejected. In fact, no ejected driver in the five-year period covered by the data escaped injury. Similarly, fire in the vehicle also significantly increases the risk of a serious or fatal injury to a truck driver involved in a traffic crash, and is associated with a substantial number of fatalities. The truck caught on fire in 17.3% of truck involvements in which the driver died, while only 0.3% of all trucks involved in crashes experienced a fire.

Of course, rollover, fire, and ejection can occur together and in various combinations. Table 10 shows the permutations of rollover, fire, and ejection observed in the accident data, and the risk of a truck driver fatality or A injury associated with each. No rollover, fire, or ejection occurred in 95.2% of all truck crash involvements, and the probability of a fatal or A injury to a truck driver in those crashes was only 0.4%. But if rollover only occurred, the risk rose to 14.1%. If only fire occurred, the risk also rose to 14.1%. And if the driver was ejected, without rollover or fire, his risk of fatal or A injuries was 54.4%. Ejection by itself is clearly the most serious event, but in combination with rollover, the truck driver's risk of fatal or A injuries increased to 85.1%. And in the five years covered by the data used here, no driver who suffered rollover, fire, and ejection, escaped either a fatal or an A injury.

Single-vehicle crashes of course also include crash types that present very low risk to the truck driver, such as collisions with pedestrians, bicyclists, and other non-motorists. Most of the non-fixed object crashes are collisions with parked vehicles or animals. These crash types represent only 0.1% and 0.9% of truck driver fatalities and A injuries, respectively. Note that the most harmful event was unknown in 8.6% of single-vehicle crashes and 14.4% of truck driver fatality or A injury crashes.

Crash event	Probability of fatal or A injury	Percent of fatalities and A injuries	Percent of all crash involvements
No rollover, fire, or ejection	0.4	35.2	95.3
Rollover only	14.1	49.7	4.3
Fire only	14.1	2.9	0.2
Ejection only	54.4	2.5	0.1
Rollover and fire	45.2	2.2	0.1
Rollover and ejection	85.1	6.9	0.1
Fire and ejection	96.1	0.3	0 (<0.05)
Rollover, fire, and ejection	100.0	0.2	0.0*
Source: 1995-1999 TIFA and GES			

Table 10. Truck driver injury and rollover, fire, and ejection

As might be expected, rollover is the primary harmful event in a single-vehicle crash in which a truck driver is killed or seriously injured. Rollover was the most harmful event in 63.1% of fatal or A injury single-vehicle crashes, compared with only 8.6% of the single-vehicle crashes in which the driver was uninjured, and 15.1% in all single-vehicle crashes (See Table 11).

Most harmful event	Fatal/A injury	Other injury	No injury	Unk.	Total
Rollover	63.1	44.4	8.6	4.1	15.1
Fire	2.0	0.4	0.8	0.0	0.7
Other non-collision	2.7	4.0	7.9	1.6	6.9
Ped./bike/non-motorist	0.1	0.2	2.7	2.0	2.2
Train	2.5	1.3	0.4	0.0	0.5
Other non-fixed object	0.9	3.0	34.2	49.5	29.6
Hard object	6.9	10.3	7.8	2.7	7.8
Soft object	6.4	12.0	23.8	29.5	21.9
Other fixed object	1.0	2.4	7.5	6.0	6.6
Unknown	14.4	22.1	6.5	4.5	8.6
Total	100.0	100.0	100.0	100.0	100.0
Source: 1995-1999 TIFA and GES					

Table 11. Percentage of Most Harmful Event in Single Vehicle Crashes By Truck Driver Injury

The other primary events posing an injury risk are collisions with fixed objects. Both the TIFA and GES data include a code for objects struck. These objects were categorized into "hard" and "soft" based on the amount of damage to the truck and the extent to which the objects were judged to be yielding in the event of a collision. "Hard" fixed objects include bridge piers and abutments, concrete barriers, culverts, and rock embankments. "Soft" fixed objects include light poles, trees, shrubbery, ditches, and crash attenuators. The goal of the classification was to separate “unyielding” from “yielding” objects. “Yielding” objects might be expected to slow the truck down when struck and to absorb some of the collision energy, while bridge abutments and rock embankments are essentially fixed. Trees constituted a very large fraction of the “soft” objects, which is somewhat problematic. Trees with a small diameter trunk are correctly included as “soft” in this classification, but larger trees are more likely to be relatively unyielding. Neither the TIFA data, which incorporate the FARS most harmful event variable, nor the GES data include information on trunk size. An arbitrary decision was made to include trees in the “soft” category. The most harmful event in 6.9% of truck driver fatalities and A injuries was a collision with a hard object, while 6.4% were collisions with “soft” objects.

2.3. Summary

Truck crash data and the literature show that a large proportion (~70%) of crashes in which truck occupants are significantly injured are single vehicle crashes, with truck-truck crashes being the second most dangerous to truck occupants. Rollover of the truck is the most significant injury-causing event involved in a majority (~60%) of these crashes. The important occupant injury mechanisms are ejection from the cab (involved in approximately $1/3^{rd}$ of all severe crashes), entrapment or crush, occupant striking interior surfaces (steering wheel, windshield, roof etc.) and post crash fire. The most promising countermeasures to improve the post crash safety of occupants include occupant restraints (seat belt and airbags – with most studies agreeing that restraint systems are the most effective of all protection countermeasures), improved strength windshields and doors (to ensure occupant retention in the cab), more forgiving interior surfaces (energy absorbing steering column, padded interior surfaces etc.), and improved cab structure to provide occupant survival space.

Overall, it is clear that significant improvements in truck occupant safety can be achieved in the near future using a combination of currently developed and emerging occupant protection technology.

3. Occupant Protection – Truck Cab Rollover Crashworthiness

3.1. Introduction

Examination of the literature on truck crashes and study of the available crash databases presented in the preceding chapters of this report, show that the safest location for truck occupants involved in a crash is the truck cab; i.e., ejection of the occupant from the cab greatly increases the probability and severity of injuries (by approximately a factor of 286 for driver fatality). Therefore, the first priority in developing countermeasures intended to prevent truck occupant injury must be to retain the occupant in the cab. A previous study (Campbell and Sullivan, 1991) conducted at UMTRI addressed this issue and outlined a series of recommendations that included strengthening door latches, and reinforcing windshields and windows. Once retention of the occupant is achieved a layered series of systems can be applied to improve the injury outcome of truck occupants involved in crashes.

The first line of defense in this system is the cab itself. Retention of the occupant in the cab can be effective only if the cab provides sufficient survival space and crash force and acceleration absorption to mitigate the effects of the crash. Detailed statistics on truck occupants who are severely or fatally injured by entrapment and crush in the cab are not readily available. However, several previous studies (discussed in more detailed in the truck crash literature review section) addressed the problem of cab crush through examination of selected samples of truck crashes. Berg (1997) indicated that entrapment occurred in approximately 36% of a set of truck crashes that were studied in detail. An earlier study by Seiff (1985) indicated that entrapment is involved in 22% of fatal truck crashes.

Cab crush occurs in two principal crash types: (i) Rollover and (ii) Frontal crash into fixed objects or other heavy vehicles. Of these, cab frontal crashworthiness is relatively simpler to analyze and will be considered (more briefly) in the section on occupant restraint and interior impact protection systems. Crash data analysis presented earlier showed that rollover is the most common event in severe (causing fatal or A injury to truck occupants) heavy truck crashes, occurring approximately 63.1% of the time, either singly or in combination with other crash events. Here we shall consider the issue of truck cab integrity (to assure occupant survival space) in rollover type crashes.

3.2. Rollover Crashworthiness

The issue of rollover crashworthiness of heavy trucks and the design of appropriate roll prevention and protection devices for these vehicles was previously examined by UMTRI and presented in Winkler *et al.*, (1998). The vehicle models used in the study were based on the TruckSim® truck dynamics simulation package, developed at UMTRI. The simulation package contains a set of truck dynamics models developed at UMTRI, and a complete simulation environment that allows, the execution of various vehicle maneuvers, computing of the corresponding velocities, accelerations, and forces at various (user specifiable) points on the vehicle and the post processing of the data for analyzing vehicle behavior. Simulations of a selected set of vehicles (from the NTSB special report, 1992), were developed to study their dynamics when subjected to maneuvers that cause them to undergo rollover. The study specifically focused on the trailer or cargo tank of the vehicles and the design of devices to prevent and protect that part of the vehicle from damage. Complete details of the models and vehicle parameters may be found in the UMTRI report prepared as part of that study.

In the present study, we shall use these simulations with suitable modifications to study the dynamics of the tractor and the crashworthiness of the cab in protecting the driver and other truck occupants. This study will not suggest specific cab or add on structure designs, but will instead attempt to estimate the strength/energy dissipation capabilities that these designs must satisfy, to provide the occupants with sufficient survival space.

3.2.1. Truck Roll Dynamics

The simplest possible description of the roll behavior of the truck cab is a single degree of freedom model that considers only the tractor as a single rigid body. Then the minimum lateral acceleration required to initiate rollover of the tractor can be calculated from equation 1,

$$a_y = g * \frac{T_w}{2h_{cg}} \qquad (1)$$

where a_y is the vehicle lateral acceleration, g is the acceleration due to gravity, T_w is the tractor track width and h_{cg} is the height of the tractor center of gravity.

However, in practice, the dynamics of the tractor are considerably more complex. The motion of the tractor itself is modified by the compliance characteristics of the tire and suspension system (which effectively reduces the resistance to roll i.e., the tractor rolls over at a lateral acceleration lower than that predicted by equation 1). Further, in the case of a tractor trailer combination it is usually the trailer that first becomes unstable, initiates rollover and pulls the tractor into roll. Thus it is necessary to use complete a vehicle simulation model (such as those available in the TruckSim® package) to properly predict the roll dynamic behavior.

Figures 1 and 2 show screen captures of the TruckSim® simulation environment, displaying how a particular vehicle model can be selected and its parameters defined for the particular simulation to be performed. The truck models may then be put through specific maneuvers by defining vehicle speed, steering and acceleration or braking inputs.

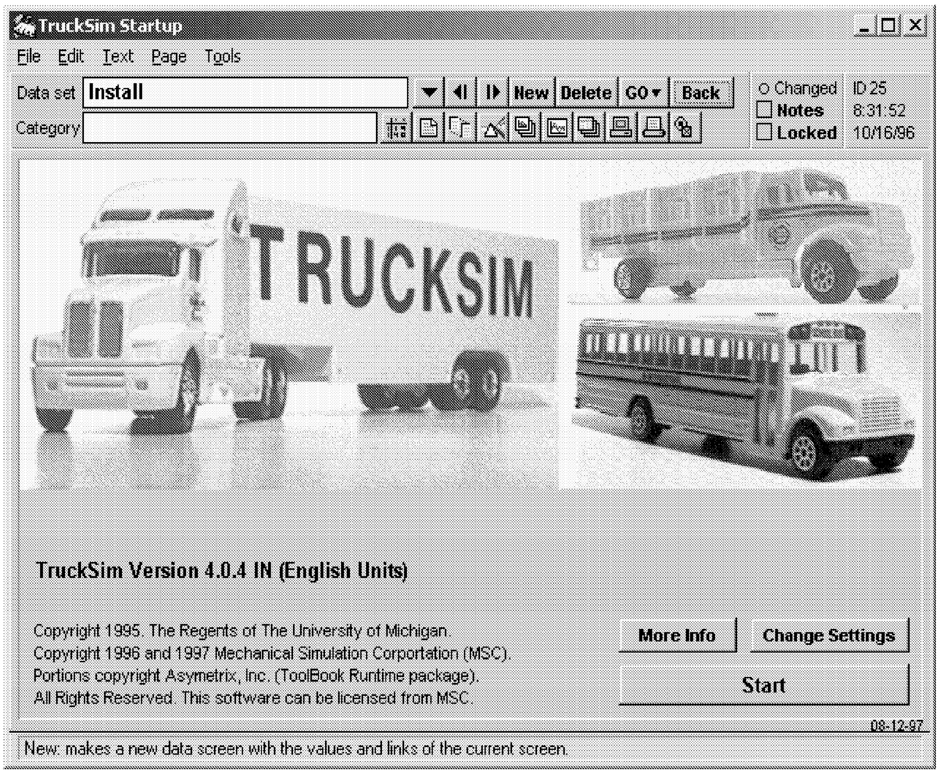

Figure 1. Screen capture of TruckSim® startup screen

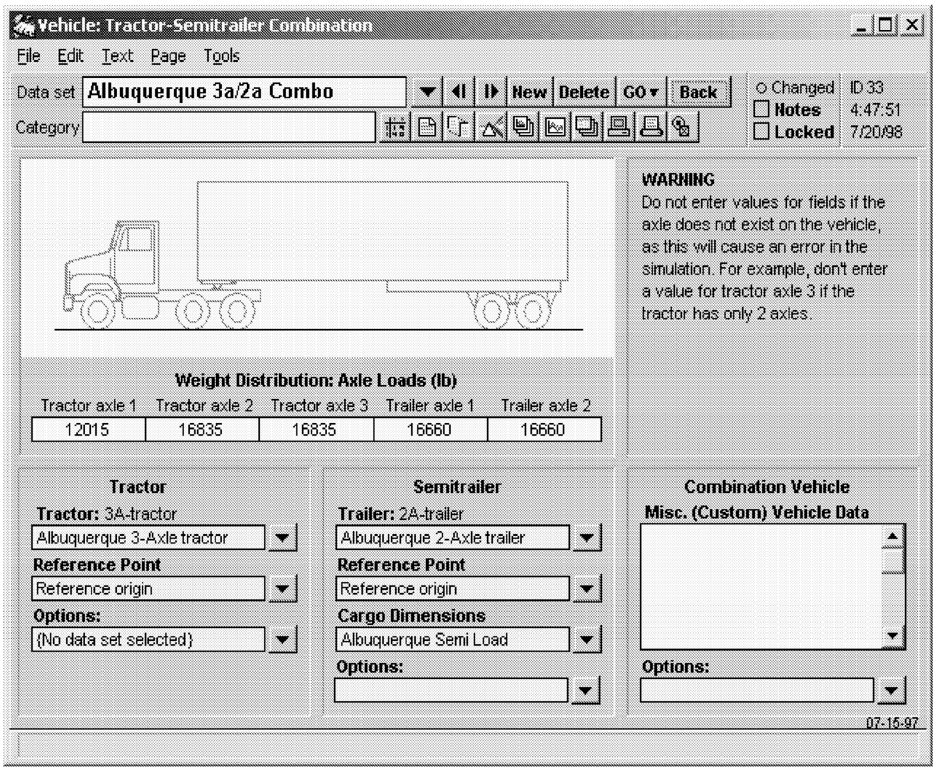

Figure 2. Screen capture of TruckSim® vehicle definition screen

Figures 3, 4, and 5 show individual frames from an animation of a truck simulation run where the truck is driven initially in a straight line and then steered to attempt to follow a circular path. The vehicle initial velocity is set at 55mph. The simulation is allowed to run until rollover. Figure 3, shows the truck in forward motion at the start of the simulation. Figure 4, shows the truck at approximately the midpoint of the simulation run and the truck can be seen to be turning and beginning rollover and figure 5, shows the truck almost completely rolled over (just before simulation ends at 90^{o} of roll).

