HEAVY TRUCK AGGRESSIVITY REDUCTION: STATISTICS, ANALYSIS, AND COUNTERMEASURES

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16. Abstract

This document presents a study that (i) analyzed the causes of heavy truck aggressivity, (ii) evaluated their relative importance in terms of frequence and injury outcomes to occupants of light vehicles in crashes with trucks, (iii) derived detailed models relating collision factors to injury outcomes, and (iv) proposed and evaluated truck structural countermeasures for mitigating light vehicle injury in crashes with trucks.

Two-vehicle truck/light vehicle crashes account for 65% of all truck crash involvements and 60% of fatal truck involvements. Crashes involving the truck's front have the highest probability of a fatal or incapacitating injury. Collisions with the truck's side account for about the same number of deaths or injuryies but have a lower probability of injury. Injury counts and probabilities are also present for other crash configurations.

Collision and injury models were derived to predict occupant injury outcomes from fundamental collision variables: mass, velocity, direction of travel, structural properties of colliding vehicles, and available restraint systems. Simulation results showed that reducing peak vehicle deceleration resulted in lower injury risk for most injury measures.

Prevention of frontal underride, energy-absorbing truck structures, and deflection were evaluated as countermeasures. Reduction of up to 27%-37% in fatality counts are possible by preventing underride. Crushable structures of 2.6m would produce almost 25% reduction in fatalities. Deflection could reduce fatality from 46% to 72%, though these results only account for the impact with a truck, not any secondary collisions with other vehicles or roadside structures.

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Trucks, crash data, aggressivity, countermeasures	Unlimited

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SI* (MODERN METRIC) CONVERSION FACTORS

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		
mL	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)

EXECUTIVE SUMMARY

It is well understood, both through evaluations of roadway crash data and through crash analysis, that in collisions between trucks and light vehicles (typically passenger automobiles), the lighter vehicle suffers greater damage than in collisions with another like vehicle. This increased damage severity is termed agressivity and results primarily from the mismatch or incompatibility (in mass, structural strength and vehicle geometry) between the colliding vehicles.

This document presents a study that (i) Analyzed the causes of heavy truck aggressivity, (ii) Evaluated their relative importance (in terms of frequency of occurrence and injury outcomes of the occupants of the light vehicle) in the US traffic system, (iii) Derived detailed models relating collision factors (vehicle properties, speed, deceleration levels) to injury outcomes and (iv) Proposed and evaluated the benefits of truck structural countermeasures for mitigating collision severity (as suffered by the light vehicle).

Study Tasks:

1) Literature Review: A survey of the literature in the area of truck aggressivity (and countermeasures) was completed with particular reference to the European experience, both to present the current state of the art in the analysis and mitigation of heavy truck aggressivity and to understand the effectiveness of mandated countermeasures in improving accident outcomes. The results of these studies showed that significant reductions in heavy truck aggressivity were possible through the use of structural countermeasures.

2) Data Analysis: A detailed analysis of crash data was performed, to obtain an up to date description of the heavy truck aggressivity problem in the context of the US road system. A detailed classification of truck-light vehicle collisions was derived, including the collision type, the types of vehicles involved in the collision, the velocity distribution of the colliding vehicles and the injury outcomes (severity and frequency) of the light vehicle occupants. The data analysis served to guide the rest of the study, in terms of modeling the various collision types, the performance of the vehicle structure and restraint systems and the resulting injuries to the vehicle occupants. Further, the analysis allowed the focusing of the study on those types of crashes (and their corresponding countermeasures) that cause the greatest damage and offer the greatest potential for severity reduction. The data analysis also serves as the baseline for estimating the benefits of proposed countermeasures.

The types of crashes addressed here—two-vehicle truck/light vehicle crashes—account for 65% of all truck crash involvements and 60% of fatal truck involvements. There are about 250,000 such crashes annually. While almost 75% of the crash involvements produce no injury in the light vehicle, there are almost 3,000 fatalities, 10,000 A-injuries, and 16,000 B-injuries to occupants of light vehicles in these crashes.

Crashes involving the truck's front have both the highest probability of a K or A-injury and account for most fatal and serious injuries. Fifty-seven percent of fatal truck/light vehicle involvements and 59% of light vehicle fatalities occur in crashes involving the front of the truck. A fatal or A-injury in the light vehicle occurs in 24.7% of front opposite direction crashes and in 12.5% of front perpendicular crashes. These are the highest injury rates of the crash types studied.

Collisions with the side of a truck account for about the same number of K or A-injuries as the front, but injury probability is somewhat lower and depends critically on the mode of the collision. Same direction sideswipes have the lowest K/A injury probability at 2.1% of all crash types examined, while opposite direction sideswipes have a much higher probability (10.7%). Crashes in this mode can be similar to frontal crashes if the light vehicle underrides the truck and engages the axles. When the angle of impact is perpendicular, injury probabilities are lower when the front of a light vehicle strikes the side of a truck than if the front of a truck strikes the side of a light vehicle, 8.1% to 12.5%. In side perpendicular collisions, energy absorbing structures on the light vehicle have a chance to work if the light vehicle strikes the cab or axles, but when the truck is the striking vehicle, there is much less structure on the light vehicle to protect its occupants.

Same direction crashes involving the front or rear of the truck point out the crucial role of geometrical mismatch between trucks and light vehicles. In these crashes, light vehicle K/A injury probabilities are higher if the light vehicle strikes the rear of the truck than if the truck is the striking vehicle, 5.4% to 3.9% respectively. Comparison with light vehicle/light vehicle collisions indicates that underride probably contributes to higher injury probabilities in collisions with the rear of a truck. When a light vehicle is struck in the rear, injury probabilities are higher by about a factor of three if the striking vehicle is a truck. But when a light vehicle strikes the rear of another vehicle, the probability of a K or A-injury is about six times greater if the vehicle strikes a truck than if it strikes another light vehicle.

In sum, truck fronts are a primary target for any effort to reduce truck aggressivity in collisions with light vehicles. Collisions involving truck front ends account for 60% of light vehicle fatalities as well as the highest probability of a fatality in the light vehicle. Reducing frontal aggressivity would provide the greatest gains, though likely also the greatest challenge.

3) Collision and Injury Models: Collision and injury models were then derived that predicted occupant injury outcomes from fundamental collision variables (mass, velocity, direction of travel, structural properties of colliding vehicles, the available occupant restraint systems etc.). The models were constructed in a two stage manner. The first was a physical representation of the collision process, with the inputs being the collision variables and the outputs, the estimates of the accleration levels, total velocity change, and crush levels experienced by the vehicle occupants. These outputs were then used by the second stage injury models to predict the occupant injury outcomes. The models were derived based both on crash data and simulation studies.

Results of the collision and injury modeling effort are consistent in showing that the likelihood of fully restrained (three-point belts plus airbags) drivers sustaining severe or fatal injuries to the head, face, neck, thorax, abdomen, or spine in frontal crashes up to 50-mph Δv is surprisingly low, and generally less than 5%. However, results from analysis of the NASS data show that the likelihood increases significantly for drivers who are not using the available belt restraints, and are therefore restrained only by the airbag. Most importantly relative to the issue of truck countermeasures is the finding that, for both restraint conditions, reducing the Δv by 10 mph reduces the likelihood of severe and fatal injuries by 60 to 70%.

The fundamental physical process that takes place during the collision is that the colliding vehicles are brought to a stop through the dissipation of their kinetic energies. This dissipation takes place through the crush of the vehicle structures and depending on the vehicle structural stiffnesses and crush space available can take place over different time intervals. A short time interval results in high deceleration levels resulting in correspondingly high forces and occupant injury severity, while longer intervals allow a more gradual deceleration of the colliding vehicles. Thus increasing the crush space by making the truck structure less stiff offers the possibility of significantly improving injury outcomes. NCHRP report 350 (Menges *et. al.*, 1997) uses 20g as a threshold level of peak deceleration for a collision to be considered survivable, and this threshold is of significance in the analysis that performed in this study.

The simulation results show that reducing the peak vehicle deceleration resulted in reductions in injury risk for most major injury measures. The most important observation from the simulation results is the fact that for a particular deceleration level the simulations show almost constant injury likelihoods or injury criterion levels irrespective of the crash Δv (this is especially true for the 20g level). While more detailed simulations (and experimental studies) for a wider range of crash conditions would be desirable (which are beyond the scope of this study), this result seems to indicate that injury outcomes are much more dependent on the deceleration level than on the vehicle Δv.