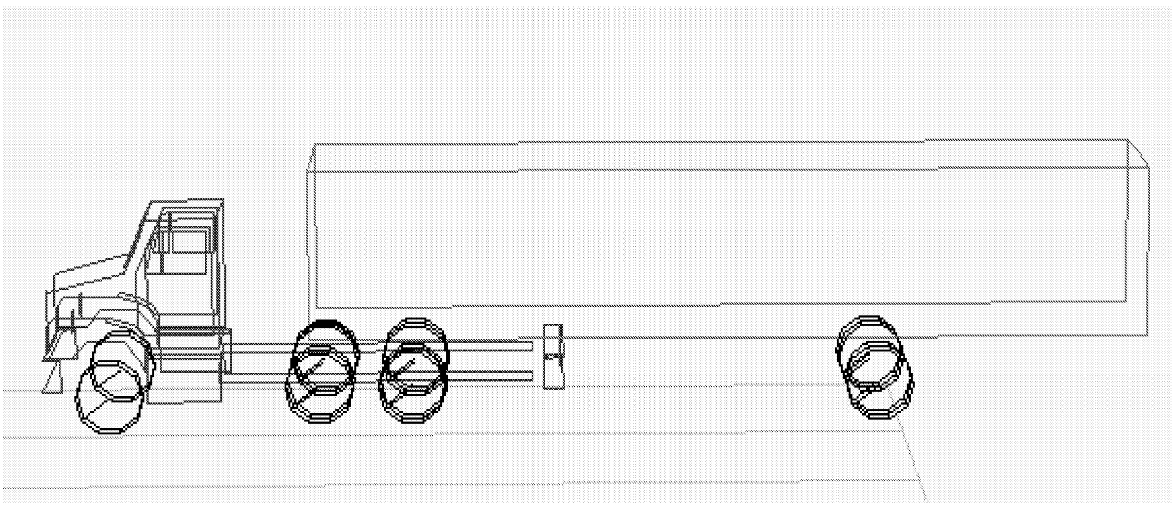

Figure 3. View of truck animation from beginning of a rollover simulation run

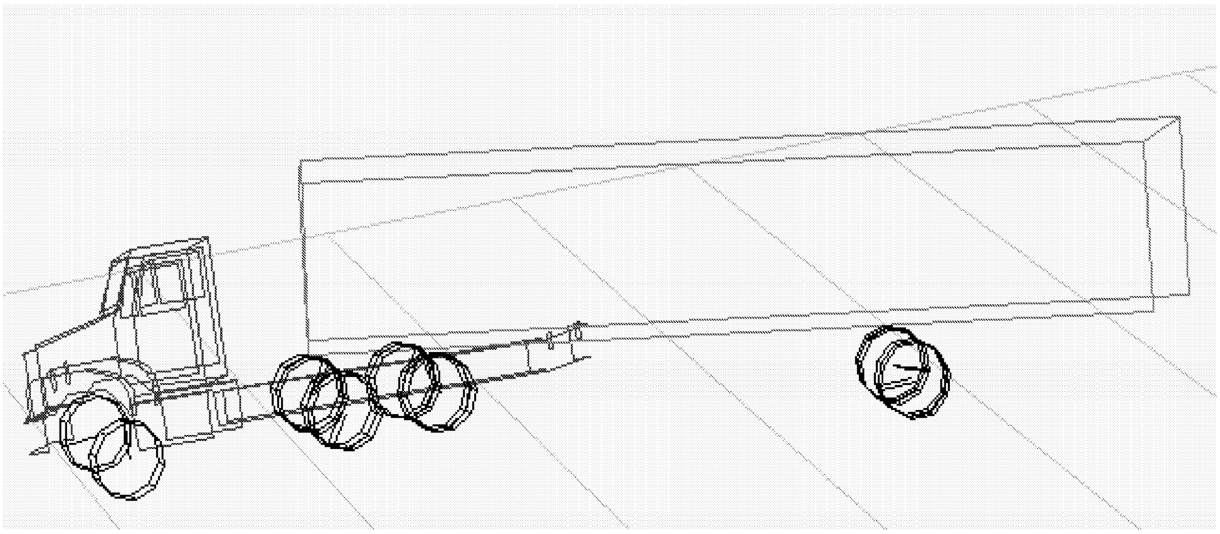

Figure 4. View of truck animation showing truck beginning to rollover

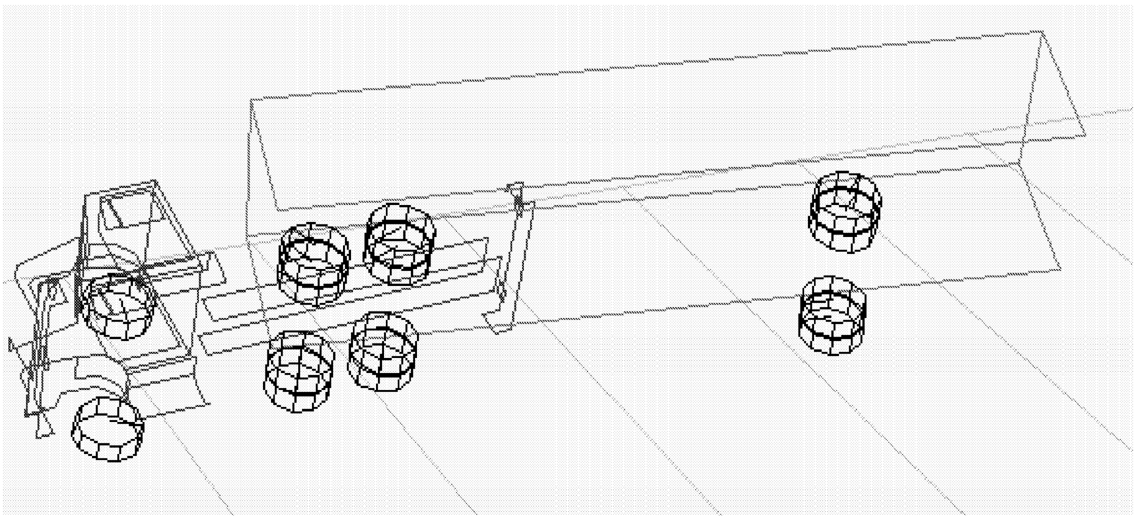

Figure 5. View of truck animation towards end of rollover simulation (just before cab strikes the ground)

Figures 6, 7 and 8, show the tractor roll angle, the tractor roll velocity and the vertical velocity of the tractor center of gravity corresponding to the above simulation.

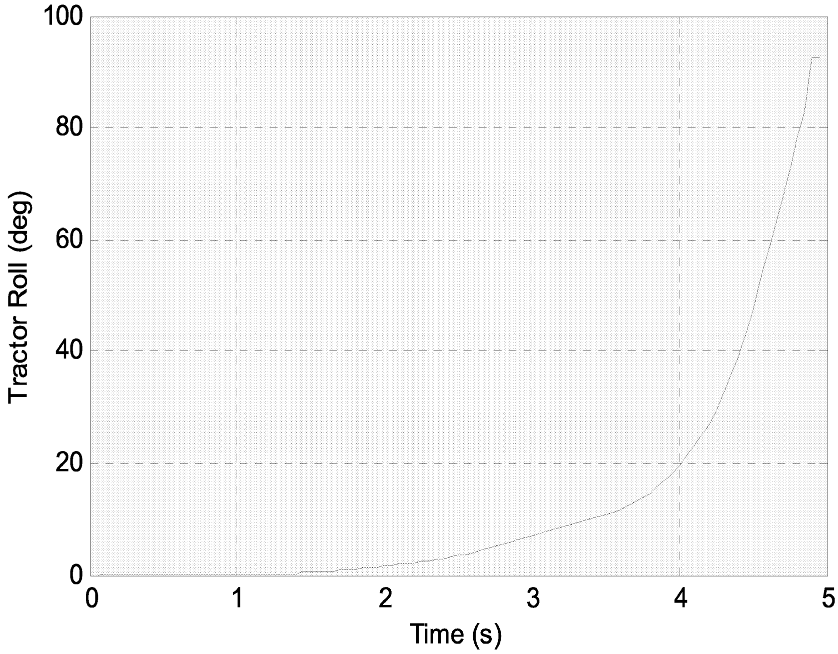

Figure 6. Tractor roll from vehicle simulation (55mph)

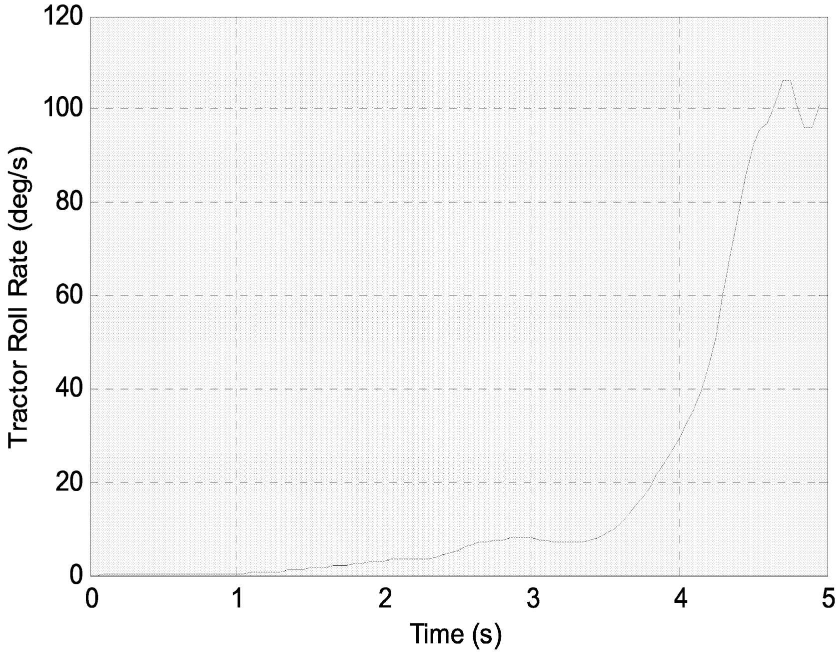

Figure 7. Tractor roll velocity from vehicle simulation (55mph)

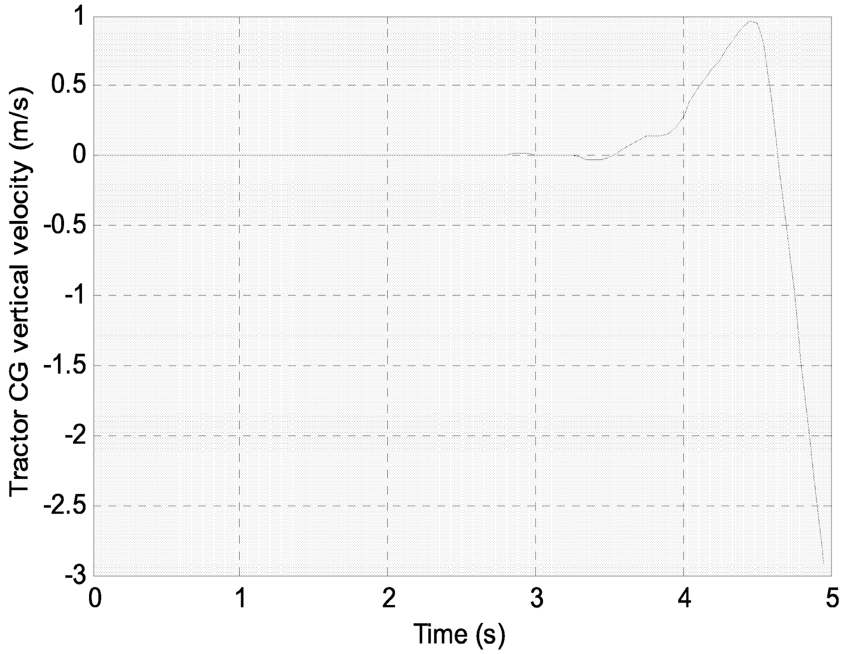

Figure 8. Tractor CG vertical velocity from vehicle simulation (55mph)

3.2.2. Cab crashworthiness

Crush or intrusion of vehicles in crashes results from the dissipation of the vehicle kinetic energy in deforming the vehicle structure. In the most severe of truck crashes the tractor undergoes 180^o of roll and comes to rest on its roof. The impact process during this rollover is complex, involving initial impact of the side or corner of the cab with the ground and then continuing roll until the rollover process is completed. Thus the crush or damage of the cab is distributed over its, side, corner and roof. Further, if specific roll protection devices are attached to the truck structure, the behavior of these structures during impact is affected by the distribution and geometry of these devices. A detailed analysis of this impact process is beyond the scope of the present study. Instead we will consider a total intrusion or crush distance available (either just for the roof structure or as a combined crush of roof and add on protective devices) and derive a relationship between this crush distance and the crush strength required.

The total kinetic energy of the tractor results from a combination of the energy due to the vertical velocity of the vehicle center of gravity and the roll velocity of the tractor. The final values (just before impact) of these variables can be obtained from the simulations and the total kinetic energy is given by

$$K.E. = 0.5 * M * V_{zcg}^2 + 0.5 * I_r * \omega_{rcg}^2 \tag{2}$$

where M is the mass of the tractor, V_{zcg} is the final vertical velocity of the tractor center of mass, I_r is the roll moment of inertia of the tractor and the ω_{rcg} is the final roll rate of the tractor.

A set of simulations was performed for a truck-trailer combination, where the vehicle is driven at a constant forward velocity and at a predetermined point in the simulation run a steering input is applied to cause the truck to follow a semicircular path of radius 500ft. Simulation runs with forward velocities of 45mph and increasing in 5mph increments up to 75mph was performed. The simulations are stopped at the instant when some point on the tractor cab strikes the ground. The object of these simulations is not to mimic any particular maneuver in real driving, but to simply apply greater and greater lateral accelerations, find the minimum lateral acceleration that causes rollover and then obtain estimates of the vehicle motion variables in the rollover process for a range of accelerations. From these estimates the energy dissipation characteristics required to protect the occupant from crush injury can be calculated.

Figures 9, 10 show the tractor roll angle and the roll rate for the 45mph run. As can be seen from the figures the roll remains bounded (i.e., the tractor does not roll over). The tractor center of gravity (CG) vertical velocity is not plotted since without rollover it essentially remains close to zero.

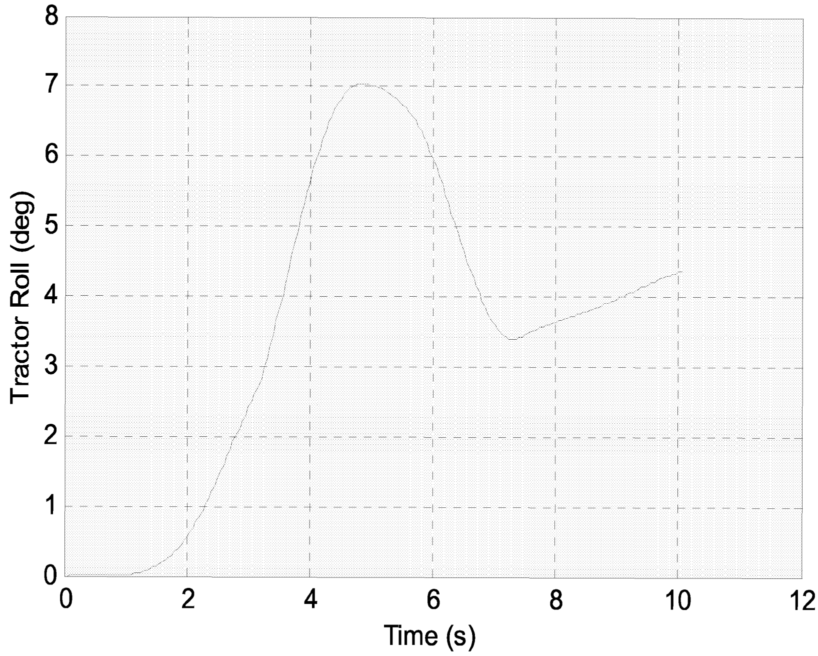

Figure 9. Tractor roll from vehicle simulation (45mph)

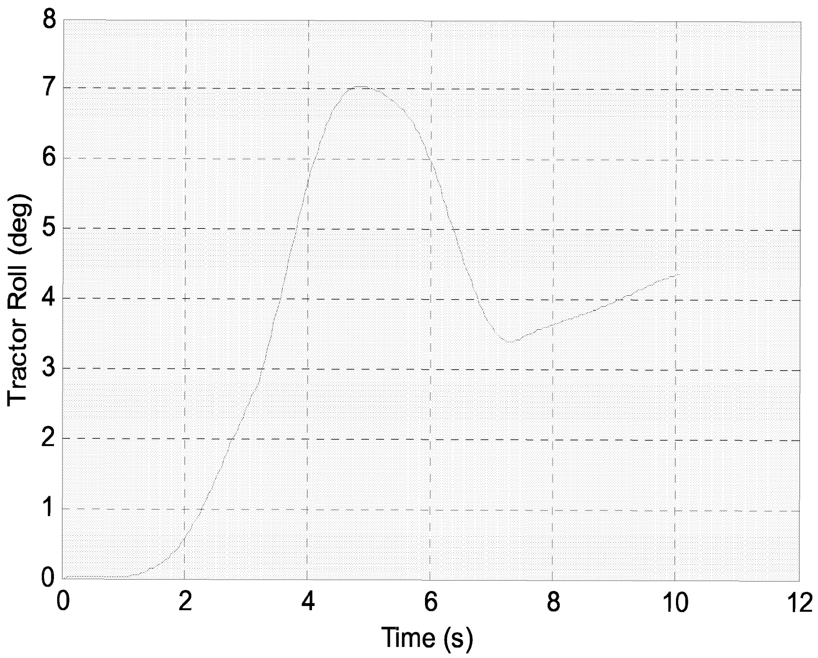

Figure 10. Tractor roll rate from vehicle simulation (45mph)

Figures 11 - 22 show tractor roll, roll rate and CG vertical velocity for simulations from 50mph to 75mph. At 50mph the tractor roll at contact with the ground is about 84 ° since some structures on the side of the tractor are actually outboard of the wheels and contact the ground first. It can be seen that as the forward velocity increases the maneuver becomes more severe leading to quicker rollover and higher peak roll rates. However, the final vertical velocity of the tractor CG appears to behave in a more complicated fashion, first increasing and then decreasing. This is due to fact that, the lower the velocity the lower the roll angle of the tractor at ground impact; i.e., at 50mph the tractor barely rolls over and contacts the ground at approximately a roll of 84° or falls on its side. In this case the CG does not have time to fall through its entire height above the ground and thus does not convert all its potential energy into kinetic energy (i.e., velocity). As the velocity increases the wheels lose contact with the ground, the roll angle goes past 90° and the tractor roof comes into contact with the ground first. This results in the tractor CG falling through increasing heights as roll angle increases up to 90° and then decreasing for greater roll angles and thus exhibiting the behavior seen in the simulations.

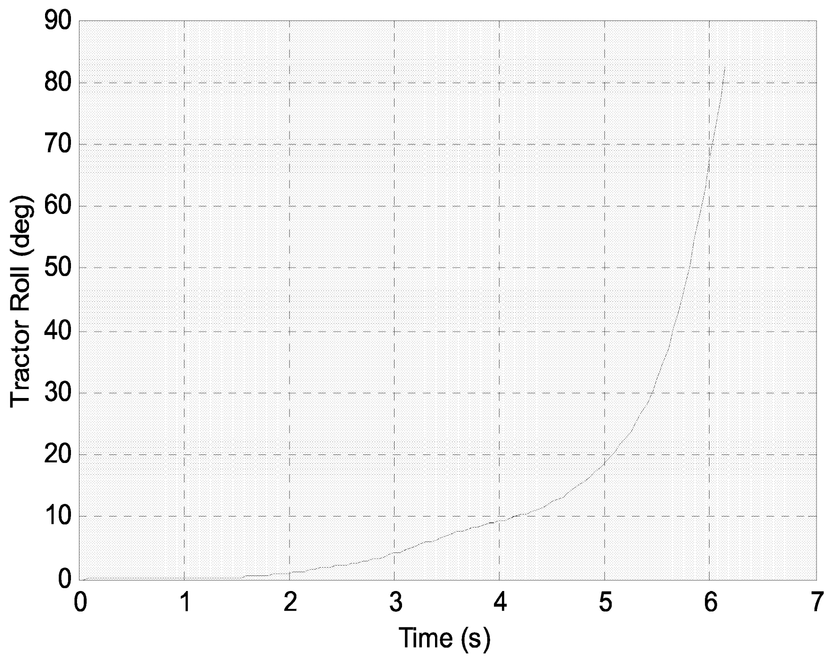

Figure 11. Tractor roll from vehicle simulation (50mph)

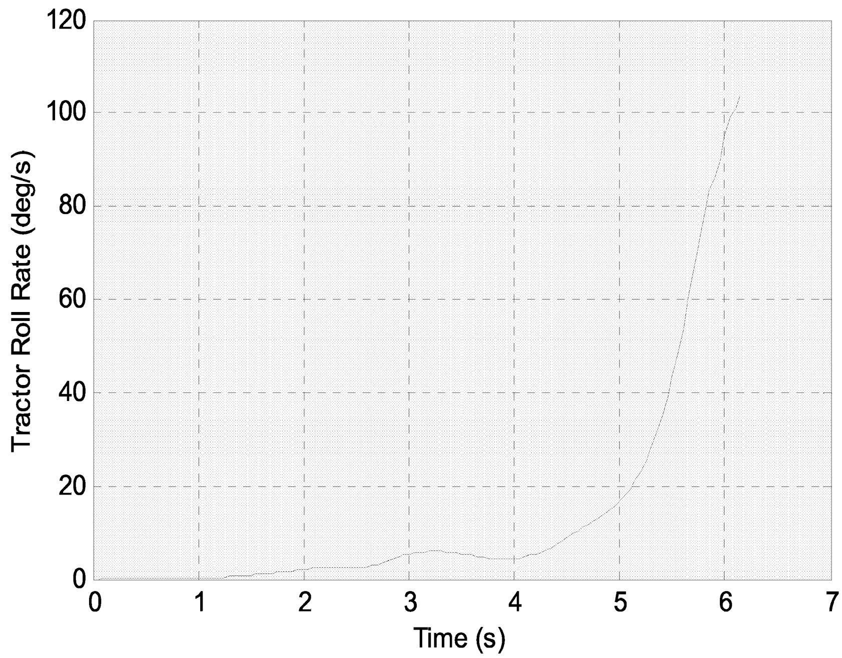

Figure 12. Tractor roll rate from vehicle simulation (50mph)

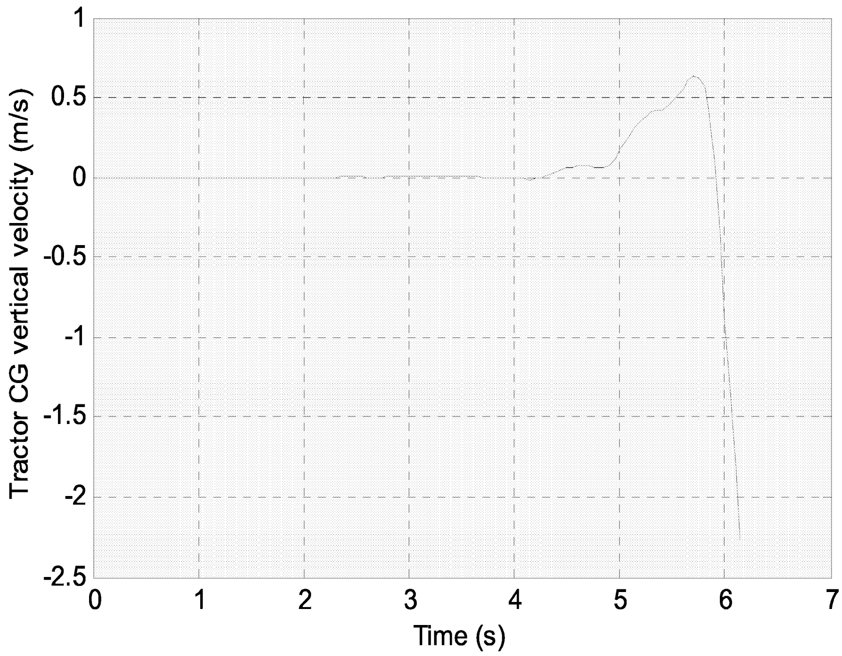

Figure 13. Tractor CG vertical velocity from vehicle simulation (50mph)

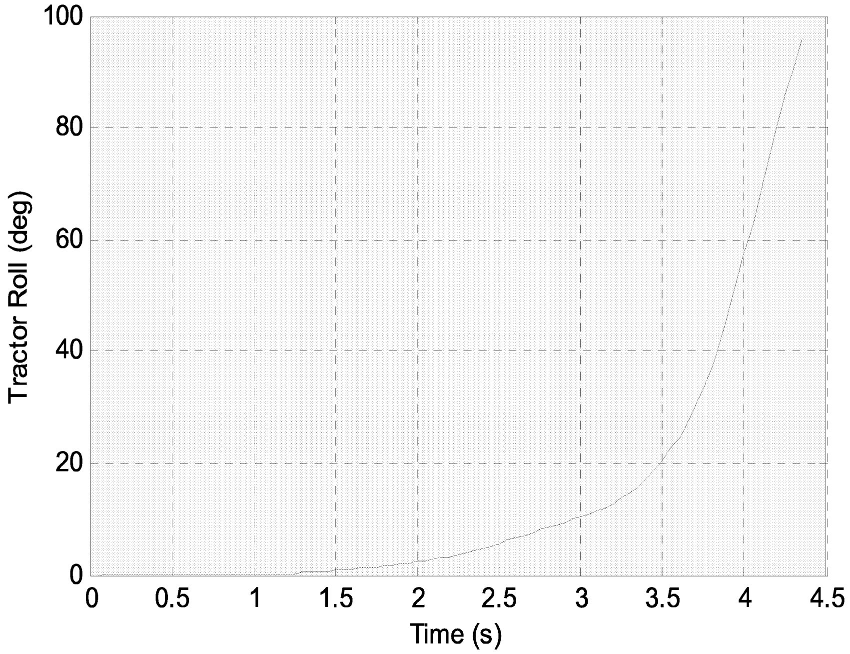

Figure 14. Tractor roll from vehicle simulation (60mph)

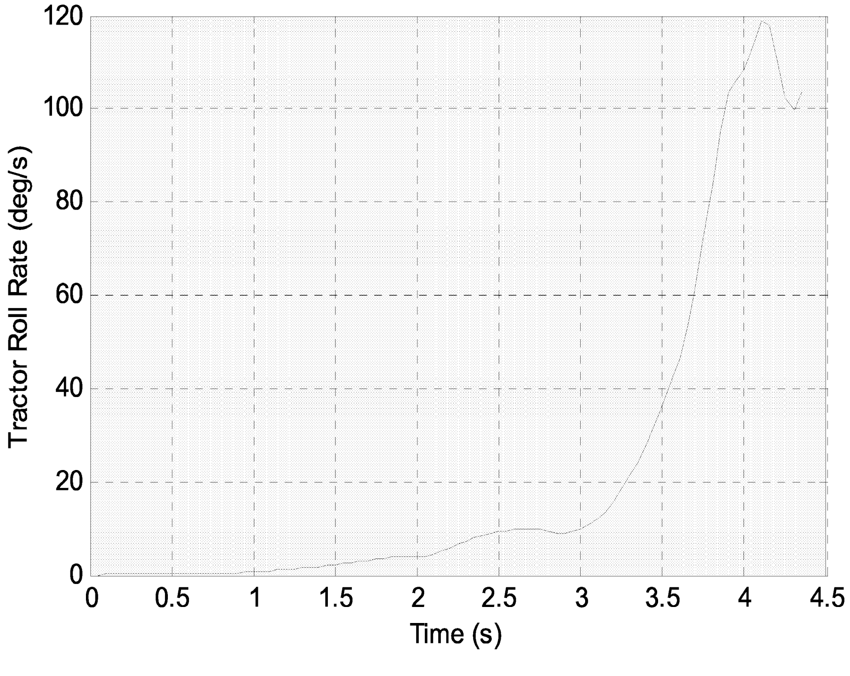

Figure 15. Tractor roll rate from vehicle simulation (60mph)

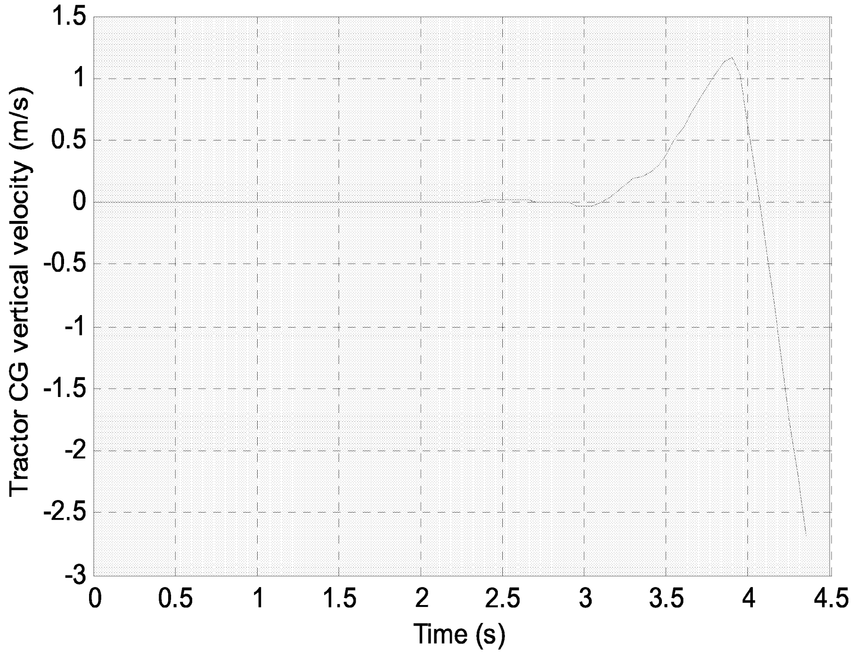

Figure 16. Tractor CG vertical velocity from vehicle simulation (60mph)

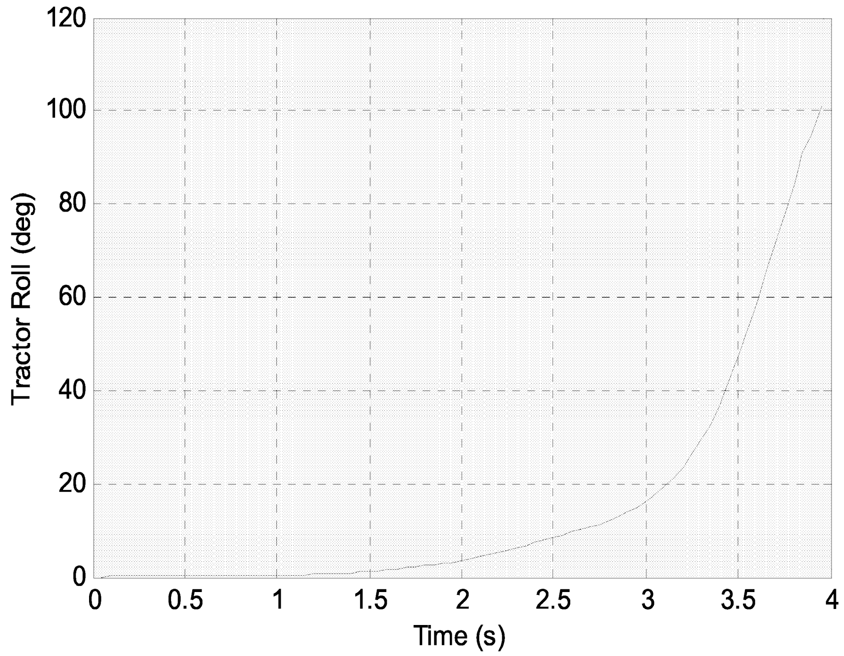

Figure 17. Tractor roll from vehicle simulation (65mph)

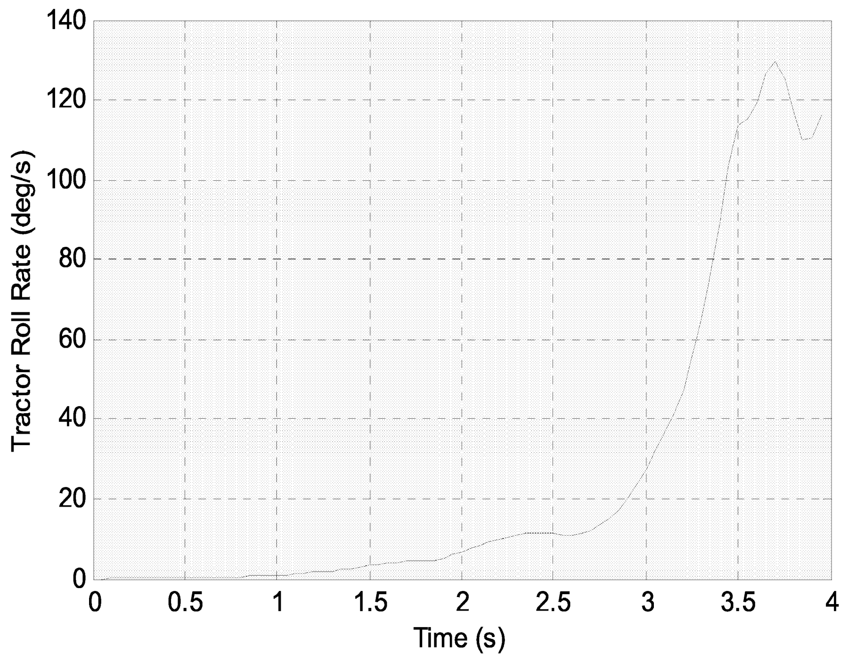

Figure 18. Tractor roll rate from vehicle simulation (65mph)

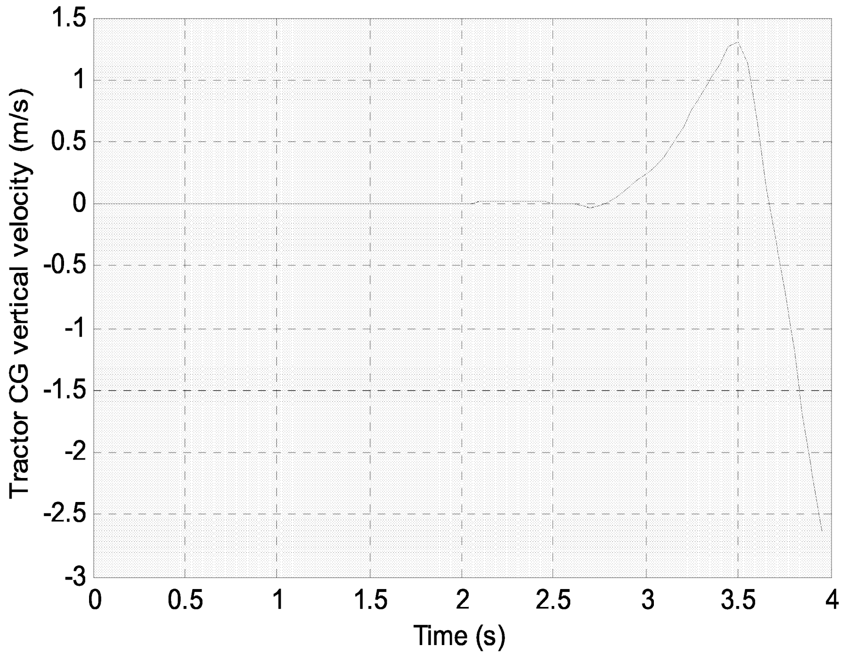

Figure 19. Tractor CG vertical velocity from vehicle simulation (65mph)