These results therefore indicate that any countermeasure that reduces the Δv and/or deceleration levels of a passenger vehicle involved in a frontal collision with a heavy truck will significantly reduce the probability of severe and fatal injuries to passenger-car occupants. While the primary analysis has been performed for frontal crashes of passenger vehicles, similar results were found for side impacts, and similar conclusions apply.

4) Countermeasures: Based on the preceding analysis of crash data and the collision and injury models various aggressivity countermeasures were proposed and evaluated, with the focus being on the collision type responsible for the greatest proportion of damage and injuries (collisions with the front of the truck). Three principal countermeasures were analysed – prevention of front underride, crash attenuation using energy absorbing truck structures and reduction of the total energy dissipated in the crash process by deflection of the impacting light vehicle.

The first step in improving the crash outcome of the light vehicle and its occupant is to prevent underride through the use of suitably designed guards. Analysis of the crash data along with use of the collision and injury models shows that a reduction of 27%-37% in fatality counts are possible when underride is prevented depending upon the availability and use of occupant restraint systems (3-point seat belts, seat belt load limiters and pretensioners, and air bags) in the passenger automobile.

Once underride is prevented occupant injury outcomes can be improved through the apppropriate management of the collision energy, to reduce occupant Δv and deceleration levels. Two methods of such energy dissipation or management in truck/light vehicle collisions or strikes are (i) Attenuation of the collision forces or acceleration levels by increasing the time over which the collision Δv takes place, through the use of softer (less stiff) or energy absorbing truck structures and (ii) Deflection of the striking automobile such that not all the energy of the car is dissipated in the collision.

Attenuation of the collision through the use of energy absorbing structures requires the availability of crush space in the truck structure. Assuming truck structural designs that can accommodate 2.6m (approximately 8') crush results in a saving of almost 25% of the lives lost and this saving can be raised to nearly 50% with about 4.0m (approximately 12', though such a large crush space may be feasible only with quite significant changes in truck design) of available crush.

Truck structures that deflect the impacting vehicle result in great reductions in the severity of the collision, due to the fact that not all the energy of the impacting vehicle is dissipated during the crash. Thus the occupants of the lighter vehicle undergo a lower Δv and therefore experience improved injury outcomes. This countermeasure seems to offer the greatest potential benefits with possible fatality reductions ranging from 46%-72% depending again on the use of the restraint systems in the light vehicle. However, these estimates do not take into account what happens to the automobile after it exits the collision and the possible results of secondary collisions with the traffic stream or other roadside structures.

Recommendations:

Based on the results of the analysis conducted in this study, some specific measures to reduce heavy truck aggressivity can be suggested.

- Front underride prevention: It is clear (both from crash data, observation of crash damage, and from collision and injury modeling analysis) that when the impacting light vehicle underrides the front of the truck, the injuries to its occupants are likely to be most severe, with a high probability of a resultant fatality. Further the largest number of fatal crashes results from collisions with the front of the truck. Thus the first line of defense in reducing heavy truck crash severity, must be the prevention of front underride. This may be accomplished either through changes in the truck front structure to ensure that these structural members are low enough engage the crash absorbing mechanism of the light vehicle or through the use of properly designed underride guards added to the existing truck structure. The analysis in this study showed that 27%-37% reductions in fatalities is possible through prevention of front underride.

- <u>Crash attenuating truck front structure:</u> Once underride is prevented crash outcomes can be improved through proper management and dissipation of the collision energy. The literature reviewed in this study presented several examples of innovative truck structures that can perform such an energy dissipating function. These include, front underride guards that are designed to deflect and absorb collision energy, truck fronts built of collapsible structural members, an add-on (mounted on existing truck structure) crash attenuator, etc. All of the above work with existing truck designs and by providing upto 8' of crush space, offer potential reductions in fatalities of approximately 25%. With more radical changes in truck design (changes in position of the truck engine, cab and associated structural members) it may be possible to achieve crush distances of as great as 12' and in this case the as much as a 50% reduction in fatalities can be achieved.

- <u>Deflecting front structure:</u> Another method of managing the collision energy is to deflect the impacting vehicle, through the use of an appropriately designed truck structure. This produces large reductions in the collision energy absorbed by the light vehicle and thus greatly improves (46%-72% fatality reduction) the resulting injury outcomes. The greatest drawback of this countermeasure is the possibility of secondary collisions, and further analysis of this aspect must be undertaken before adoption.

- <u>Layered application of countermeasures:</u> All the countermeasures suggested here were analysed independently, however they can be used simultaneously to in a layered system of aggressivity reduction (and of course in conjunction with other non-structural countermeasures) to provide greater improvements in crash outcomes.

In conclusion, this study provides a detailed analysis of the truck aggressivity problem in the context of the US road system, presents techniques and models for analysing collisions and injury outcomes, and shows that significant improvements in injury outcomes are possible throught the use of appropriately designed truck structural countermeasures.

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We are also grateful to Ken Campbell, Christopher Winkler and Robert Ervin (all of the University of Michigan Transportation Institute), for providing us with the weight of their considerable experience in the field of truck safety, through discussions on the current state of the art and guidance on research directions. We would also like to thank Joel MacWilliams of the UMTRI BioSciences department for his insights into crash injury mechanisms and models.

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CHAPTER 1: INTRODUCTION

In collisions between vehicles of different types, the negative consequences are disproportionately distributed with the occupants of the smaller, lighter, and less sturdily built vehicle suffering the most damage. This asymmetry is especially pronounced when a light vehicle (Gross Vehicle Weight Rating [GVWR] > 10,000lbs) collides with a heavy truck (GVWR > 26,000lbs). In such accidents the smaller and less stiff vehicle bears the brunt of the process of dissipating the energy of the collision, greatly increasing the potential of occupant injury or death.

The principal cause of this accident severity (aggressivity) is the mismatch or incompatibility between the vehicles involved in the collision. This mismatch may be in vehicle mass, vehicle structure stiffness, and energy dissipation characteristics or in vehicle geometry. Given the nature of the colliding vehicles, very little can be done about the mass incompatibility. However, the other sources of vehicle mismatch are more amenable to mitigation through the use of appropriate countermeasures.

This document presents a study that: (i) analyzed the causes of heavy truck aggressivity, (ii) evaluated their relative importance (in terms of frequency of occurrence and injury outcomes of the occupants of the light vehicle) in the U.S. traffic system, (iii) derived detailed models relating collision factors (vehicle properties, speed, deceleration levels) to injury outcomes, and (iv) proposed and evaluated the benefits of heavy truck structural countermeasures for mitigating collision severity (as suffered by the light vehicle).

A survey of the literature in the area of heavy truck aggressivity (and countermeasures) was completed with particular reference to the European experience. This was done to present the current state of the art in the analysis and mitigation of heavy truck aggressivity and to understand the effectiveness of mandated countermeasures in improving accident outcomes.

A detailed analysis of crash data was performed to obtain an up to date description of the heavy truck aggressivity problem in the context of the U.S. road system. A thorough classification of heavy truck-light vehicle collisions was derived including the collision type, the types of vehicles involved in the collision, the velocity distribution of the colliding vehicles, and the injury outcomes (severity and frequency) of the light vehicle occupants. The data analysis served to guide the aggressivity analysis in terms of modeling various collision types, the performance of vehicle structure and restraint systems, and the resulting injuries to the vehicle occupants. The analysis focused the study on those types of crashes (and their corresponding countermeasures) that cause the greatest damage and offer the greatest potential for severity reduction. The data analysis also served as the baseline for estimating the benefits of proposed countermeasures.

Collision and injury models were derived that predicted occupant injury outcomes from fundamental collision variables (mass, velocity, direction of travel, structural properties of colliding vehicles, the available occupant restraint systems, etc.). The models were constructed in a two-stage manner. The first was a physical representation of the collision process with the inputs being the collision variables and the outputs being the estimates of the acceleration levels, total velocity change, and crush levels experienced by the vehicle occupants. These outputs were then used by the second stage injury models to predict the occupant injury outcomes. The models were derived based both on crash data and simulation studies.

Based on the preceding analysis of crash data and the collision and injury models, various aggressivity countermeasures were proposed and evaluated; the focus was on the collision type responsible for the greatest proportion of damage and injuries (collisions with the front of the heavy truck). Three principal countermeasures were analyzed: prevention of front underride, crash attenuation using energy absorbing heavy truck structures, and reduction of the total energy dissipated in the crash process by deflection of the impacting light vehicle. It was shown that each of these measures individually could produce reductions in fatality counts ranging from 25 to 75% (depending on the crash type and assumptions regarding use of occupant restraint systems). Greater improvements may be possible using the countermeasures in a simultaneous or layered system.