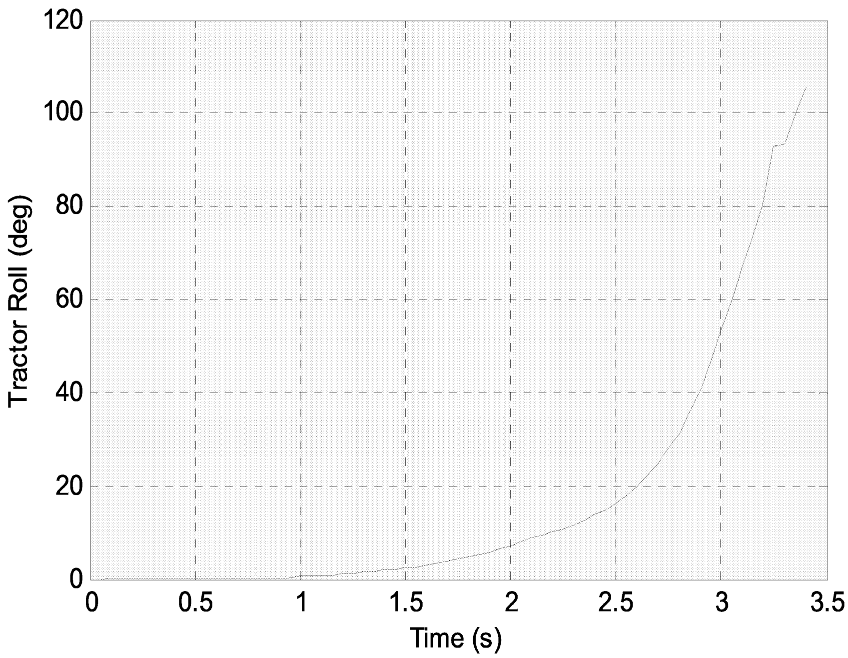

Figure 20. Tractor roll from vehicle simulation (75mph)

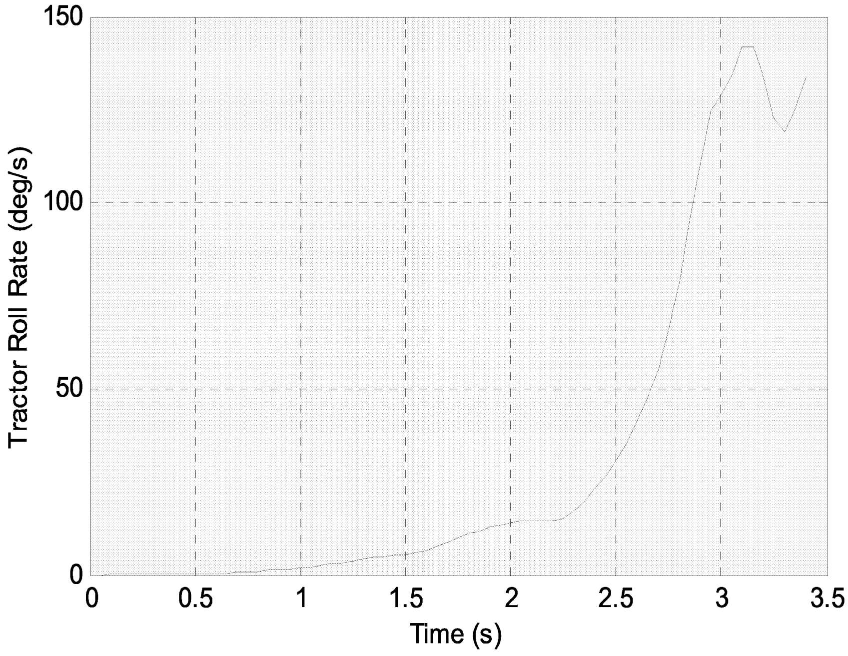

Figure 21. Tractor roll rate from vehicle simulation (75mph)

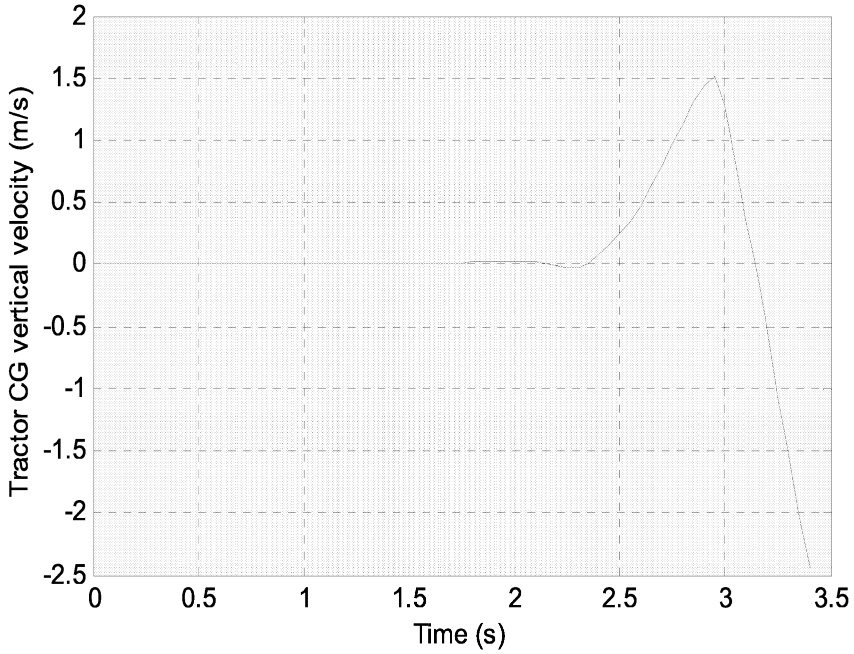

Figure 22. Tractor CG vertical velocity from vehicle simulation (75mph)

Table 8 shows the values of the tractor roll, roll rate and CG vertical velocity at ground impact. Where the simulation shows some oscillation near and through the ground plane the peak roll rate is taken as a conservative estimate.

Simulation run	Forward velocity (mph)	Final Roll (deg)	Peak Roll Rate (deg/s)	Final CG vertical velocity (m/s)
1.	45	No Rollover	No Rollover	No Rollover
2.	50	84	101	2.35
3.	55	93	105	2.9
4.	60	97	118	2.7
5.	65	101	129	2.6
6.	70	105	136	2.4
7.	75	107	142	2.2

Table 8. Vehicle motion variables at ground impact

We assume values of 10000kg for the tractor mass and 6000 kg-m^2 for the tractor roll moment of inertia and estimate the energy to be dissipated for each simulation run using equation 2. The results of the computation are shown in Table 9. It is interesting to note that the kinetic energy to be dissipated is highest for the 55mph roll maneuver and lower for the more severe maneuvers. Of course this is dependent on the vehicle geometry used in the simulations (higher cab roof heights reduce final vertical velocity for greater roll angle at impact) and the mass and inertia properties of the tractor. For estimating the required crush strength of the tractor cab we will use this peak value of 52125J as the energy to be dissipated in the rollover process.

Run No.	Tractor KE (J)
1.	No rollover
2.	38122
3.	52125
4.	49174
5.	49007
6.	45702
7.	42626

Table 9. Vehicle motion variables at ground impact

The crush strength of real life structures is not constant with deformation and instead peaks quickly and then tends to decline. We reproduce here a figure from a previous report on truck aggressivity performed at UMTRI to illustrate this and to discuss the effect on total intrusion.

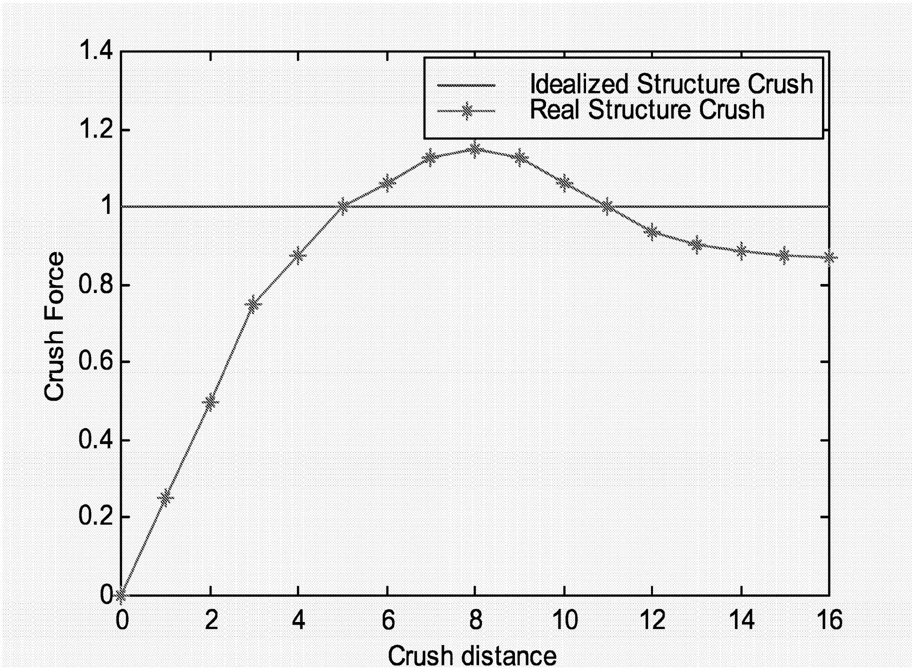

Figure 23. Relationship between vehicle acceleration and stopping distance

Figure 23 shows the comparison between the constant crush force assumption and the likely crush force available during the deformation of a real structure. The area under both curves represents the energy dissipated in the collision and thus must be equal to each other and the total kinetic energy of the impacting vehicle (in cases where the impacting vehicle is brought to a complete stop). Thus the crush of a real structure is likely to be greater than that of an ideal structure. However the assumption that all the kinetic energy is absorbed in crush is conservative. Some of the energy is dissipated in vehicle to road friction and thus provides some compensating conservatism in the calculation to offset the earlier described error due to the assumption of a constant crush strength.

As mentioned earlier we will also assume a uniform available crush distance over all parts of the cab structure to simplify the calculation. Then the work done in crushing this structure is given by the crush strength (or force) multiplied by the distance through with the structure is deformed. I.e.,

$$W_c = F_c * d_c \tag{3}$$

where, W_c is the crush work, F_c is the crush force and d_c is the crush distance. By conservation of energy this work must be equal to the kinetic energy of the tractor and thus a relationship between the available crush space and crush strength can be plotted as shown in figure 24.

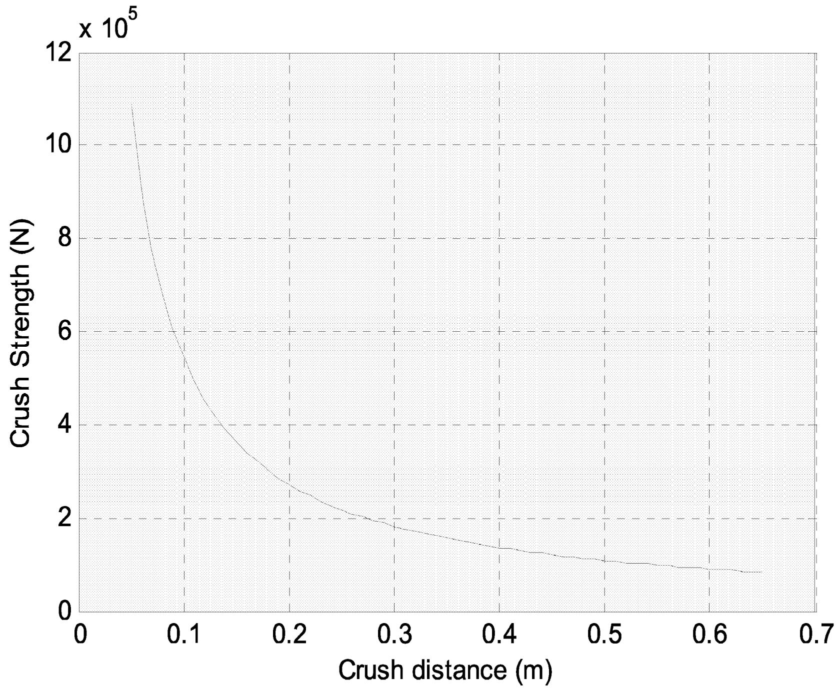

Figure 24. Relationship between crush distance and required crush strength

Figure 24, shows the plot of required crush strength for crush distances up to approximately 0.6m (24 inches). Several studies (Berg, 1997, Cheng, 1996) indicate that this is the practical upper limit of the available crush space. With this assumption a crush strength of 100000N (or approximately 22000lbs) would be required. A more realistic crush space assumption may be 12 inches. In this case the required strength goes up to 180000N (39000lbs). An earlier study (SAE 1997, CRP-13) examined the issue of truck cab strength and suggested methods of reinforcing the cab structure. The experimental and FEA structural analyses performed there indicate that achieving the above required structural strength is feasible and would significantly reduce cab intrusion into the occupants survival space.

3.3. Cab rollover integrity benefit estimation

Tables 10, 11 and 12 show the injury rates (both raw numbers and %) for the US road system in the 5 year period 1995-1999, for truck occupants. The figures are broken down to show the rates for crashes with and without rollover and cases in which the occupants were wearing safety belts, not wearing safety belts and in which the use of safety belts is unknown.

Rollover	Belt use=yes		
Frequency	Rollover No	Rollover Yes	Total
Fatal	374	368	742
A injury	5,709	8,044	13,753
B injury	16,066	12,026	28,092
C injury	35,298	9,948	45,246
Unk. sev.	905	23	928
No injury	1,283,386	28,958	1,312,344
unknown	5,910	244	6,154
Total	1,347,648	59,611	1,407,259
	no	yes	Total
Fatal	0.03	0.62	0.05
A injury	0.42	13.49	0.98
B injury	1.19	20.17	2.00
C injury	2.62	16.69	3.22
Unk. sev.	0.07	0.04	0.07
No injury	95.23	48.58	93.26
unknown	0.44	0.41	0.44
Total	100.00	100.00	100.00

Table 10. Injury rate comparison for rollover (belted occupant)

belt use= no			
Frequency	Rollover No	Rollover Yes	Total
Fatal	751	1,084	1,835
A injury	1,650	3,055	4,705
B injury	4,647	4,638	9,285
C injury	5,597	4,016	9,614
Unk. sev.	214	261	475
No injury	119,235	4,437	123,672
unknown	1,638	7	1,645
Total	133,732	17,498	151,230
Frequency	no	yes	Total
Fatal	0.56	6.19	1.21
A injury	1.23	17.46	3.11
B injury	3.47	26.51	6.14
C injury	4.19	22.95	6.36
Unk. sev.	0.16	1.49	0.31
No injury	89.16	25.36	81.78
unknown	1.22	0.04	1.09
Total	100.00	100.00	100.00

Table 11. Injury rate comparison for rollover (unbelted occupant)

Frequency	Rollover no	Rollover yes	Total
Fatal	312	275	587
A injury	499	576	1,075
B injury	1,623	906	2,528
C injury	4,109	691	4,800
Unk. sev.	431	23	454
No injury	223,863	3,320	227,183
unknown	85,040	394	85,434
Total	315,876	6,184	322,060
Frequency	no	yes	Total
Fatal	0.10	4.45	0.18
A injury	0.16	9.31	0.33
B injury	0.51	14.64	0.78
C injury	1.30	11.17	1.49
Unk. sev.	0.14	0.37	0.14
No injury	70.87	53.69	70.54
unknown	26.92	6.36	26.53
Total	100.00	100.00	100.00

Table 12. Injury rate comparison for rollover (belt use unknown)

As mentioned earlier, reliable data on injuries due to entrapment and crush are difficult to come by. However some previous studies (discussed in more detail in the literature review), such as, Berg (1997) study and Simon (2001) provide figures that indicate that the probability of a serious (fatal or A injury) injury is increased by approximately a factor of 5 (33% in crashes with vs. 7% in crashes without) by intrusion. Estimates from examination of crash data indicate that entrapment is involved in approximately 22% - 36% of crashes with serious injuries (Berg 1997, and Seiff 1985. Tables 10 and 11 show that the risk and severity of occupant injury is significantly higher in crashes with rollover. Further in the case of rollover the use of a safety belt provides a 10 fold reduction in the injury rate while in crashes without rollover the use of a safety belt provides almost twice (20 times) reduction in fatalities. This suggests that some other factor from which the safety belt does not provide protection is causing these injuries. This factor is likely to be (as observed in examinations of individual truck crashes) the crush of the tractor cab/roof structure. Therefore an assumption that cab crush is a significant factor in approximately 30% (in the middle of the previously mentioned range) of rollover type crashes is likely to be quite conservative. Based on this assumption and further assuming that if cab crush is prevented the 5 times lower injury likelihood rate estimated for the overall crash population holds for the rollover case also, we can make the following computation to estimate the reduction in fatalities.

$F_{rollover}$ = No. of annual fatalities with rollover (belted+unbelted+unknown) =345 (4)

Estimated fatalities in crashes with crush = $F_{rc} = F_{rollover} * 0.3 = 103.5$ (5)

Estimated fatalities if crush prevented = $F_{rc} * 0.2 = 20.7$ (6)

Estimated Reduction in fatalities if crush prevented = 82.8 (7)

3.4. Summary

Rollovers represent the most severe of the various types of truck crush accounting for approximately 63% of fatal or A injuries to truck occupants. The highest priority in any crash and particularly in rollover type crashes is retention of the occupant in the cab along with maintaining sufficient survival space. This chapter presented a simulation based analysis of the truck rollover process and computed the vehicle motion variables. These variables were then used to estimate the energy dissipation and structural strength requirements of the cab structure. It was also estimated that an annual reduction in fatalities of over 80 (out of about 345 rollover related fatalities – corresponding to approximately a 23% reduction) is possible if cab structural integrity can be improved sufficiently to prevent crush in rollover. While the calculations presented here are necessarily approximate due to the lack of accurate data, they are also quite conservative, indicating that improvement in cab structural strength can achieve significant benefits in reducing severe injuries among truck occupants.

4. Occupant Protection – Cab Interior

4.1. Introduction

Once the issue of providing sufficient crash survival space inside the cab has been addressed, further improvement in occupant protection can be achieved by the addition of a second layer of injury countermeasures to reduce the peak accelerations experienced by the occupants by dissipating their kinetic energy in a controlled manner and to prevent or reduce the severity of injuries due to impact with the truck interior structure (windshield, cab roof etc.,) or components (steering wheel, instrument panel etc.) The principal way of providing such protection is the use of restraint systems (safety belts and airbags).

There is considerable agreement in the truck safety literature (presented in detail in the literature review) about the qualitative benefits of using safety belts and (to a lesser extent, due the more recent introduction and lesser experience with) airbags. Safety belts in particular provide protection against multiple injury mechanisms including (i) Ejection: previous studies have shown that the use of safety belts reduces the incidence of ejection in truck crashes involving some level of occupant injury to virtually zero (< 1%) versus observed ejection rates of approximately 10% for unbelted occupants (ii) Interior impacts: Safety belts also prevent or reduce the severity of interior impacts (iii) Survival space: Safety belts provide protection by ensuring that the occupant is held in the space designed to be uncompromised by intrusion in crashes involving crush of cab structure.

4.2. Effectiveness of Safety Belt use

We shall now consider US truck crash data to evaluate the potential benefits of the use of safety belts.

Before we begin the analysis it is useful to keep the following in mind. Belt use information in both TIFA and GES is taken primarily from police reports. Since most uninjured or lightly-injured persons are out of their vehicles by the time the police arrive, in most instances the reporting officer has to rely on the statements of the involved parties. Thus it is likely that belt use is most accurately recorded for fatally- or seriously-injured persons, and less accurate when the officer has to rely on statements. The bias of self-reporting will be to overstate belt use, since using restraints is a legal requirement in many states, and, increasingly, often a company's requirement. This may have a tendency to cause some overestimation in the effectiveness of belt use.

Table 13 shows the frequency of fatal, A, B and C injuries in truck crashes on US public roads over the period 1995-1999. The most interesting point is that 58% of fatalities occur in crashes involving unbelted drivers, even though such crashes make up only 8% of all crashes. Similarly A, B and C injuries in unbelted drivers are also over represented, though the disproportionality is not quite as large.

Frequency	Belted	Unbelted	Unknown	Total	Belted %	Unbelted%	Unknown%	Total
Fatal	742	1,835	587	3,164	23.5	58.0	18.6	100.0
A injury	13,753	4,705	1,075	19,533	70.4	24.1	5.5	100.0
B injury	28,092	9,285	2,528	39,905	70.4	23.3	6.3	100.0
C injury	45,246	9,613	4,800	59,659	75.8	16.1	8.0	100.0
Unknown Sev	928	475	454	1,856	50.0	25.6	24.4	100.0
No injury	1,312,345	123,673	227,183	1,663,201	78.9	7.4	13.7	100.0
Unknown	6,154	1,645	85,434	93,233	6.6	1.8	91.6	100.0
Total	1,407,260	151,231	322,060	1,880,550	74.8	8.0	17.1	100.0
	74.8	8.0	17.1	100.0				

Table 13. Injury type & frequency with belt use (TIFA+GES 1995-1999)

The above data can also be examined in terms of injury rates or likelihood. Table 14 shows the injury rates for each type of injury as a percentage of total truck crashes. It can be seen that the fatality likelihood is greater by a factor of 24 for unbelted drivers. The injury rates for the other injury level show similar (though as noted earlier, less dramatic) relationships.

Frequency	Belted%	Unbelted%	Unknown%	Total%
Fatal	0.05	1.21	0.18	0.17
A injury	0.98	3.11	0.33	1.04
B injury	2.00	6.14	0.78	2.12
C injury	3.22	6.36	1.49	3.17
Unknown Sev	0.07	0.31	0.14	0.10

No injury	93.26	81.78	70.54	88.44
Unknown	0.44	1.09	26.53	4.96
Total%	100.00	100.00	100.00	100.00

Table 14. Injury type & frequency with belt use (TIFA+GES 1995-1999)

However the data in tables 13 and 14 include all truck crashes, the vast majority of which cause no injury to the truck occupants (most of injuries in multiple vehicle truck crashes occur in the other vehicles). Therefore a better way to evaluate the effectiveness of truck occupant injury protection is to consider the injury rates in only those crashes where the occupant sustained some known level of injury as shown in table 15.

Frequency	Belted%	Unbelted%
Fatal	0.84	7.21
A injury	15.66	18.50
B injury	31.98	36.50
C injury	51.52	37.79
Total	100.00	100.00
Some injury%	6.24	16.32

Table 15. Injury type & frequency with belt use (in crashes with occupant injury)

Table 15 shows an interesting trend. The likelihood of a fatal injury is dramatically higher, while the rates for other injuries are somewhat comparable. However, this must be considered in the context of the last row of Table 15, which shows the rate of some level of injury, which is higher (16.32% to 6.24%) for unbelted drivers. This suggests (the intuitively sensible explanation) that the essential effect of wearing a safety belt is to lower the injury severity, i.e., fatal injuries become A injuries, A injuries become B and so on.

The severity of injuries in any crash is directly related to the velocity change of the involved vehicles. Thus it is useful to examine the effectiveness of safety belts in relation to collision velocities. Collision velocities or change in velocity is not directly available from crash reports. However, it is possible to meaningfully use the speed limit of the road on which the crash took place as a proxy for crash severity.

	Speed limit (mph)							
Injury Type	to 30	30-35	40-45	50-55	60-65	70-75	Unknown	Total
Fatal	4	19	62	364	192	92	9	742
A injury	366	1,846	2,265	4,730	1,388	3,142	16	13,753
B injury	792	4,322	4,116	13,325	3,431	2,090	17	28,092
C injury	2,661	7,603	9,333	17,951	5,240	2,443	16	45,246
Unk. sev.	692	94	52	75	14	0	0	928
No injury	164,943	299,987	288,680	360,733	131,030	64,632	2,339	1,312,344
unknown	378	2,314	1,516	1,787	147	12	0	6,154
Total	169,836	316,185	306,024	398,965	141,441	72,410	2,397	1,407,259

Table 16. Injury data in relation to vehicle speed (Belted)

	Speed Limit (mph)							
Injury Type	to 30	30-35	40-45	50-55	60-65	70-75	Unknown	Total
Fatal	0.00	0.01	0.02	0.09	0.14	0.13	0.38	0.05
A injury	0.22	0.58	0.74	1.19	0.98	4.34	0.65	0.98
B injury	0.47	1.37	1.35	3.34	2.43	2.89	0.71	2.00
C injury	1.57	2.40	3.05	4.50	3.70	3.37	0.67	3.22
Unk. sev.	0.41	0.03	0.02	0.02	0.01	0.00	0.00	0.07
No injury	97.12	94.88	94.33	90.42	92.64	89.26	97.59	93.26
unknown	0.22	0.73	0.50	0.45	0.10	0.02	0.00	0.44
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 17. Injury frequency (%) in relation to vehicle speed (Belted)

	Speed Limit (mph)							
Injury Type	to 30	30-35	40-45	50-55	60-65	70-75	Unknown	Total
Fatal	25	107	154	922	408	180	39	1,835
A injury	235	448	718	2,269	367	665	3	4,705
B injury	503	918	1,439	5,209	699	514	4	9,285
C injury	1,027	1,128	2,009	4,366	747	269	69	9,613
Unk. sev.	49	0	241	130	0	55	0	475
No injury	21,106	33,232	24,818	32,766	8,455	2,803	493	123,673
unknown	324	702	1	614	2	1	0	1,645
Total	23,269	36,534	29,379	46,276	10,678	4,487	608	151,231

Table 18. Injury data in relation to vehicle speed (Unbelted)

	Speed Limit (mph)							
Injury Type	to 30	30-35	40-45	50-55	60-65	70-75	unknown	Total
Fatal	0.11	0.29	0.52	1.99	3.82	4.01	6.41	1.21
A injury	1.01	1.23	2.44	4.90	3.43	14.83	0.49	3.11
B injury	2.16	2.51	4.90	11.26	6.55	11.45	0.66	6.14
C injury	4.41	3.09	6.84	9.43	7.00	6.00	11.29	6.36
Unk. Sev.	0.21	0.00	0.82	0.28	0.00	1.22	0.00	0.31
No injury	90.70	90.96	84.47	70.81	79.18	62.47	81.14	81.78
Unknown	1.39	1.92	0.00	1.33	0.02	0.02	0.00	1.09
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 19. Injury frequency (%) in relation to vehicle speed (Unbelted)

Tables 16, 17, 18 and 19 show the injury data and rates for speed ranges from 30 mph up to 75 mph. While it is clear (as expected) that injury rates increase with increasing speed for both belted and unbelted occupants, the data allows us to examine an important question with regard to the protective effect of safety belts: Is there a range of crashes that are so severe that safety belts offer no useful protection?

Examination of the data immediately shows that the answer to this question is no. At every speed range safety belts offer significant reductions in injury severity and rate. Even at the highest speed safety belts offer approximately a 30 fold reduction in fatality rate and a 4 fold reduction in the rate of occurrence of any injury.

However the relative benefits do vary with the speed range considered. This is for two reasons.

At the lower speeds use of safety belts virtually eliminates the risk of fatalities, with only 23 fatalities occurring in 2.2 million crashes that occurred on roads with speed limits below 35 mph, resulting in a fatality incidence of less than 0.001%. In the unbelted case this incidence rises to 132 in 59,833 crashes or 0.22%. At higher speeds the benefits in terms of improvement in injury rates is not quite as large since both belted and unbelted occupants suffer significant fatality rates, due to the fact that the greater energy involved in the collisions is sufficient in some of the crashes to still cause fatality even after attenuation by the safety belt.

However, improvements in injury rates offer only a partial picture of the potential savings offered by safety belts. The actual number of lives saved or injuries reduced depends also on the number of crashes that take place in a given speed range. Thus we can compute the potential savings by comparing the number of actual unbelted fatalities or injuries in a given speed range with the corresponding expected number if all these occupants were using safety belts. This computation is shown in Table 20 with the first column in each speed range showing the actual fatalities where the safety belt was not used and the second column showing the expected number of fatalities with the use of the safety belt. It can immediately be seen that tremendous reductions in fatalities and other injuries are possible with use of safety belts. The estimated reduction in fatalities is 1723 (over the 5 year 1995-1999 period) or approximately 54%. Reductions in the A, B and C injuries are estimated to be 17%, 16% and 8% respectively. As discussed earlier the lower reduction in the less severe injuries is likely to be due to the conversion of the more serious injuries to lower level injuries.

	Speed Limit (mph)												Total Reduction
Injury Type	to 30		30-35		40-45		50-55		60-65		70-75		
Fatal	25	0	107	4	154	6	922	42	408	15	180	6	1723
A injury	235	51	448	212	718	217	2269	551	367	105	665	195	3371
B injury	503	109	918	501	1439	397	5209	1546	699	259	514	130	6340
C injury	1,027	365	1128	877	2009	896	4366	2082	747	395	269	151	4780
Total injuries	1790	525	2601	1594	4320	1516	12766	4221	2221	774	1628	482	16214

Table 20. Estimated injury reduction with safety belt use

4.3. Cab Interior Impact Countermeasure Modeling

The issue of cab crashworthiness in rollover was considered in detail earlier. Cab crashworthiness and structural integrity is also of importance in the crash type that causes the second highest number of fatalities, that of a frontal crash into a fixed object or another heavy vehicle. However, analysis of this collision mode is simpler than rollover and will be considered briefly here to both address the structural requirement for preventing crush and to generate information about the crash parameters (velocity change, acceleration) for use in analyzing the benefits of cab interior countermeasures. We shall first consider the kinetic energy of the truck cab in frontal collisions.

4.3.1. Truck Crash Velocity Distributions

Closing speeds are generally not available in crash files, and they do not exist in any crash data file that allows crash configuration to be reconstructed at the level of detail found in this analysis. However, UMTRI maintains a special purpose data set that has closing speeds for certain fatal crashes involving tractor-semitrailer combinations. These data were collected for Sandia National Laboratories as part of a project to characterize collision severity in fatal truck crashes. The collision severity file comprises eight years of data, 1992-1999.

The data collected are based on information from police reports and telephone interviews. Crash involvements are classified according to the primary type of impact, as described above: with another truck; with a car or light vehicle; with a railroad train; with a fixed object; with a non-fixed object; and so on. Then within each category, additional data is collected on a sample of the involvements. For each crash, the primary impact is identified. Then data are collected on the travel speed of the vehicles, skid distances, angles of impact, and the weight of the colliding objects. A roadway coefficient of friction is assigned based on the roadway surface type and condition (dry, wet, or icy). Impact speeds are calculated using travel speeds and skid distances. From the impact speeds and angle of impact, the relative velocity of the colliding vehicles is calculated.

The data is collected on a specialized sample of crashes involving tractor-semitrailers. First, the TIFA file, which provides the set of cases for which the Sandia collision severity data is collected, is itself a sample for most of the data years represented. Second, only cases from states for which estimates of travel speed are regularly available are included. Finally, only a sample of car/truck cases is included in the data. Since data collection effort is primarily concerned with major impacts on the truck, cases that are inherently minor in terms of collision damage (e.g., truck/light vehicle crashes) to the truck are under-sampled, while cases that present a major threat to the integrity of the vehicle, such as impacts with other trucks or railroad trains, are over-sampled. Sample fractions are recorded at every stage of sampling, so weights may be calculated to estimate national totals from the sample. These weights were used to produce the distributions of impacts shown.

Estimates of a value called Peak Contact Velocity (PCV) are calculated. The PCV value is basically the collision ∇V, assuming an inelastic collision. PCV is defined as follows:

$$PCV_t = Vr/(1+M_t/M_o) \qquad (8)$$

where:

V_r = relative velocity

M_t = truck mass

M_o = other vehicle mass

Estimates of the PCV of the vehicles at impact are generated for the sampled cases. These estimates are as reliable as the underlying data. Much of the information used in making the estimates is taken from police reports. Typically, a crash reconstruction was not undertaken. Angles of impact are estimated by UMTRI from the scene diagrams found on police reports. Measurements of skid distances are typically included in police reports, either in the narrative or scale diagram. The roadway coefficient of friction is assigned from a table of estimates based on the roadway surface type and condition, rather than measured at the scene. Travel speed is estimated by the reporting police officer, based on witness reports and whatever other evidence he may choose to use.

Each value used in the calculation of PCV is thus subject to error. The estimates are made as carefully as possible, but are limited by the source materials. Nevertheless, every effort was made to make the data as accurate as possible. After coding, each case was reviewed at least once by a mechanical engineer. These data are the only crash data available for which relative velocities are systematically provided. Only crashes involving tractor-semitrailers are included; only fatal involvements are included.

The distributions provided are for collisions in which the impact was with the front of the truck and in which the first event in the crash was not a rollover. By excluding first-event rollovers, the focus is narrowed to collision-induced injuries. Distributions are provided for all combinations of driver injury level (either fatal and A-injuries or a less-severe injuries, including no injury) and belt use (restrained or unrestrained, as defined above).

Figure 25 shows the velocity distribution for truck crashes on the US road system over the years 1992 – 1999. Figure 26 shows the velocity distribution of crashes with K or A injury to the truck occupant and figure 27 shows the velocity distribution for crashes without K or A injuries.