In summary, this study presents a detailed analysis of the heavy truck aggressivity problem in the context of the U.S. road system. Furthermore, this study shows that significant improvements in the injury outcomes of the light vehicle occupants are possible using appropriately designed and implemented heavy truck structural countermeasures.

CHAPTER 2: LITERATURE REVIEW

A significant body of research exists in the general area of reducing vehicle aggressivity in collisions. A major portion of this research documents the conditions prevailing in, and the experience gained from, the European driving environment, though some studies pertaining to the U.S. have also been performed. Further, considerable experience in the reduction of light truck and passenger automobile aggressivity has been accumulated by automobile manufacturers. An excellent survey of light truck aggressivity research can be found in Gabler and Hollowell (1998).

Research efforts in the area of vehicle aggressivity can be classified into 3 broad categories: (i) studies that define the problem and analyze its impact through crash data analysis, (ii) studies that model the physical causes of aggressivity, and (iii) studies that propose and evaluate countermeasures. Presented here is a summary of the subject matter, methodology, and conclusions of the studies in each of these categories.

Vallet (1988), Riley (1988, 1985), Bloch (1987), and Danner and Langweider (1987) were all studies that analyzed European crash data. Knight and Simmons (2000) found that, in the United Kingdom, heavy vehicles are responsible for 17% of fatal road accidents while constituting only 7% of the total vehicle population. In the U.S., Clarke et al., (1987) defined the problem and the significant issues for study. Data from Texas were analyzed to show that a light vehicle-heavy truck frontal collision is 7.5 times more likely to result in a fatality than a light vehicle-light vehicle frontal collision. All the above studies agree that heavy trucks exhibit significant aggressivity (in the sense of accounting for accident fatality, injury, and property damage costs disproportionately higher than their representation in the vehicle population). Mango and Garthe (1998) presented a method of obtaining detailed injury information by linking the National Highway Transportation Safety Administration's (NHTSA) Fatal Accident Reporting System (FARS) with the Vital Statistics Multiple Cause of Death (MCOD) database.

Braver et al. (1998) used a combination of accident scene photographs and police reports to estimate the incidence of underride/override in fatal crashes between light vehicles and heavy trucks in the state of Indiana during 1993. The study estimated that 63% of fatal accidents involved underride and concluded that underride was significantly underreported in the FARS database. The study further concluded that preventing underride would have substantially reduced the likelihood of death or serious injury in about 21% of the underride crashes.

Blower and Campbell (2000) also examined the incidence of underride in fatal rear-end crashes (a light vehicle collides with the rear of a heavy truck) as part of the University of Michigan Transportation Research Institute's (UMTRI) Trucks Involved in Fatal Accidents (TIFA) survey. Their study is in substantial agreement with Braver et al. (1998), finding that approximately 60% of all fatal rear-end crashes during 1997 involved underride. They also found that rear end guards (when present on the heavy truck and generally conforming to a standard established in 1952) did not appear to provide consistent improvement in safety.

The principal causes of heavy truck aggressivity are mass, structural, and geometric mismatches. Smith (1998) examined the change in velocity (Δv) of the vehicles involved in a collision, taking into consideration the fact that the collision may be offset (i.e., the line of action of the collision forces does not pass through the line drawn through the center of masses of the two vehicles). If the mass of the light vehicle and the heavy truck are denoted as m_c and m_t and their respective changes in velocity are denoted as Δv_c and Δv_t, then (Smith, 1998):

$$\Delta v_c = \sqrt{\frac{2Em_t}{m_c\left(m_c\delta_c + m_t\delta_t\right)}} \qquad (1)$$

where δ is the radius of gyration of the vehicle and E is the total energy dissipated in the collision. Assuming a perfectly inelastic collision (the coefficient of restitution in automobile collisions drops below 0.1 and decreases steadily as the closing velocity increases above 10 mph; Smith and Noga, 1982), Δv_c can be expressed in terms of the relative velocity before collision v_r as follows:

$$\Delta v_c = \frac{m_t}{m_c + m_t} v_r \qquad (2)$$

It is clear from the above equations that as the mismatch between the mass of the heavy truck and light vehicle increases, a larger proportion of the dissipated energy is borne by the lighter vehicle. At a mass ratio of 10:1 Δv_c, this is over 90% of the relative velocity at impact.

Jawad (1997) studied the effect of structural mismatch on aggressivity and showed that as the ratio of the colliding vehicle stiffness deviated from unity, the peak accelerations of the softer vehicle increased significantly, leading to a higher potential of occupant injury. However, this aggressivity cannot be quantified (as is commonly done in biomechanical injury models) in terms of Δv since this value depends on the mass of contacting vehicles and not on their stiffness. The aggressivity results primarily from the fact that the softer vehicle undergoes a greater proportion of the crush deformation needed for energy dissipation, leaving a smaller survival zone for its occupants.

The energy dissipated in a collision is absorbed by the deformation of the contacting vehicle structures. A number of studies have modeled this energy absorption process with models ranging from complex finite element simulations (Lugt et al., 1988; Bedewi et al., 1996), to simple lumped mass–spring systems (Jawad, 1997). More recently, Omar et al. (1998) presented an empirical, neural network model that had the capability to characterize the nonlinear nature of the vehicle deformation process.

The third cause of heavy truck aggressivity, geometric mismatch, is caused by the heavy truck structural members overriding and not (or only partially engaging) the energy dissipating structure of the smaller vehicle. This results in a smaller effective crush length and a correspondingly smaller survival zone for the occupant of the light vehicle. This may be considered the most important cause of aggressivity in that it accounts for a significant proportion of the damage inflicted by heavy trucks. This cause of aggressivity is also the most amenable to improvement through the use of appropriately designed countermeasures.

Knight and Simmons (2000) analyzed accident statistics from the United Kingdom to evaluate the effectiveness of various countermeasures, both structural and system, that used a combination of technologies to warn against, actively prevent, or intervene during collisions. They estimated that heavy truck structural modifications alone could produce a 25% decrease in light vehicle-heavy truck collision fatalities.

A number of studies have been performed in Europe that evaluated the use of underrun guards. Adalian et al. (1998) presented experimental results from crash tests using heavy trucks fitted with a front underrun protection device. De-coo and Nieboer (1994) presented a study performed for the Dutch Ministry of Transport. Prototypes of energy absorbing structures using crumple tube techniques were developed, and experimental results and mathematical simulations were used to show the feasibility of reducing the injury potential of light vehicle-heavy truck collisions by modifying heavy truck front geometry and stiffness.

Thomas (1991) focused on front underride and the effect of front underride guards on reducing fatalities and injuries. They studied a sample of 95 accident cases in Great Britain from 1988. All of the accidents involved light vehicles colliding with the front of "heavy goods vehicles," essentially medium and heavy trucks. All of the collisions involved fatal injuries. In these crashes, the authors estimated that the light vehicle was overridden by the heavy truck in 88% of the collisions. The authors also estimated that if the trucks had been equipped with rigid underride guards, about 29% of the fatalities would have been avoided.

Robinson and Riley (1994) presented road accident data from national sources in Great Britain and a more detailed analysis of police reports of fatal accidents. National statistics for two-vehicle accidents in 1991 showed 77 accidents and 92 fatalities in accidents where the light vehicle impacted with the front of a heavy truck. A more detailed analysis was conducted from a four-year sample (1988-1991) of 619 fatal light vehicle-heavy truck front end collisions. For each of the 756 light vehicle occupant fatalities, a judgment was made as to whether fitting a front underrun protection system to the heavy truck might have reduced the severity of the injury to non-fatal. It was estimated that rigid front underrun protection systems would have prevented 165 of the 756 light vehicle occupant fatalities (22%) in the four-year sample of fatal accidents, and energy absorbing systems could have saved 193 lives (26%).

In a study involving the fronts and sides of heavy trucks, Rechnitzer (1993) estimated that 35% of the fatalities that occurred in 25 fatal accidents could have been saved by energy-absorbing front underride guards. This estimate is somewhat higher than the benefits of front underride guards studied in other countries. One possible explanation is that the fronts of Australian heavy trucks are more aggressive than elsewhere because of "bullbars" that are common in that country. In the four crashes involving the sides of heavy trucks, he estimated that one of the three fatalities could have been prevented by side underride guards. This was a case of a bicyclist striking the side of a heavy truck. The paper did not specifically provide an estimate of the incidence of underride in frontal or side collisions.

With respect to light vehicle impacts on the side of heavy trucks, Robinson (1994) estimated that strengthening existing side guards could prevent 7% of fatalities that occur in side impacts, fitting the strengthened side guards to heavy trucks currently exempt could save another 3%, and fitting strong guards behind the rear wheels could save an additional 9%. The strengthened guards would be functional primarily in "glancing" impacts, such as opposite direction sideswipes in which the underriding light vehicle, absent side guards, engages the heavy truck's axles. The greatest benefit would be realized for guards that could be effective in perpendicular impacts with closing speeds up to 40 miles per hour and glancing impacts up to 60 mph.

Rear underride guards were required on some heavy trucks at the time of the research. Rear guards were found to be effective in protecting belted occupants up to a closing speed of 30 mph. Above that speed, the guard either broke off or was bent back if struck at one edge. No estimate was given of the proportion of fatalities prevented by the existing guard. Robinson suggested that a strengthened guard, one that would survive impacts up to closing speeds of 50 mph, could save 30% of fatalities in collisions with the rear of heavy trucks.

Once underride is prevented, the reducing collision severity becomes a matter of managing the energy of the vehicles involved in a collision, such that the occupants do not undergo extreme g-forces or be crushed due to collapse of the vehicle structure. Due to the overwhelmingly large energy levels (especially since most of the energy is absorbed by the lighter vehicle) that must be dissipated in all but the lowest speed collisions, relatively few studies exist that demonstrate the feasibility of such energy management through the use of crash cushioning or collapsible structures. However, a pair of related publications, Carney et al. (1998) and Carney et al. (1996), describe a simulation and crash test based development of a crash attenuating system that serves to define some bounding requirements on the physical structure and capabilities of such crash energy management systems. The authors set as their design criteria the achievement of the occupant protection guidelines set forth in NCHRP 350 (Menges et al., 1997). The authors conclude from analysis of the collision physics that an attenuation distance of approximately 3.7m would be needed to satisfy these guidelines under a direct 100km/h relative velocity collision. A crash attenuator constructed of high-molecular weight/high-density polyethylene that could be mounted to the heavy truck structure was then designed and demonstrated to perform adequately both using lumped and finite element model simulations and crash tests.

Rakheja et al. (1999) studied the feasibility of using an energy absorbing underride guard to reduce the severity of light vehicle-heavy truck collisions. The design parameters of the underride guard were optimized (with respect to a performance criterion that balanced intrusion versus peak accelerations of the impacting light vehicle) using both simulation and hardware in the loop tests. The authors presented a number of possible designs that result in peak accelerations (320m/s^2, 235m/s^2, 156 m/s^2) corresponding to intrusion distances (0.307m, 0.398m, 0.605m respectively) for a head-on collision at a relative velocity of 50km/h. It should be noted however, that the 50km/h relative velocity for which the design was optimized is a relatively low closing speed; furthermore, the authors do not present analysis of how these numbers translate into changes in the expected occupant injury levels.

Mendis et al. (1996) described the design of a heavy truck front end that swivels on impact, thus deflecting the impacting vehicle and reducing the proportion of the closing velocity that has to be dissipated in the collision. This paper was based on an earlier experimental study performed by Prasad et al. (1995) at NHTSA's Vehicle Research and Test Center (VRTC). Various designs were tried out for the swiveling front end structure, including locating a hinge at the center of the heavy truck frontal structure. It was found that the hinge point itself was a source of increased aggressivity. The design that was finally recommended for use was based on a honeycomb structure that was designed to crush in such a manner as to produce a swiveling effect of the front end and thus deflect the impacting vehicle. The study showed that the swiveling heavy truck front end appeared to be effective in reducing severity of offset light vehicle-heavy truck collisions.

Though not directly relevant to this study, it should be mentioned here that, apart from the structural countermeasures discussed above, some more advanced countermeasure systems that integrate a number of different technologies have also been proposed and studied. These systems include sensors that warn of impending collisions, intervene to prevent collisions, and also deploy protective structures such as external airbags to mitigate crash severity. Knight and Simmons (2000) discussed the use of such technology and estimated a further decrease in fatalities (over the use of only structural countermeasures) of approximately 25%. Another interesting approach to severity reduction is a system described by Shinar et al. (1997) that senses an emergency braking situation from rate of release of the accelerator pedal and applies maximum braking to either prevent, or reduce, the closing velocity of collisions.

CHAPTER 3: CRASH DATA ANALYSIS

Introduction

This analysis presents a description of two-vehicle, heavy truck/light vehicle crash involvements. The purpose of the analysis is to determine the distribution of impacts around the perimeter of heavy trucks involved in traffic crashes, along with the severity of those crashes measured in terms of fatalities and injuries in the light vehicle. The heavy truck crash involvements considered are limited to two-vehicle crashes in which one of the vehicles is a heavy truck and the other a light vehicle. The truck category includes all medium and heavy trucks with a GVWR over 10,000lbs. The light vehicles in the crash are all passenger vehicles or light trucks with a GVWR less than 10,000lbs. Table 1 shows the distribution of light vehicle types in these crashes.

Data

Three files contributed data for this analysis: the FARS file, the TIFA file, and the General Estimates System (GES) file. Three years of data, 1996 through 1998, were used from each file. The TIFA file (and associated FARS records) supplied all information about fatal crash involvements, including counts of fatalities and non-fatal injuries in those crashes. The TIFA file was used to identify all medium and heavy trucks involved in fatal crashes during the three-year period. The person records (to count injuries and fatalities) of all occupants of the light vehicles were obtained from FARS. The GES file was used to extend the analysis to non-fatal truck-involved crashes. It is also used to estimate the number of injuries to light vehicle occupants involved in non-fatal crashes. The strategy of combining TIFA and GES data was pursued because the GES file is known to underestimate truck involvements in fatal crashes. By using data from TIFA and FARS, correct estimates can be made for fatalities and injuries in fatal involvements. GES supplies the best estimates available for non-fatal crash involvements. The combination of TIFA and GES data in this manner supplies the most accurate distribution of crash severity for truck involvements available.

Truck Impact Variable

To partition the data by impact point around the truck, a new variable, "truck impact," is defined. Table 1 shows the categories and definitions for each category. The truck impact variable indicates the contact point on the truck and the relative motion of the two vehicles prior to contact. This variable is developed primarily from the accident type variable found in both the GES and TIFA files. In many crash types, the accident type variable can be used directly to assign the impact point on the truck. However, the contact point on the truck is ambiguous in some crash types. For those cases, codes for the contact points were consulted to develop an algorithm to assign the appropriate truck impact code. Crash types that did not fit into any of the first nine levels were coded as "other crash type" (98). All unknown crash types were coded as 99. The routines used to generate the truck impact variable in the TIFA and GES data are provided in Appendix A.

Table 1. Definitions for truck impact variable

Impact point on the truck and relative motion	Definition
Front, same direction (1):	All crash types where the front of the truck was the contact point, and both vehicles were traveling in the same direction. For most of the front same direction impacts, impact to the other vehicle was observed to be rear. Some impacts were at an angle.
Front, opposite direction (2):	All crash types where the truck had a front impact with another vehicle traveling in the opposite direction. All head-on collisions.
Front, perpendicular (3):	All crash types where the truck had a front impact with another vehicle traveling perpendicular to the truck. The impact to the other vehicle was on either the left or the right side.
Rear, same direction (10):	All crash types where the truck was struck in the rear. Usually the contact point on the other vehicle was front, but there were some with angle impacts and rear impacts (backing).
Sideswipe, same direction (20):	All crash types where both the truck and other vehicle, traveling in the same direction, have side impacts.
Left sideswipe, opposite direction (30):	All crash types where the truck had a left side impact with another vehicle traveling in the opposite direction. Most of these crashes occurred when one of the vehicles tried to make a turn into the opposite path from the other vehicle at an intersection or turned across the path of the other vehicle from the opposite direction.
Right sideswipe, opposite direction (31):	All crash types where the truck had a right side impact with another vehicle traveling in the opposite direction.
Left side, perpendicular (40):	All crash types where the truck was struck on the left side by another vehicle traveling perpendicularly to the direction of the truck.