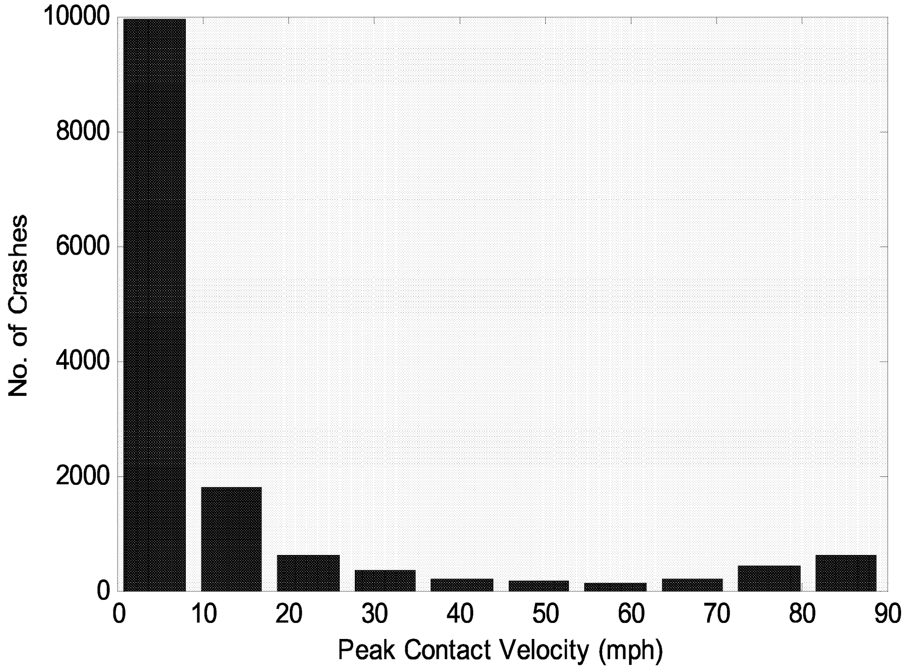

Figure 25. Peak Contact Velocity (∇V) for Truck Crashes (1992-1999)

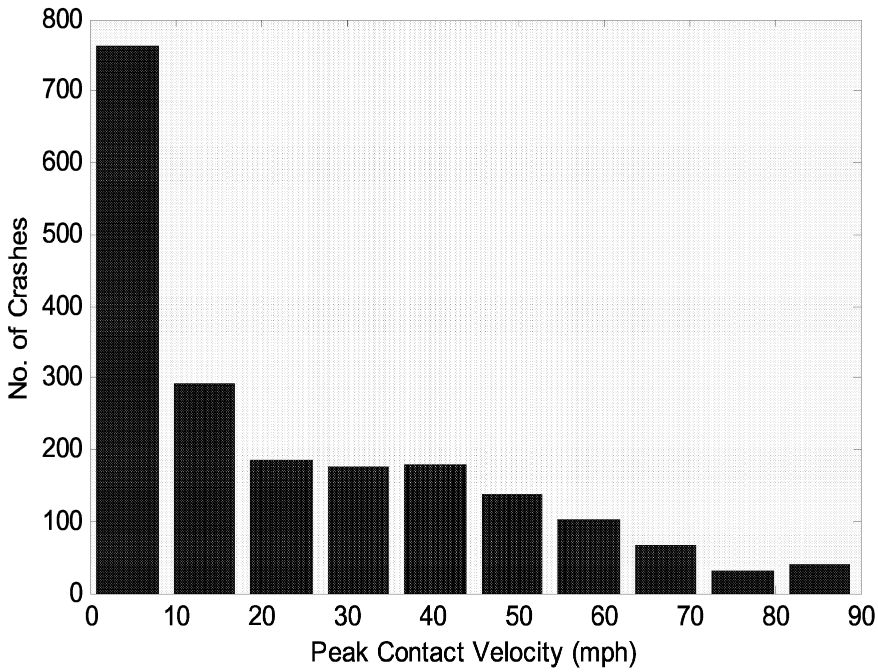

Figure 26. Peak Contact Velocity (∇V) – K or A Injury Crashes

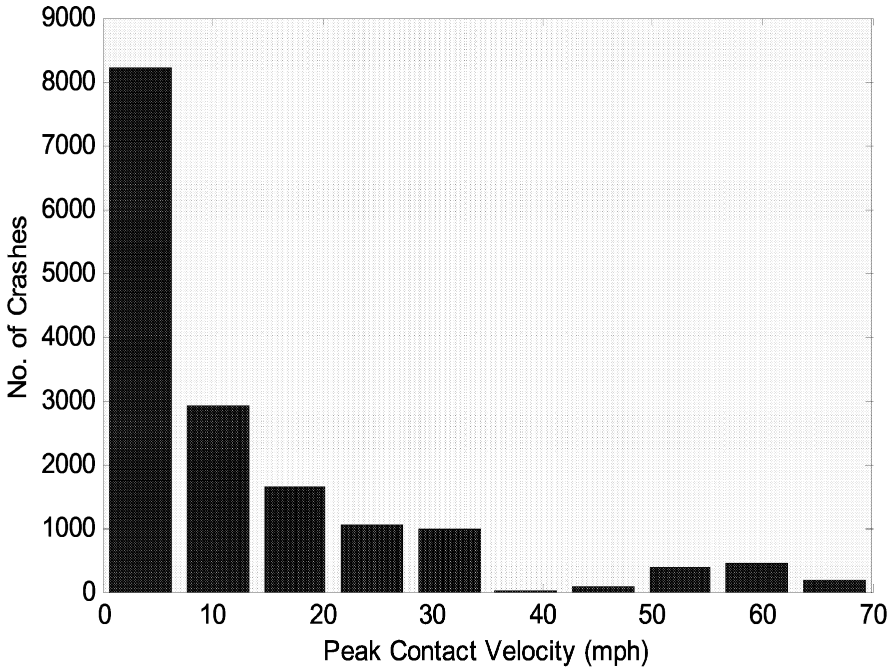

Figure 27. Peak Contact Velocity (∇V) – No K or A Injury Crashes

It is clear from the figures that the ∇V in the vast majority of truck crashes is quite low. Even in the more severe crashes (with K or A injuries) over 50% of the crashes had a ∇V of 20mph or less. Thus it is feasible that appropriate improvements in truck cab structural strength can provide occupant protection benefits in a significant number of crashes.

4.3.2. Cab Structural Crashworthiness

The kinetic energy of the vehicle must be dissipated in bringing it to a stop and the primary mechanism for this is crush of the cab structure. As done earlier we shall assume that the tractor mass is 10000kg. The kinetic energy is given by

$$K.E. = 0.5 * M * V^2 \tag{9}$$

Since approximately 63% (from figure 26) of severe truck crashes have a ∇V of 22.5mph (10m/s) or below, we shall use this velocity for determining the cab structural strength required to prevent occupant crush. Therefore the K.E. is

$$K.E. = 0.5 * 10000 * 10^2 = 0.5e6J \tag{10}$$

As done in the case for the rollover crashworthiness analysis we can construct a figure showing the relationship between the available crush space and the corresponding required crush strength.

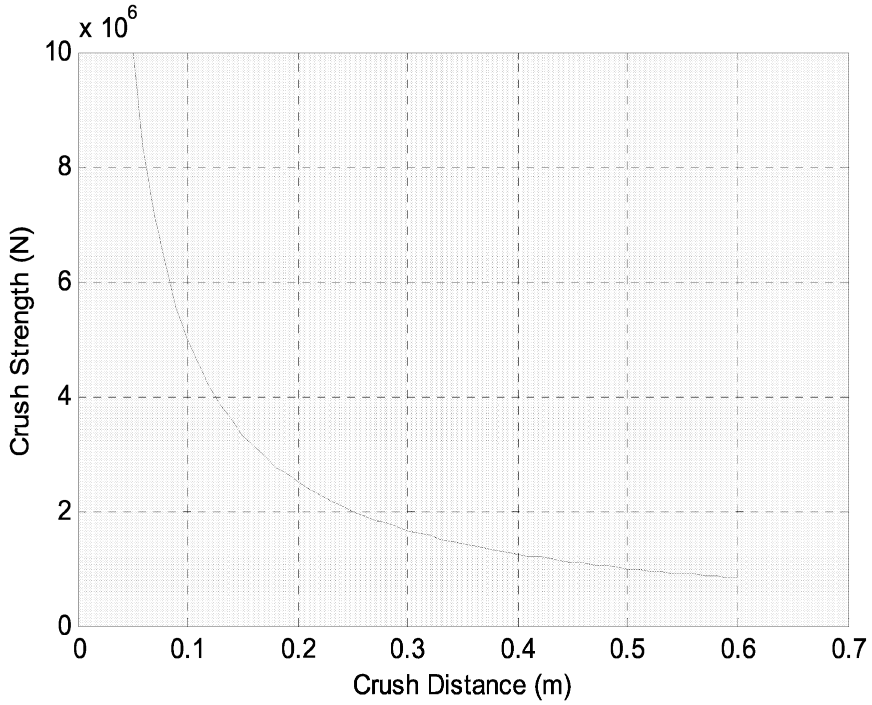

Figure 28. Relationship between crush distance and strength for frontal crash

Assuming the availability of 24 inches (0.6m – Note that typically passenger automobiles have about 1m of crush space available and therefore requiring truck cab designs to allow 24inches of crush space seems not unreasonable) of crush space, the required crush strength is approximately 8e5N (roughly 180000lbs). Rossow (1995) presents results from a previous SAE truck crashworthiness study completed in 1994 and descriptions of the European Community ECE-R29 crash standards that indicate the trucks currently have a frontal crash strength of approximately 80,000lbs. Thus raising this frontal strength by a factor of about 2.5 will provide protection from intrusion in almost $2/3^{rds}$ of frontal truck crashes. It should be noted that along with strengthening the cab front structure, the cab rear must also be reinforced since (based on examination of individual crashes) cab damage occurs due to secondary impacts from the trailer and the payload. Rossow (1995) indicates that the ECE R29 standards call for the cab rear to be able to withstand a force equal to 20% of the maximum payload of the truck.

4.3.3. Cab Crash Modeling

Several previous studies (Berg *et. al.,* 1997, Horii *et. al.,* 1987) have examined the issue of modeling frontal crashes and present both simulations and measurements from frontal crash tests. Examination of the data and the simulation results show that the crash pulse generated in a frontal crash of a heavy vehicle has the following characteristics.

- The time period of the crash pulse (the duration over which the vehicle is decelerated to a stop) is roughly constant (approximately 50ms) and independent of the ΔV undergone by the truck.
- It is generally well recognized that vehicle collisions are quite inelastic, with coefficients of restitution generally below 0.1 and decreasing even further as the velocity (or energy) of a collision increases. The crash measurements provided in the above mentioned studies support this assumption, showing very little rebound of the vehicle after the collision.
- Viscous damping (energy dissipation by forces proportional to the vehicle velocity) is also quite small.

The above points leads to the development of a simple model that approximates measured crash pulses quite well. This model can be written down as,

$$\ddot{x} = -(k/m) * x \tag{11}$$

Where x is vehicle displacement m is the vehicle mass and k is a restoring (spring) force constant which has a velocity dependent characteristic as shown in figure 29.

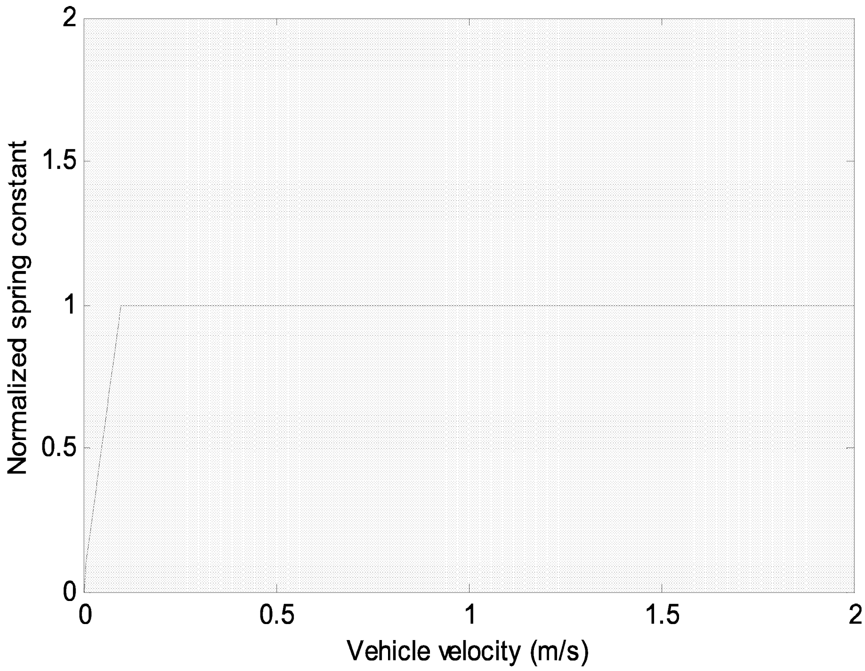

Figure 29. Restoring force spring constant (normalized)

The physical meaning of such a model for the restoring force is that the restoring force is non-zero and constant for most of the collision process but decreases as the vehicle comes to a stop and consistent with the assumption of inelasticity is zero once the vehicle collision energy is dissipated. Choosing a value of 1.5e3 (N/kg-m) for the constant value of the term (k/m) provides a crash pulse that lasts for approximately 50ms (consistent with crash simulation and test results). The shape and magnitude of the pulse are shown for a 22.5mph (10m/s) ∇V crash in figure 30.

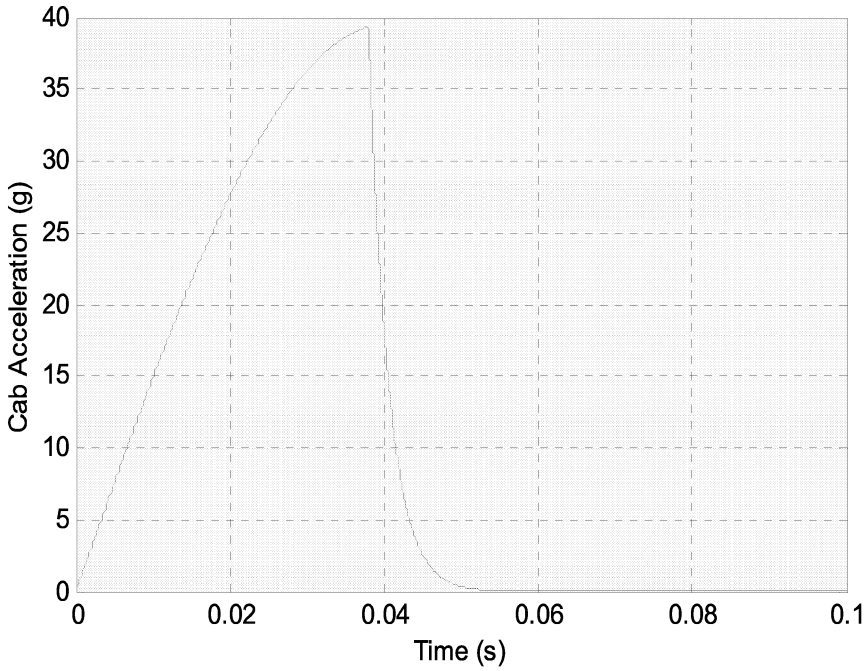

Figure 30. Cab acceleration pulse (22.5mph crash)

The peak acceleration is approximately 40g and the crash duration is about 50ms agreeing very closely with sled test and simulation results provided by Horii (1987) and Berg (1997). The generated crash pulses can be used in MADYMO occupant injury models to evaluate the effectiveness of various cab interior occupant protection measures

4.4. Occupant injury model

An occupant injury model was created using the MADYMO software package to accept the crash pulse input generated by the vehicle crash model and generate occupant injury measures as output. The model consists of a conventional style heavy truck cab, with a Hybrid III 50th percentile male dummy (version 6.4) developed by TNO MADYMO. The truck geometry and structural properties are based on data published in a previous research report (SAE CRP 13, 1997).

4.4.1. Truck Interior

The truck interior components except the steering wheel are represented as in the model as 2-dimensional planes. As shown in figure 31 the cab is made up of a floor, firewall, toe pan, knee bolster, instrument panel, steering wheel and seat. The shell of the cab is rigidly coupled. The seat is attached to the floor of the cab via a spring-damper system. This system allows the seat approximately six inches of travel. At the beginning of the simulation the seat is placed at its midrange position. The shoulder belt is attached to a fixed point on the lower left part of the cab and feeds through a D-ring and attaches to a buckle that is attached to the seat. Both ends of the lap belt are attached directly to the seat. The model includes an airbag (shown deployed in figure 32) positioned on the top face of the steering wheel, and set to trigger 30ms after simulation begins (in simulation runs where the airbag is used).

4.4.2. Inputs and outputs

The model is a six degree of freedom system that, for frontal crashes, accepts accelerations in the X direction. However, it can accept accelerations in the other directions as well for simulating other crash modes. The model outputs include, head center of gravity accelerations (from which head injury criteria or HIC are derived), chest deflection, lumbar spine, neck, femur and tibia forces and torques.

Simulations were run for the cases of occupant not wearing a safety belt, wearing a safety belt but no air bag and wearing safety belt and with activated airbag. The results were used in estimating the potential benefits of safety belts and airbags in reducing occupant injury as described in the next section.