Impact point on the truck and relative motion	Definition
Right side, perpendicular (41):	All crash types where the truck was struck on the right side by another vehicle traveling perpendicularly to the direction of the truck.
Other crash type (98):	These are crash types that did not be fit into any of the above nine levels.
Unknown crash type (99)	Crash type could not be determined.

The levels are used to describe the impact point on the truck and the relative motions of the two vehicles. The code levels were chosen to provide the most information available about the point of contact on the truck and the motions of the two vehicles. (Code levels can be aggregated if that is appropriate.) In examining the data, it proved impossible to distinguish right side from left side same-direction sideswipes. Most would have fallen into a "same direction sideswipe, side unknown" category. Accordingly, all same direction sideswipes were combined. Numbers in parentheses are the respective codes.

The system of categorizing crash types by the relative motion of the vehicles and truck contact point was designed to provide the most reliable information about the crash configurations. The variable for contact point in the TIFA and GES files does not provide directly information about the vectors of motion of the vehicles, although the contact point variable was used as a consistency check to make sure that specific crash configurations were understood correctly.

While it would be highly desirable to have information on impact points more fine-grained than "front," "rear," and "side," the data files used in the analysis could not provide more useful detail. The impact location variables in FARS and GES provide only coarse information on impact locations. The initial impact point variable in FARS employs a clock face metaphor to assign impact points. The FARS coding manual shows a diagram in which the entire front of the truck would be coded "12 o'clock," the left side of the cab would be coded "11 o'clock," and the right side of the cab would be coded "1 o'clock." Moreover, although the GES variable that codes "initial point of contact" includes codes for "front left corner," "front right corner," etc., those codes are used in fewer than 1% of cases. Effectively, only front, side, and rear are available for nonfatal crashes. Figure 1 provides the distribution of initial impact points around the perimeter of the truck as coded in FARS. The figure is modeled after the instructions in the FARS coding manual.

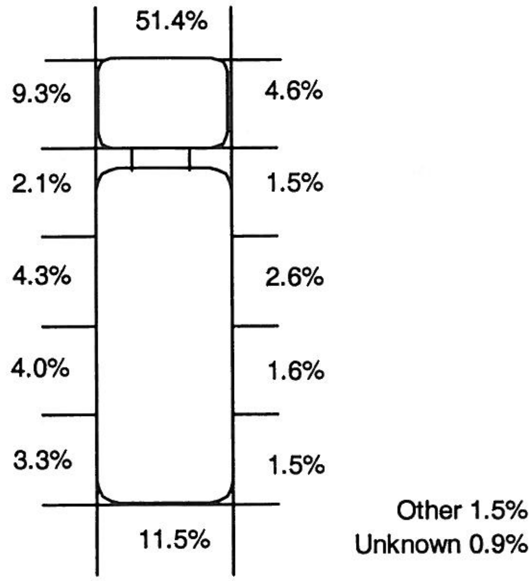


Figure 1. Initial contact point on a truck in two-vehicle, truck/light vehicle fatal involvements (TIFA 1994-1998)

State police accident reports use different systems to capture impact locations. Because of the different systems states use to coded contact point, it is at least plausible to argue that in a frontal crash, codes of 11 o'clock or 1 o'clock for contact point reflect offset or corner impacts on the truck. It is left up to the reader whether to adopt that interpretation.

In the remainder of this analysis, crash types will be categorized by the system described above. This is not the preferred situation; however, the accident data simply does not provide information on contact points at the desired level of detail. On the other hand, this system has the advantage of incorporating vector of motion.

Results

Table 2 shows the overall distribution of truck involvements by the number of vehicles involved and the type of crash. The table provides some context for the set of involvements that are the focus of the analysis. This analysis focuses on truck crash involvements with one light vehicle. These involvements account for about two-thirds of all truck traffic crash involvements. Single vehicle involvements account for 20% of all truck crash involvements while crashes involving more than two vehicles account for 7.5%. Many of these latter crashes involve a light vehicle striking the truck, but it is not possible using existing crash data to associate contact points with particular vehicles when there is more than one other vehicle involved in a crash.

Table 2. All truck fatal and non-fatal involvements by number of vehicles and other vehicle/non-motorist type (TIFA, GES 1996-1998)

Vehicles Involved		Fatal involvements		Non-fatal involvements		Total	
		N	%	N	%	N	%
Single vehicle	Ped/bike/non-motorist	1,076	7.0	3,167	0.3	4,243	0.4
	Other single vehicle	1,513	9.9	220,735	19.3	222,248	19.1
Two vehicles	Truck/light vehicle	9,089	59.3	744,298	65.0	753,387	64.9
	Truck/truck	741	4.8	93,208	8.1	93,949	8.1
More than two vehicles		2,916	19.0	84,032	7.3	86,948	7.5
Total		15,335	100.0	1,145,441	100.0	1,160,776	100.0

Table 3 shows the distribution of crash severity for two-vehicle, truck/light vehicle crash involvements. The measure of severity is assigned by the most severe injury to any person involved in the crash, whether a truck occupant or an occupant of the other vehicle. In almost 74% of the involvements, no one was injured. Minor injuries (C-injuries, defined as "not visible, complaint of pain") account for only 10.7%. At least one fatality occurred in 1.2% of the involvements, and it could not be determined whether an injury occurred in 3.1% of the involvements. The unknown injury category is entirely accounted for by the GES data.

Table 3. Crash severity two-vehicle truck/light vehicle crash involvements (TIFA, GES 1996-1998)

Crash severity	N	%
Property damage only	556,189	73.8
Possible Injury (C)	80,938	10.7
Non-incapacitating Injury (B)	48,850	6.5
Incapacitating Injury (A)	32,208	4.3
Injured, severity unknown (U)	2,621	0.3
Fatal Injury (K)	9,089	1.2
unknown	23,493	3.1
Total	753,387	100.0

Table 4 shows the distribution of body style of light vehicles involved in two-vehicle fatal and non-fatal crashes. Most of the light vehicles are passenger cars or light trucks; motorcycles and mopeds make up a small percentage (0.3%). The primary difference between the body types of the light vehicles in fatal and non-fatal crashes is the greater proportion of unknown body types in the non-fatal (GES) data. For example, almost 26% of the light vehicles in non-fatal crashes are coded "unknown auto type" compared with only 1.1% of the light vehicles in the data covering fatal involvements. The GES data are coded entirely from police reports. The GES coders have no access to any other information. In contrast, FARS analysts can draw on information from a number of sources, which likely explains their ability to provide more detail about body type.

Table 4. Distribution of body style of light vehicles in two-vehicle truck/light vehicle crashes (TIFA, GES 1996-1998)

Body style	Fatal involvements		Non-fatal		Total	
	N	%	N	%	N	%
Convertible	40	0.4	1,670	0.2	1,710	0.2
2dr Sedan/HT/Coupe	1,618	17.8	95,179	12.8	96,797	12.8
3dr/2dr Hatchback	371	4.1	11,628	1.6	11,999	1.6
4dr Sedan/HT	3,172	34.9	204,808	27.6	207,980	27.6
5dr/4dr Hatchback	132	1.5	6,009	0.8	6,141	0.8
Station Wagon	232	2.6	15,797	2.1	16,029	2.1
Hatchback/unknown doors	19	0.2	1,199	0.2	1,218	0.2
Other auto	29	0.3	18	0.0	47	0.0
Unknown auto type	104	1.1	193,704	25.9	193,808	25.7
Auto Pickup	16	0.2	405	0.1	421	0.1
Limousine	0	0.0	290	0.0	290	0.0
Compact Utility	421	4.6	16,492	2.2	16,913	2.2
Large Utility	44	0.5	1,676	0.2	1,720	0.2
Utility Station Wagon	38	0.4	5,271	0.7	5,309	0.7
Utility Unknown Body	4	0.0	10,117	1.4	10,121	1.3
Minivan	452	5.0	17,015	2.3	17,467	2.3
Large Van	223	2.5	5,011	0.7	5,234	0.7
Step Van-Light	17	0.2	0	0.0	17	0.0
Step-in/Walk-in van	0	0.0	43	0.0	43	0.0
Other Van type	5	0.1	0	0.0	5	0.0
Unknown Van type	6	0.1	29,197	3.9	29,203	3.9
Compact Pickup	823	9.1	33,320	4.5	34,143	4.5
Standard Pickup	1,026	11.3	33,142	4.5	34,168	4.5
Pickup w/Camper	13	0.1	10	0.0	23	0.0
Convertible Pickup	2	0.0	0	0.0	2	0.0
Unknown Pickup	14	0.2	46,116	6.2	46,130	6.1

Body style	Fatal involvements		Non-fatal		Total	
	N	%	N	%	N	%
Unknown other Light truck	0	0.0	14,244	1.9	14,244	1.9
Motorcycle	261	2.9	1,836	0.3	2,097	0.3
Moped	7	0.1	104	0.0	111	0.0
Total	9,089	100.0	744,298	100.0	753,387	100.0

Table 5 shows the distribution of impacts around the truck for both fatal and non-fatal involvements. Involvements are assigned by the most severe injury in the crash. In most cases, the most severe injury occurred in the light vehicle.

Table 5. Distribution of impact around the truck by crash severity two-vehicle, truck/light vehicle involvements (TIFA, GES 1996-1998)

Impact Type	Fatal involvements		Non-fatal involvements		Total	
	N	%	N	%	N	%
Front, same direction	693	7.6	130,051	17.5	130,744	17.4
Front, opposite direction	2,995	33.0	18,596	2.5	21,591	2.9
Front, perpendicular	1,446	15.9	33,011	4.4	34,457	4.6
Rear, same direction	1,124	12.4	127,627	17.1	128,751	17.1
Sideswipe, same direction	432	4.8	257,181	34.6	257,613	34.2
Left sideswipe, opp. dir.	563	6.2	34,546	4.6	35,109	4.7
Right sideswipe, opp. dir.	205	2.3	12,937	1.7	13,142	1.7
Left side, perpendicular	538	5.9	31,327	4.2	31,865	4.2
Right side, perpendicular	359	3.9	20,816	2.8	21,175	2.8
Other crash type	545	6.0	75,375	10.1	75,920	10.1
Unknown crash type	189	2.1	2,832	0.4	3,021	0.4
Total	9,089	100.0	744,298	100.0	753,387	100.0

The distribution of impact point for fatal involvements differs significantly from the distribution for non-fatal involvements. Over 56% of the fatal involvements include contact with the front of the truck. Almost one-third occur in front, opposite direction (head-on) collisions. An additional 15.9% occur in collisions in which the front of the truck strikes a light vehicle moving perpendicularly to the motion of the truck ("broadside" collision). Collisions in which the truck is struck in the rear by the light vehicle account for 12.4% of two-vehicle, truck/light vehicle fatal involvements. Same direction sideswipes account for less than 5% of these fatal involvements. In contrast, over one-third of non-fatal, two-vehicle truck/light vehicle crash involvements are same direction sideswipes, and another third are same direction collisions, crashes in which either the truck was struck in the rear (17.1%) or the truck struck the light vehicle in the rear (17.4%).

Fatal involvements favor collision types in which the vehicles were moving in opposite directions; in non-fatal involvements, the vehicles are predominantly (68.6%) moving in the same direction. Similarly, the front of the truck is involved in 56.5% of fatal two-vehicle truck/light vehicle involvements, while contact is with the side of the truck in almost half (47.6%) of non-fatal involvements.

In Table 6, the measure of injury severity is the most severe injury in the light vehicle. This is probably the most appropriate measure in considering truck aggressivity since the purpose of addressing aggressivity is reduce fatalities and injuries in light vehicles involved in traffic crashes with heavy trucks. Once again, the cell counts in Table 7 are of heavy trucks involved in traffic crashes. The top third of the table shows the frequency counts. Column percentages are shown in the middle third of the table. These percentages show the distribution of each injury severity across the impact categories; the bottom third of the table shows row percentages. The row percentages may be regarded as estimates of the probability of injury in the light vehicle for each truck impact point.

Table 6. Most severe injury in light vehicle by truck impact point (TIFA, GES 1996-1998)

Truck impact	Most severe injury in light vehicle							Total
	Fatal	A injury	B injury	C injury	Unknown injury	No injury	Unknown	
Front same direction	648	4,446	7,167	21,954	991	92,799	2,739	130,744
Front opposite direction	2,974	2,364	3,568	3,356	83	8,879	367	21,591
Front perpendicular	1,425	2,869	3,808	4,863	237	21,134	120	34,457
Rear	1,113	5,791	8,582	10,236	144	99,785	3,101	128,751
Sideswipe same direction	397	4,993	9,022	18,822	668	217,801	5,911	257,613
Left sideswipe opposite direction	555	3,263	3,312	3,844	41	23,323	772	35,109
Right sideswipe opposite direction	205	1,116	1,760	1,421	84	8,467	89	13,142
Left side perpendicular	526	2,289	3,329	3,745	84	21,093	799	31,865
Right side perpendicular	353	1,123	3,167	2,796	70	13,447	220	21,175
Other crash type	453	2,912	2,956	5,015	18	63,521	1,046	75,921
Unknown crash type	188	35	118	62	0	2,618	0	3,021
Total	8,837	31,201	46,788	76,114	2,420	572,867	15,163	753,389
	column percentages							
Front same direction	7.3	14.2	15.3	28.8	41.0	16.2	18.1	17.4
Front opposite direction	33.7	7.6	7.6	4.4	3.4	1.5	2.4	2.9
Front perpendicular	16.1	9.2	8.1	6.4	9.8	3.7	0.8	4.6
Rear	12.6	18.6	18.3	13.4	5.9	17.4	20.5	17.1
Sideswipe same direction	4.5	16.0	19.3	24.7	27.6	38.0	39.0	34.2
Left sideswipe opposite direction	6.3	10.5	7.1	5.1	1.7	4.1	5.1	4.7
Right sideswipe opposite direction	2.3	3.6	3.8	1.9	3.5	1.5	0.6	1.7
Left side perpendicular	6.0	7.3	7.1	4.9	3.5	3.7	5.3	4.2
Right side perpendicular	4.0	3.6	6.8	3.7	2.9	2.3	1.4	2.8
Other crash type	5.1	9.3	6.3	6.6	0.8	11.1	6.9	10.1
Unknown crash type	2.1	0.1	0.3	0.1	0.0	0.5	0.0	0.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	row percentages							
Front same direction	0.5	3.4	5.5	16.8	0.8	71.0	2.1	100.0
Front opposite direction	13.8	10.9	16.5	15.5	0.4	41.1	1.7	100.0
Front perpendicular	4.1	8.3	11.1	14.1	0.7	61.3	0.3	100.0
Rear	0.9	4.5	6.7	8.0	0.1	77.5	2.4	100.0
Sideswipe same direction	0.2	1.9	3.5	7.3	0.3	84.5	2.3	100.0
Left sideswipe opposite direction	1.6	9.3	9.4	10.9	0.1	66.4	2.2	100.0
Right sideswipe opposite direction	1.6	8.5	13.4	10.8	0.6	64.4	0.7	100.0
Left side perpendicular	1.7	7.2	10.4	11.8	0.3	66.2	2.5	100.0
Right side perpendicular	1.7	5.3	15.0	13.2	0.3	63.5	1.0	100.0
Other crash type	0.6	3.8	3.9	6.6	0.0	83.7	1.4	100.0
Unknown crash type	6.2	1.1	3.9	2.1	0.0	86.7	0.0	100.0
Total	1.2	4.1	6.2	10.1	0.3	76.0	2.0	100.0

Table 7.Counts of fatalities and injuries to the occupants of the other vehicle in two-vehicle, truck/light vehicle crashes (TIFA, GES 1996-1998)

Truck impact	Fatalities		A injuries		B injuries	
	N	%	N	%	N	%
Front same direction	786	7.5	6,026	15.4	9,485	15.9
Front opposite direction	3,619	34.6	3,257	8.3	4,386	7.4
Front perpendicular	1,773	17.0	4,224	10.8	5,740	9.6
Rear	1,226	11.7	6,755	17.2	10,400	17.5
Sideswipe same direction	416	4.0	6,384	16.3	10,806	18.1
Left sideswipe opposite direction	604	5.8	3,763	9.6	4,412	7.4
Right sideswipe opposite direction	234	2.2	1,313	3.3	2,289	3.8
Left side perpendicular	619	5.9	2,656	6.8	4,153	7.0
Right side perpendicular	407	3.9	1,514	3.9	4,103	6.9
Other crash type	521	5.0	3,263	8.3	3,649	6.1
Unknown crash type	240	2.3	104	0.3	133	0.2
Total	10,445	100.0	39,259	100.0	59,556	100.0

The highest probability of a fatal injury in the light vehicle occurs in frontal, opposite direction impacts. Almost 14% of light vehicles involved in this type of collision with a truck incurred a fatal injury in the light vehicle. This is by far the most severe collision type represented here. Front perpendicular collisions have the second highest probability of fatality at 4.1%. In contrast, the same-direction collision types have low probabilities of fatality and relatively high probabilities of no injury in the light vehicle. In 84.5% of same direction sideswipe collisions with a truck, no one was injured in the light vehicle. There was no injury in 77.5% of light vehicles that struck a truck in the rear, and no injury in 71.0% of light vehicles struck in the rear by a truck. See Appendix B for histograms of injury probabilities by collision type.