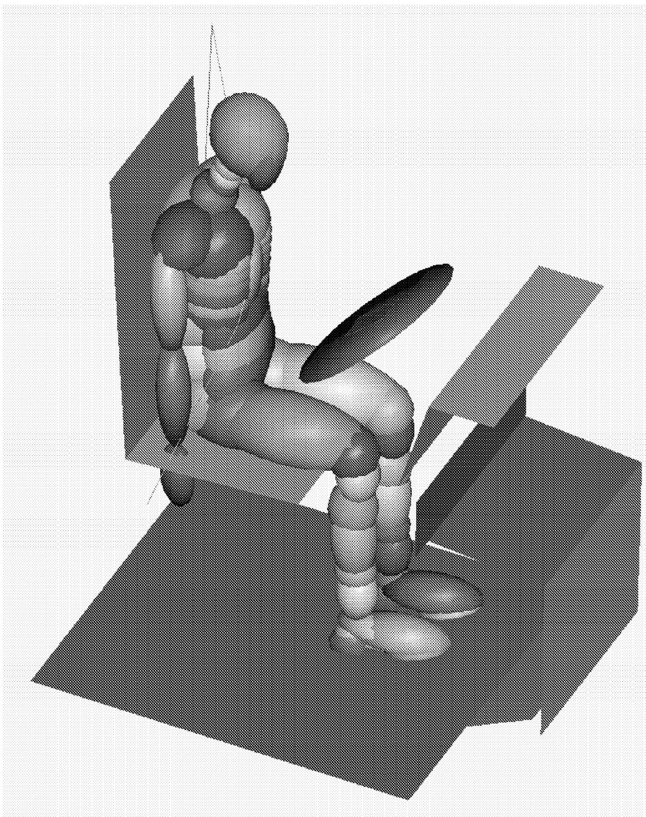

Figure 31. MADYMO Occupant injury model

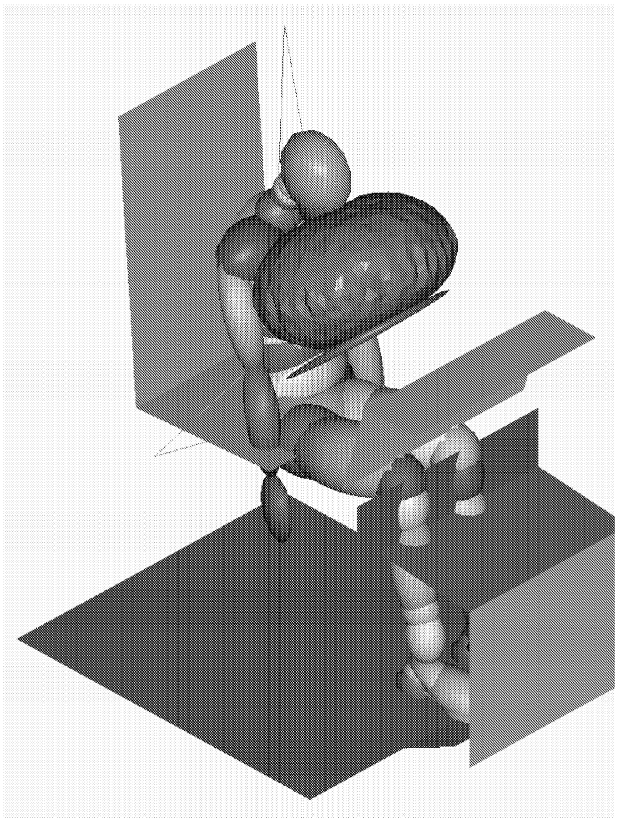

Figure 32. MADYMO Occupant injury model (showing deployed airbag)

4.5. Restraint System Benefit Estimation

We earlier computed the benefits of using safety belts using crash data. This computation can be repeated using simulation and the results compared.

4.5.1. Safety belts

Table 21 shows the HIC and probability of greater than AIS 4 level injury (roughly corresponds to K or A injury) as crash ∇V increases for the cases of occupant wearing and not wearing a safety belt. Table 22 shows the corresponding numbers using chest acceleration as the injury measure. The tables demonstrate the earlier observations from the crash data that using safety belts significantly decreases the probability of a K or A injury.

No.	∇V	HIC belt	Prob. AIS+4	HIC no belt	Prob. AIS+4

			(belt)		(no belt)
1.	7.5	0 (no steering contact)	0.0%	0 (no steering contact)	0.0 %
2.	15	105	1%	209	1.4%
3.	22.5	167	1.3%	406	3.3%
4.	30	249	1.8%	804	14.2%
5.	37.5	657	8.7%	1521	73.2%
6.	45	908	19.8%	1910	95.1%
7.	52.5	1206	45.0%	2234	97.8%
8.0	60	1617	80.2%	2481	99.3%

Table 21. HIC and AIS $\geq$ 4 Injury probability for frontal crash

No.	∇V	Chest acceleration (g) belt	Prob. AIS+4 (belt)	Chest acceleration (g) no belt	Prob. AIS+4 (no belt)
1.	7.5	12.4	0.6	17.9	1.0
2.	15	25.3	1.8	41.2	6.2
3.	22.5	38.3	5.0	67.1	34.7
4.	30	51.3	13.0	94.7	82.8
5.	37.5	64.5	30.1	123.8	98.0
6.	45	77.6	55.1	154.1	99.8
7.	52.5	90.9	78.1	185.4	99.9
8.0	60	104.1	91.1	217.7	99.9

Table 22. Chest acceleration and AIS $\geq$ 4 Injury probability for frontal crash

We can now estimate the potential benefits of using safety belts in improving injury outcomes. The previously discussed ∇V distributions can be further resolved to show the number of fatalities in which the injured occupant was not wearing a safety belt.

Table 23 shows the number of crashes (TIFA-GES 1995-1999) analyzed by the object into which the truck crashed when the occupant was not wearing a seat belt. Table 24 shows the location and direction of the crash for truck-truck crashes. From these tables the relevant data are the number of crashes into fixed objects (here we shall assume that these crashes were primarily frontal since the data does not provide information on angle of impact), and the number of frontal truck-truck crashes, since it is these frontal crashes that result in the greatest severity of occupant injuries.

From Table 24 we see that 23.90% ($\frac{23813+2083+3880}{124651}*100$) of truck-truck crashes are frontal crashes. From Table 23 we can compute that a total of 2613 ($0.2390*10939$) such crashes (with unbelted occupants) occurred in 1995-1999. Table 23 also shows that 12987 crashes into fixed roadside objects took place in the same period. Thus we can compute

$$\text{Annual unbelted frontal crashes} = \frac{2613+12987}{5} = 3120 \qquad (12)$$

Belt use=no								
	Fatal	A injury	B injury	C injury	Unk. sev	No injury	unknown	Total
Truck	253	521	1,229	855	31	8,037	13	10,939
Car/pickup	161	434	1,799	3,113	126	83,914	1,282	90,828
Fixed object	398	472	962	896	60	10,199	0	12,987
Non-fixed	25	14	248	48	1	10,191	240	10,768
Train	79	98	171	291	0	40	0	679
Roll	825	2,096	3,068	2,836	153	3,161	7	12,146
Fire	46	109	0	13	0	200	0	368
Immersion	14	0	0	135	0	90	0	240
Other	32	41	40	72	0	4,496	95	4,776
Unknown	2	919	1,768	1,352	105	3,346	9	7,500
Total	1,835	4,705	9,285	9,613	475	123,673	1,645	151,231
Truck	2.31	4.76	11.24	7.82	0.28	73.47	0.12	100.00
car/pickup	0.18	0.48	1.98	3.43	0.14	92.39	1.41	100.00
Fixed object	3.06	3.63	7.41	6.90	0.46	78.53	0.00	100.00
Non-fixed	0.23	0.13	2.31	0.45	0.01	94.65	2.23	100.00
Train	11.64	14.49	25.14	42.92	0.00	5.82	0.00	100.00

Rollover	6.79	17.26	25.26	23.35	1.26	26.03	0.05	100.00
Fire	12.48	29.66	0.00	3.55	0.00	54.30	0.00	100.00
Immersion	5.84	0.00	0.00	56.53	0.00	37.63	0.00	100.00
Other	0.67	0.86	0.84	1.51	0.00	94.13	1.98	100.00
Unknown	0.03	12.26	23.57	18.02	1.40	44.60	0.12	100.00
Total	1.21	3.11	6.14	6.36	0.31	81.78	1.09	100.00

Table 23. Crash vehicle type data for unbelted occupant (TIFA-GES 1995-1999)

Other vehicle is a truck								
Frequency	Fatal	A injury	B injury	C injury	Unk. severity	No injury	unknown	Total
Front same dir	154	785	893	1,294	2	20,483	202	23,813
Front opposite	135	38	472	31	0	1,271	136	2,083
Front perpendicular.	40	83	318	317	0	3,122	0	3,880
Rear same	17	360	734	1,634	19	20,042	465	23,271
Sideswipe same	19	243	452	678	0	29,186	1,991	32,569
L sideswipe opp.	17	100	1,487	275	0	12,065	1,400	15,343
R sideswipe opp.	9	6	36	197	0	1,385	0	1,633
L perpendicular	13	31	84	365	0	4,392	6	4,892
R perpendicular	8	17	175	29	0	1,629	6	1,863
Other	38	236	479	919	0	11,759	910	14,341
Unknown	8	3	29	10	0	912	0	962
Total	458	1,902	5,159	5,750	21	106,246	5,115	124,651
Front same dir	0.65	3.30	3.75	5.43	0.01	86.02	0.85	100.00
Front opposite	6.48	1.82	22.67	1.50	0.00	60.99	6.55	100.00
Front perpendicular.	1.03	2.13	8.18	8.18	0.00	80.48	0.00	100.00
Rear same	0.07	1.55	3.16	7.02	0.08	86.12	2.00	100.00
Sideswipe same	0.06	0.75	1.39	2.08	0.00	89.61	6.11	100.00
L sideswipe opp.	0.11	0.65	9.69	1.79	0.00	78.63	9.12	100.00
R sideswipe opp.	0.55	0.39	2.19	12.06	0.00	84.81	0.00	100.00
L perpendicular	0.27	0.63	1.73	7.47	0.00	89.79	0.12	100.00
R perpendicular	0.43	0.92	9.38	1.55	0.00	87.40	0.32	100.00
Other	0.26	1.65	3.34	6.41	0.00	82.00	6.35	100.00
Unknown	0.83	0.31	3.03	1.04	0.00	94.79	0.00	100.00
Total	0.37	1.53	4.14	4.61	0.02	85.23	4.10	100.00

Table 24. Crash type data for truck-truck crashes (TIFA-GES 1995-1999)

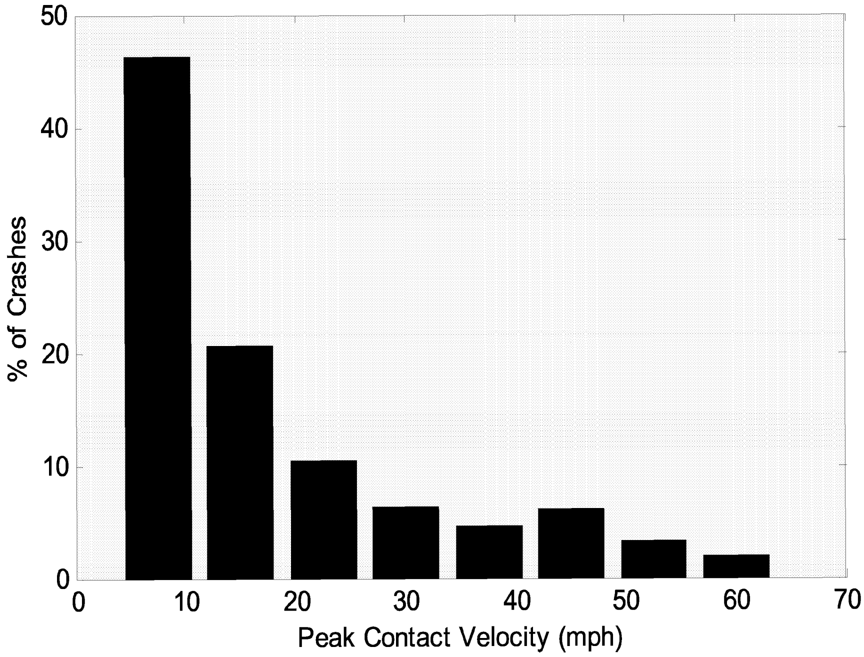

Figure 33. Peak Contact Velocity (∇V) distribution – Unbelted Crashes

Figure 33 shows the distribution of ∇V for crashes with unbelted occupants. From this we can compute the number of crashes that take place at each average ∇V and using table 13 the corresponding estimated K or A injury rates for belted and unbelted occupants. This is shown in table 25.

No.	∇V (mph)	Crashes Without Safety Belt	K or A Without Belt	K or A With Belt
1.	7.5	1447	0	0
2.	15	646	9	6
3.	22.5	325	11	4
4.	30	199	28	4
5.	37.5	146	107	13
6.	45	194	184	38

7.	52.5	103	101	46
8.0	60	61	60	49
Total			500	160

Table 25. Safety belt benefit estimation for frontal crashes (HIC)

We can repeat the calculations for the chest acceleration injury measure.

No.	∇V (mph)	Crashes Without Safety Belt (annual)	K or A Without Belt	K or A With Belt
1.	7.5	1447	14	9
2.	15	646	40	12
3.	22.5	325	113	16
4.	30	199	165	26
5.	37.5	146	143	44
6.	45	194	193	107
7.	52.5	103	103	80
8.0	60	61	61	56
Total			832	350

Table 26. Safety belt benefit estimation for frontal crashes (chest acceleration)

The chest acceleration based injury estimates are higher than those based on HIC. However both measures suggest roughly a factor of three improvement in injury outcomes when the occupant uses a safety belt. The rates shown in table 14 (from crash data) indicate an improvement factor of approximately 4. It should be noted that the actual number of K and A injuries estimated here is likely to be somewhat high since as mentioned earlier all the frontal crashes are assumed to be head on while in reality some of the crashes are likely to be less severe due to oblique impact. However, the estimates from both the simulations and crash data are in reasonable quantitative agreement (especially keeping in mind the earlier discussed point that self reporting of seat belt usage will tend to bias estimates of effectiveness upwards) and certainly in qualitative agreement that usage of safety belts is an important occupant protection measure.

4.5.2. Airbags

The analysis presented above demonstrated the efficacy of safety belts both by simulation and by using crash data. However due to the relatively recent introduction of airbags in heavy (and due to their long usage life) the proportion of trucks with airbags undergoing crashes is too small to accurately estimate the protective effect of airbags. Thus the only means of evaluating the injury reduction benefit of airbags is through the use of simulations. The analysis presented above and the agreement between the simulation and data provides confidence in the collision and injury models and the resulting estimated benefits.

As done before we can calculate the likelihood of injury for given ∇V for occupants with and without airbags (we assume in both cases that safety belts are used since the benefits of using safety belts are so clear that all mandates and compliance efforts must emphasize their use) as shown in tables 27 and 28.

No.	∇V	HIC belt	Prob. AIS+4 (belt)	HIC (belt + airbag)	Prob. AIS+4 (belt+ airbag)
1.	7.5	0 (no steering contact)	0.0%	0 (no steering contact)	0.0%
2.	15	105	1%	90	0.9%
3.	22.5	167	1.3%	121	1.0%
4.	30	249	1.8%	222	1.6%
5.	37.5	657	8.7%	492	4.6%

6.	45	908	19.8%	802	14.2%
7.	52.5	1206	45.0%	1027	29.0%
8.0	60	1617	80.2%	1193	44.3%

Table 27. HIC and AIS ≥ 4 Injury probability for frontal crash

No.	∇V	Chest acceleration (g) belt	Prob. AIS+4 (belt)	Chest acceleration (g) (belt+airbag)	Prob. AIS+4 (belt + airbag)
1.	7.5	12.4	0.6%	9.3	0.5%
2.	15	25.3	1.8%	15.6	0.8%
3.	22.5	38.3	5.0%	27.5	2.1%
4.	30	51.3	13.0%	36.6	4.4%
5.	37.5	64.5	30.1%	46.4	9.2%
6.	45	77.6	55.1%	53.4	15.0%
7.	52.5	90.9	78.1%	75.4	50.7%
8.0	60	104.1	91.1%	88.3	74.3%

Table 28. Chest acceleration and AIS ≥ 4 Injury probability for frontal crash

Thus the use of airbags in combination with safety belts provides clear benefits in reducing injury measures, extending protection beyond the use of safety belts alone. An interesting point to note is that the simulations show a generally greater benefit in reducing the chest acceleration measure, while the HIC measure shows smaller improvements. This observation is also borne out by experimental studies (discussed in the literature review) using crash dummies that indicate that the seat belt reduces HIC by making head contact with the steering column less severe, while the primary benefit of the airbag is to provide a further layer of protection by reducing the contact force between the steering wheel and the driver's torso.