Table 8 presents counts of fatalities and injuries to the occupants of light vehicles by truck impact point. In light vehicles, there was a total of 10,445 persons killed, 39,259 A (incapacitating) injuries, 59,556 B (non-incapacitating) injuries, and 102,051 C (complaint of pain) injuries in two-vehicle, truck/light vehicle collisions from 1996-1998. The distributions of deaths and injuries are quite similar to the distributions of involvements in Table 6, as is expected. Over a third of the fatalities in the light vehicles occurred in front, opposite direction collisions. Front perpendicular collisions accounted for 17.0% of the fatalities and 11.7% of fatalities occurred in rear impacts.

Table 8.Counts of fatalities and injuries to the occupants of the other vehicle in two-vehicle, truck/light vehicle crashes (TIFA, GES 1996-1998)

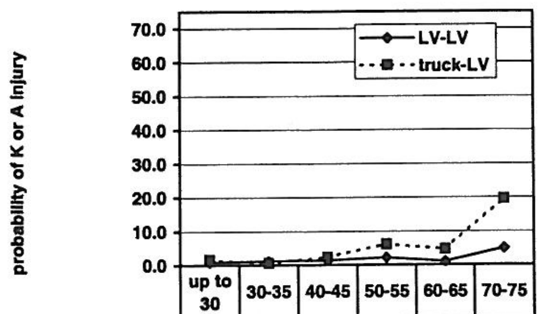
Truck impact	C injuries		Injured, unknown severity		Total casualties	
	N	%	N	%	N	%
Front same direction	31,177	30.6	1,068	36.2	48,542	22.7
Front opposite direction	4,423	4.3	154	5.2	15,839	7.4
Front perpendicular	6,416	6.3	405	13.7	18,558	8.7
Rear	13,516	13.2	210	7.1	32,107	15.0
Sideswipe same direction	24,415	23.9	790	26.8	42,811	20.0
Left sideswipe opposite direction	4,591	4.5	41	1.4	13,411	6.3
Right sideswipe opposite direction	2,130	2.1	84	2.8	6,050	2.8
Left side perpendicular	4,833	4.7	100	3.4	12,361	5.8
Right side perpendicular	3,158	3.1	73	2.5	9,255	4.3
Other crash type	7,309	7.2	27	0.9	14,769	6.9
Unknown crash type	83	0.1	0	0.0	560	0.3
Total	102,051	100.0	2,952	100.0	214,263	100.0

Almost 60% of the fatalities involved contact with the front of the truck either in same direction, opposite direction, or perpendicular (broadside) collisions. More than half of the fatalities involved contact with the front of the truck by the light vehicle from opposite or perpendicular directions. Overall, 38.7% of casualties (fatalities and injuries) involved the front of the truck, 15.0% involved the rear, and 39.2% involved contact with the sides of the truck. Impact location and orientation could not be determined for 7.2% of casualties.

Relative Aggressivity of Heavy Trucks

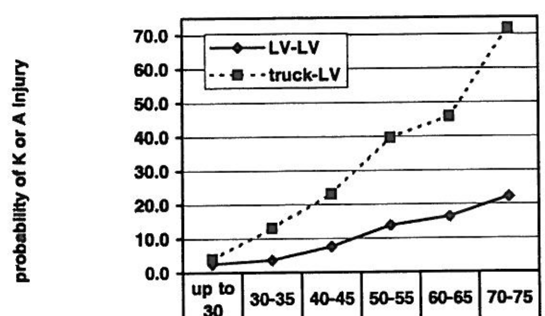
Figures 2 through 8 compare the aggressivity of trucks with light vehicles in terms of injury probability in the light vehicle for each crash type. The figures compare the probability of a fatality (K) or an A-injury in a light vehicle when involved in a collision with a truck to the K or A injury probability when involved in the same type of collision with another light vehicle. The figures focus on K or A-injuries since they represent the most serious consequences of truck/light vehicle crashes. The light-vehicle/light-vehicle crash injury probabilities serve as a baseline against which to measure truck aggressivity. The scales for each figure are reasonably comparable to show the magnitude of the difference in K or A-injury probability across the crash types. Road speed limit is used as a rough surrogate for travel speed in the figures.

Overall, across all crash types, there is a K or an A injury in a light vehicle in 5.3% of two-vehicle, truck/light vehicle crashes, compared with 2.2% if the other vehicle is a light vehicle. In other words, an occupant of a light vehicle has 2.4 times greater chance of a K or an A-injury if involved in a collision with a truck rather than with another light vehicle.



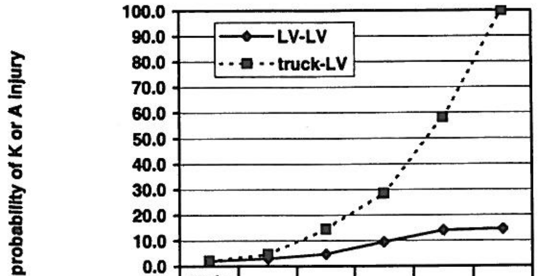
speed limit	up to 30	30-35	40-45	50-55	60-65	70-75
LV-LV	0.84	1.19	1.44	2.23	1.01	4.95
truck-LV	1.60	0.66	2.43	6.11	4.60	19.56

Figure 2. Front same direction crashes



speed limit	up to 30	30-35	40-45	50-55	60-65	70-75
LV-LV	2.55	3.66	7.59	13.75	16.29	22.23
truck-LV	4.03	13.03	23.12	39.59	45.77	71.77

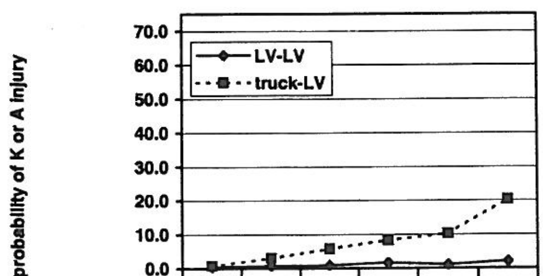
Figure 3. Front opposite direction



	up to 30	30-35	40-45	50-55	60-65	70-75
LV-LV	2.05	2.99	4.77	9.45	14.05	14.57
truck-LV	2.14	4.60	14.51	28.43	58.07	100.00

speed limit

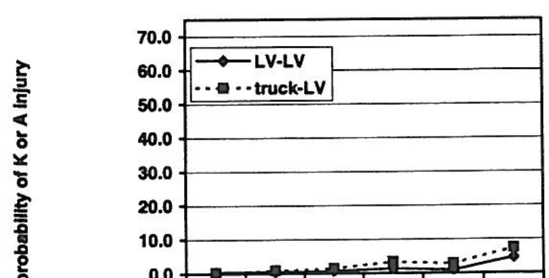
Figure 4. Front perpendicular



	up to 30	30-35	40-45	50-55	60-65	70-75
LV-LV	0.46	0.74	0.87	1.63	1.08	2.02
truck-LV	0.77	3.00	5.72	8.26	10.18	20.26

speed limit

Figure 5. Rear same direction



	up to 30	30-35	40-45	50-55	60-65	70-75
LV-LV	0.41	0.46	0.68	1.35	0.87	4.58
truck-LV	0.26	0.87	1.53	3.34	2.77	7.35