We can now translate these injury rate reductions into estimated reduction in injury numbers by combing information on the total number of frontal truck crashes with belted drivers but no airbag (table 29) and the earlier presented data on crash ∇V distributions.

Repeating the calculations we performed in equation 12, for unbelted occupant crashes, but this time for the case of belted occupants (using tables 24 and 29) we arrive at

$$\text{Annual belted frontal crashes} = \frac{0.239 * 112780 + 100619}{5} = 25514 \quad (13)$$

Belt use=yes								
	Fatal	A injury	B injury	C injury	Unk. sev	No injury	Unknown	Total
Truck	168	1,100	3,877	4,924	24	101,544	1,143	112,780
Car/pickup	90	2,651	6,522	21,985	452	942,732	3,538	977,970
Fixed object	157	1,027	3,793	5,252	33	90,049	308	100,619
Non-fixed	16	155	495	729	2	79,265	325	80,987
Train	13	51	54	55	0	941	0	1,115
Roll	249	6,428	8,088	6,651	18	21,584	238	43,255
Fire	39	204	41	20	0	2,327	0	2,631
Immersion	6	0	0	2	0	273	0	281
Other	4	350	875	1,038	15	52,384	576	55,242
Unknown	0	1,786	4,348	4,589	385	21,247	26	32,381
Total	742	13,753	28,092	45,245	928	1,312,347	6,154	1,407,261

Table 29. Crash vehicle type data for unbelted occupant (TIFA-GES 1995-1999)

The calculations of injury reductions with use of both belts and airbags are shown in tables 30 and 31, for the HIC and chest acceleration measures.

No.	∇V (mph)	Crashes With Safety Belt (annual)	K or A (Belt)	K or A (Belt+Airbag)
1.	7.5	11829	0	0
2.	15	5281	53	48
3.	22.5	2657	35	27
4.	30	1627	29	26

5.	37.5	1194	104	55
6.	45	1586	314	225
7.	52.5	842	379	244
8.0	60	499	400	221
Total		25515	1313	846

Table 30. Airbag benefit estimation for frontal crashes (HIC)

No.	∇V (mph)	Crashes With Safety Belt (annual)	K or A (Belt)	K or A (Belt+Airbag)
1.	7.5	11829	71	59
2.	15	5281	95	42
3.	22.5	2657	133	56
4.	30	1627	211	72
5.	37.5	1194	359	110
6.	45	1586	874	238
7.	52.5	842	658	427
8.0	60	499	454	371
Total		25515	2855	1374

Table 31. Airbag benefit estimation for frontal crashes (chest acceleration)

As discussed in the section on safety belt injury modeling the actual numbers in the above tables are somewhat high due to the assumption that all the frontal collisions are fully straight on, while in reality a significant proportion are likely to be oblique and thus less severe in terms of ∇V. However, the calculation provides an estimate of the overall reduction in injury rates which we can then compare to actual US crash statistics to calculate a numerical benefit in improved injury outcomes.

The HIC based calculation provides an estimate of approximately 35% while the chest acceleration based calculation estimates over 50% reduction in injury rates. Since the exact distribution of chest versus head (or combination of both) injuries is not readily available in crash data we shall conservatively use the lower estimate of 35% improvement in injury outcomes.

Frequency	Fatal	A injury	B injury	C injury	Unk. sev	No injury	Unk.	Total
Front same dir.	80	887	1,650	4,176	13	180,520	316	187,641
Front opposite	63	962	1,393	3,282	26	22,513	19	28,258
Front perpendicular	16	417	1,060	2,085	125	42,582	22	46,307
Rear same dir	4	423	1,090	5,585	31	172,293	764	180,190
Sideswipe same	15	488	919	3,489	15	344,717	2,083	351,725
L sideswipe opposite	11	310	1,477	907	0	59,976	677	63,357
R sdswp opposite	2	35	148	845	45	17,440	0	18,515
L perpendicular	8	181	520	1,463	2	38,845	281	41,301
R perpendicular	2	107	333	737	0	26,398	253	27,831
Other	21	631	1,010	2,169	5	87,789	599	92,224
Unknown	2	64	168	42	0	3,752	10	4,038
Total	224	4,506	9,769	24,780	262	996,825	5,023	1,041,388

Table 32. Truck – Truck crash injury data by crash type (TIFA-GES 1995-1999)

Table 32 shows that 159 fatalities and 2266 A injuries (summing the first 3 rows of table 32) occurred in frontal truck-truck crashes over the 1995-1999 period and Table 29 shows that 157 fatalities and 1027 A injuries occurred in crashes into fixed objects. Thus we get a total estimated annual K or A injury number in frontal crashes of:

$$\text{Annual US K or A injuries (frontal crash)} = \frac{2425+1184}{5} = 722 \qquad (14)$$

and the corresponding estimate of injury reductions is:

$$\text{Annual reduction in K or A injuries (frontal crash)} = 0.35 * 722 = 253 \qquad (15)$$

4.6. Summary

This section presented an analysis of truck cab interior occupant protection systems. However, the maintenance of sufficient survival space in the cab is a prerequisite to the effective functioning of any such protection system. The analysis of cab structural integrity in the case of rollover was presented in an earlier chapter. Cab crashworthiness and structural integrity is also of importance in the crash type that causes the second highest number of fatalities, that of a frontal crash into a fixed object or another heavy vehicle. The energy dissipation requirements (crush space and strength relationship) of the cab structure were analyzed for this crash mode. It was shown that a truck front crush strength of about 8e5N (roughly 180000lbs) will provide protection from intrusion in crashes with a ∇V of 22.5mph or less. The ∇V distribution data for truck frontal crashes (compiled by UMTRI from truck crash accident reports) shows that this increase of approximately 2.5 times in current truck frontal strength (based on a survey of the literature and European Community ECE-R29 crashworthiness standards) will prevent intrusion in almost $2/3^{rds}$ of frontal truck crashes. It should be noted that along with strengthening the cab front structure, the cab rear must also be reinforced (ECE-R29 standards call for the cab rear to be able to withstand a force equal to 20% of the maximum payload carried by the truck) since cab damage also occurs due to secondary impacts from the trailer and the payload.

The effectiveness of safety belts as a protective measure has been long acknowledged in the truck occupant safety literature. This study completed a quantitative analysis of the benefits to be gained by achieving full compliance in the use of safety belts by truck drivers. TIFA and GES data were analyzed to estimate the rates of usage of safety belts and the relative frequency and severity of injuries with and without belt usage. Combining these computations with the distribution of truck travel speeds on the US road system it was calculated that full usage of safety belts offers a potential annual reduction of 345 fatalities (out of a total annual fatality count of 633 or over 55%) and an annual reduction in A injuries of 674 (out of 3907 or 17%). As noted in the analysis the reduction in A injury rate is less dramatic than that in fatalities because the safety belt essentially reduces the severity of injuries (thus converting many would-be fatal injuries into A injuries, thus increasing the baseline injury rate). However, the calculation clearly shows that efforts to increase safety belt use offer large potential payoffs in improvements in occupant injury outcomes.

The benefits of safety belt usage can be computed from crash data because of the significant availability of belts in the current US truck population. However airbags have not penetrated the truck market to the same extent and hence their effectiveness was computed through the use of crash and occupant injury simulations.

A truck crash model was developed using crash test and simulation data available in the literature. Based on this model crash pulses were developed for the previously compiled range of truck crash ∇V values. An occupant injury model was developed using the MADYMO software package. The crash pulses were used as inputs to the occupant injury model to predict occupant injury outcomes for crashes without safety belts, with 3 point safety belt only and with 3 point safety belt and airbag.

The results of the computations with and without safety belts was compared with the previously obtained results (from crash data) and the reduction in fatality rates showed good agreement thus providing confidence in the validity of the simulation. The improvement in effectiveness (over safety belt alone) of using both safety belts and airbags was computed again using the truck crash ∇V distribution. The calculations show an estimated reduction of 253 in K and A injuries with the use of both airbags and safety belts, which corresponds to approximately a further 6% (253 out of 4540 annual K and A injuries) reduction over the use of safety belts alone.

The calculations presented in this section show that a layered use of countermeasures – (i) improving cab structural integrity (ii) use of safety belts and (iii) airbags – has the potential to significantly improve injury outcomes, reducing by more than one half the number of fatalities and by almost one-quarter the number of severe non-fatal injuries.

5. Conclusion

This document presented the results of a study undertaken to explore the feasibility of improving the crash injury outcomes of large truck (GVWR > 10,000lbs) occupants through the use of suitable crash protection systems. Four main tasks were performed as part of this study: (i) A detailed survey of the state of the art in truck occupant protection systems was compiled, (ii) Truck crash data from the US road system was compiled and analyzed (iii) Truck crash simulation models and occupant injury models were developed (iv) The potential benefits of various occupant protection countermeasures were quantitatively analyzed.

This chapter presents a summary of the results and recommendations of the study.

5.1. Discussion of Results

The first step in proposing and evaluating the benefits of truck occupant protection systems is to determine the type and frequency of crash modes, the crash events that cause injuries, and the severity and frequency of those injuries. For this purpose truck crash data from primarily two databases were analyzed. These databases are (i) Trucks Involved in Fatal Accidents (TIFA) compiled and maintained at UMTRI and (ii) The General Estimates System (GES) compiled by the National Center for Statistics and Analysis (NASS) of NHTSA.

The analysis shows that while the majority of truck crashes involve collisions with smaller vehicles, the most serious injuries to truck occupants occur in collisions with either other trucks, or fixed roadside objects. Single vehicle and truck-truck crashes account for 75% of truck driver fatalities and A injuries. About 744 fatalities and 29,000 non-fatal injuries are suffered by truck occupants annually. 633 fatalities were suffered by truck drivers and 410 of these or almost 2/3^{rds} of occurred in single vehicle crashes. Another 94 occurred in two vehicle truck-truck crashes.

The most important factors associated with severe injuries in truck crashes are ejection, rollover and fire. Overall, ejection increases the probability of driver fatality by almost 286 times, the risk of a fatal or A injury by 68.8 times, and the risk of a fatal, A or B injury by 28.5 times. Fire increases the risk of a truck driver fatality by 67.2 times, compared with the risk where no fire occurred and rollover increases the risk of a driver fatality by almost 26 times, compared with no rollover. Rollover, ejection and fire can occur singly or in various combinations. While ejection is the most dangerous factor to the truck occupant, it occurs only in 9.2% of severe (causing K and A injuries) crashes, while rollover occurs in 63.1% of severe crashes and fire occurs in 5.6% of severe crashes. Based on the data analysis and the literature the most important injury mechanisms were identified as, ejection from the cab (involved in approximately 1/3rd of all severe crashes), entrapment or crush, occupant striking interior surfaces (steering wheel, windshield, roof etc.) and post crash fire.

The above analysis suggests a clear direction for the design and implementation of occupant protection countermeasures.

The first priority is to retain the occupant in the cab (prevent ejection). Crash data shows that use of safety belts nearly eliminates the risk of ejection. Among unrestrained drivers in severe crashes (those causing K or A injuries) almost 23% were ejected, while in restrained drivers only 0.1% suffered complete ejection and 3.3% were partially ejected (though anecdotal evidence from crash examinations suggests that in many of these cases the truck cab was so severely damaged as to cause ejection of the entire seat and restraint system. Also European crashworthiness studies are exploring the use of airbags to further enhance ejection prevention. Thus use of restraint systems is an extremely effective countermeasure against ejection.

Once ejection is prevented the next step is to ensure the existence of sufficient survival space in the cab. Detailed statistics on truck occupants who are severely or fatally injured by entrapment and crush in the cab are not readily available. However several previous studies indicate that entrapment occurred in approximately 22% - 36% of severe truck crashes involve significant truck structure crush or intrusion and that the probability of a serious (fatal or A injury) injury is increased by approximately a factor of 5 (33% in crashes with vs. 7% in crashes without) in such crashes. Cab crush occurs in two principal crash types (i) Rollover and (ii) Frontal crash into fixed objects or other heavy vehicles. The vehicle motions and kinetic energies for each of these cases were analyzed separately and structural requirements for improved crashworthiness were computed.

The truck rollover crashworthiness was analyzed using previously developed TruckSim® simulation models of a tractor trailer combination. The vehicle motion variables of interest (truck cab roll rate and center of gravity vertical velocity) in the case of rollover were computed by driving the truck simulation at various forward velocities (ranging from 45mph to 75mph) and applying steering inputs to drive the truck along a curved path to create lateral accelerations that cause the truck to rollover. The resulting truck kinetic energies (sum of vertical and roll energies) at ground impact must then be dissipated through crush of the cab structure. It was estimated that a truck cab roof capable of supporting a force of 18000N (39000lbs) (Previous studies on truck cab structure strength measurement and reinforcement indicate that achieving this strength is feasible) can prevent intrusion even in the most severe roll crash (from the simulation results). Based on US crash data and analysis of rollover crashes found in the literature it was estimated that an annual reduction in fatalities of over 80 (out of about 345 rollover related fatalities – corresponding to approximately a 23% reduction).

Cab crashworthiness and structural integrity is also of importance in the crash type that causes the second highest number of fatalities, that of a frontal crash into a fixed object or another heavy vehicle. The energy dissipation requirements (crush space and strength relationship) of the cab structure were analyzed for. It was shown that a truck front crush strength of about 8e5N (roughly 180000lbs) will provide protection from intrusion in crashes with a ∇V of 22.5mph or less. Using the ∇V distribution data for truck frontal crashes (compiled by UMTRI from truck crash accident reports) it can be shown that this increase of approximately 2.5 times in current truck frontal strength (based on a survey of the literature and European Community ECE-R29 crashworthiness standards) will prevent intrusion in almost 2/3^{rds} of frontal truck crashes. It should be noted that along with strengthening the cab front structure, the cab rear must also be reinforced (ECE-R29 standards call for the cab rear to be able to withstand a force equal to 20% of the maximum payload carried by the truck) since cab damage also occurs due to secondary impacts from the trailer and the payload.

The first two issues considered here (ejection and cab crashworthiness) are concerned with maintaining integrity of the truck external structure. Once this has been achieved the occupant's kinetic energy must still be dissipated (along with the deceleration of the vehicle itself) in a controlled manner. There is considerable agreement in the occupant protection literature that safety belts are extremely effective in achieving this. Here we present a quantitative analysis of the benefits to be gained by attaining full compliance in the use of safety belts by truck drivers. TIFA and GES data were analyzed to estimate the rates of usage of safety belts and the relative frequency and severity of injuries with and without belt usage. Combining these computations with the distribution of truck travel speeds on the US road system (compiled by UMTRI in a previous study) it was calculated that full usage of safety belts offers a potential annual reduction of 345 fatalities (out of a total annual fatality count of 633 or over 55% reduction) and an annual reduction in A injuries of 674 (out of 3907 or 17%). As noted in the analysis the reduction in the A injury rate is less dramatic than that in fatalities because the safety belt essentially reduces the severity of injuries (thus converting many would-be fatal injuries into A injuries, thus increasing the baseline A injury rate). Thus, the calculation clearly shows that efforts to increase safety belt use offer large potential payoffs in improvements in occupant injury outcomes.

The final layer of occupant protection is the prevention of injuries through interior impacts. Of course safety belts themselves prevent or reduce the severity of interior impacts (while also providing other benefits such as preventing ejection, retention of the occupant in the designed survival space etc.). However, an important source of occupant interior impact injury is the steering wheel, which causes head and chest injuries, and these impact injuries can be further reduced by using airbags in conjunction with safety belts.

The benefits of safety belt usage can be computed from crash data because of the significant availability of belts in the current US truck population. However airbags have not penetrated the truck market to the same extent and hence their effectiveness must be evaluated through the use of crash and occupant injury simulations.

A truck crash model was developed using crash test and simulation data available in the literature. Based on this model crash pulses were developed for the previously compiled range of truck crash ∇V values. An occupant injury model was developed using the MADYMO software package. The crash pulses were used as inputs to the occupant injury model to predict occupant injury outcomes for crashes without safety belts, with 3 point safety belt only and with 3 point safety belt and airbag.

The results of the computations with and without safety belts was compared with the previously obtained results (from crash data) and the reduction in fatality rates showed good agreement thus providing confidence in the validity of the simulation. The improvement in effectiveness (over safety belt alone) of using both safety belts and airbags was computed again using the truck crash ∇V distribution. The calculations show an estimated reduction of 253 in K and A injuries with the use of both airbags and safety belts, which corresponds to approximately a further 6% (253 out of 4540 annual K and A injuries) reduction over the use of safety belts alone.

5.2. Summary

This document presented the results of a study to examine the feasibility and benefits of improving truck occupant injury outcomes through the use of appropriate protection systems. The study indicates that the layered use of a series of countermeasures that successively provide protection by (i) Retaining the occupant in the truck cab, (ii) Ensuring sufficient survival space through cab structural crashworthiness improvement and (iii) Reducing the crash forces and acceleration experienced by the occupant through the use of restraint systems offers potential reductions of up to $2/3^{rd}$ in severe (K or A) injuries suffered by truck occupants.

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