speed limit

Figure 6. Sideswipe same direction

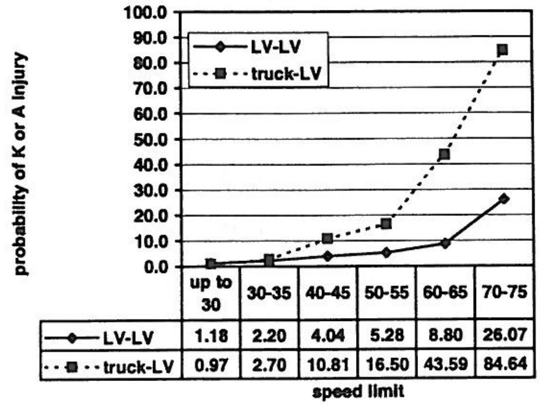


Figure 7. Sideswipe opposite direction

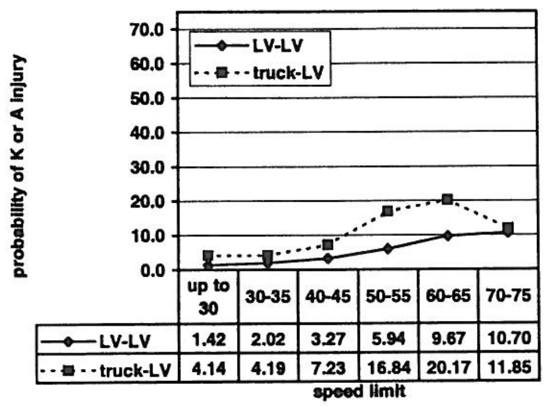


Figure 8. Side perpendicular

Generally, for all crash types, the probability of a K or an A-injury in the light vehicle increases with the road speed limit. This is true whether the other vehicle involved is a truck or a light vehicle. The figures also illustrate that the probability of a K or an A-injury in a light vehicle is always higher when the other vehicle is a truck regardless of crash type or speed limit. Finally, the figures show that in some crash types, the aggressivity of trucks and light vehicles diverge rapidly at higher speed limits, while in other crash types the extra risk of collision with a truck, as measured by the probability of a K or A-injury, is relatively stable across speed limits.

In opposite direction collisions (Figures 2 and 6), the probability of a K or an A-injury increases rapidly at higher speed limits for both front and sideswipe crashes. In both crash types, trucks are much more aggressive in terms of producing K or A-injuries in the light vehicle. When the opposite direction crash is a sideswipe, injury probability increases slowly in light vehicle/light vehicle (LV/LV) crashes up to the 60-65 speed limit group.

Injury probability is much lower in the same direction crash types (Figures 1, 4, and 5). Same-direction sideswipes have the lowest K or A-injury probabilities across all speed limits for both truck/LV and LV/LV crashes. Front same-direction crashes have similarly low K/A-injury probabilities for both truck/LV and LV/LV crashes except at the highest speed limit range, where the probability of a K or an A-injury in a light vehicle is almost four times higher if the striking vehicle is a truck than if it is another light vehicle.

However, there is a difference in K/A injury probability when a light vehicle strikes the rear of a truck rather than the rear of another light vehicle (Figure 4). K/A probabilities in the light vehicle are significantly higher when striking a truck within each speed limit group and increasingly diverge at higher speed limits.

There are also interesting differences between truck/light vehicle and light vehicle/light vehicle crashes when vehicle motions are perpendicular. In front perpendicular crashes (Figure 3), the side of a light vehicle is struck by the front of a truck or another light vehicle. When the striking vehicle is a truck, K/A probability in the light vehicle increases rapidly with the speed limit. If the striking vehicle is the front of another light vehicle, K/A probability increases, but at a slower rate.

In side perpendicular crashes (light vehicle into side of truck or light vehicle; Figure 7), K/A probabilities in the light vehicle are somewhat greater if the light vehicle strikes the side of a truck than if it strikes the side of another light vehicle. But the differences are not as great as front perpendicular crashes. In side perpendicular crashes, energy-absorbing structures in the light vehicle may be engaged if it strikes the truck's axles or cab.

Summary of TIFA and GES Data Analysis

A total of 9,089 fatal and an estimated 744,298 non-fatal crash involvements between truck and light vehicles took place between 1996 and 1998. More than 40% of non-fatal involvements were sideswipes (both same and opposite direction) and about 25% were front impacts. More than 50% of fatal involvements included contact with the front of the truck.

From the distribution of crash severity variables, almost 74% of the involvements were observed to be property damage only cases, with no injury or fatality to the occupants; 4.3% were A-injury, 6.5% were B-injury, and 10.7% C-injury crashes.

Over a three year span, a total of 10,445 deaths occurred in the light vehicle in truck/light vehicle crashes. About 60% of these fatalities occurred when the front of the truck hit the light vehicle. Out of a total of 214,263 injuries (including fatal injuries) to light vehicle occupants, about 40% resulted from front impacts and 30% from sideswipes of all kinds.

Relative Velocity in Fatal Tractor-Semitrailer/Light Vehicle Collisions

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 four years of data, 1994 to 1997. The data is based on information from police reports and telephone interviews. Crash involvements are classified according to the primary type of impact: with another truck, with a light vehicle, with a railroad train, with a fixed object, with a non-fixed object, etc. Within each category, additional data is collected on a sample of the involvements. For each crash, the primary impact is identified. Data is then 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 cases. First, the TIFA file, which provides the set of cases for which the Sandia collision severity data, is collected (itself a sample for 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 light vehicle/truck cases is included in the data. Since the 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. All tables below present weighted frequencies.

Cases in which the primary collision in the crash was an automobile or light truck were selected for the present analysis. An analysis file was constructed in which variables describing the other vehicle in the collision were appended to the truck record. With this additional information, the impacts could be distributed around the perimeter of the truck using the same algorithm as in the earlier analysis of the TIFA and GES files.

Estimates of the relative velocity of the vehicles at impact, at each point around the truck, are generated for truck/light vehicle collisions. These estimates are as reliable as the underlying data. Much of the information used in making the estimates of the relative velocities 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 relative velocity 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.

Table 9 shows the distribution of impacts around the perimeter of the truck in the Sandia collision data where the collision was with a light vehicle. This table may be compared with distribution in the column for fatal involvements in Table 5 above. The fatal column in Table 5 includes all two-vehicle, light vehicle/truck collisions for the years 1996 through 1998. Table 9 covers the years 1994-1997, and trucks in the table are limited to tractor-semitrailers. Only cases in which a valid relative velocity could be estimated are included. Despite the differences in coverage, the two distributions are in reasonable agreement. Though based on only 195 unweighted cases, the weighted distribution approximates the distribution of crash types for all trucks involved in fatal crashes.

Table 9. Light vehicle/tractor-semitrailer involvements by truck impact point in fatal involvements (Sandia collision data, 1994-1997)

Truck impact	N	**Weighted N**	%
front same direction	18	670	9.7
front opposite direction	57	2,072	30.1
front perpendicular	33	1,159	16.9
rear	29	1,003	14.6
sideswipe same direction	9	299	4.3
left sideswipe opposite direction	10	340	4.9
right sideswipe opposite direction	7	245	3.6
left side perpendicular	13	400	5.8
right side perpendicular	3	110	1.6
other crash type	15	553	8.0
unknown crash type	1	29	0.4
total	195	6,880	100.0

Table 10 shows the classification of the other vehicle in the collision. This table may be compared with the fatal column in Table 4. Again, the distributions are in reasonable agreement. Accordingly, it plausible to argue that the sample of cases for which relative velocities were calculated reasonably represents the closing speeds in fatal tractor-semitrailer accident involvements with a light vehicle.

Table 10. Body type of other vehicle in light vehicle/tractor-semitrailer involvements (Sandia collision data, 1994-1997)

Body type of other vehicle	Weighted N	%
Convertible	29	0.4
2dr Sedan/HT/Coupe	1,184	17.2
3dr/2dr Hatchback	346	5.0
4dr Sedan/HT	2,001	29.1
5dr/4dr Hatchback	62	0.9
Station Wagon	198	2.9
Sedan/HT/unknown doors	47	0.7
Other/Unknown auto type	156	2.3
Compact Utility	585	8.5
Large Utility	47	0.7
Utility Station Wagon	44	0.6
Minivan	296	4.3
Large Van	109	1.6
Other Van type	59	0.9
Compact Pickup	405	5.9
Standard Pickup	997	14.5
Cab chassis Based	33	0.5
Motorcycle	253	3.7
Moped	29	0.4
Total	6,880	100.0

Table 11 displays the results of calculations of the relative velocity of the truck and the lig vehicle by the point of impact around the truck. The mean relative velocity and the standa deviation of the distribution are shown for each impact point. The column headed “N” sh raw number of cases for which the mean and standard deviation statistics were calculated. relative magnitude of the mean velocities is plausible. The highest mean relative velocitie in collisions where the vehicles were going in opposite directions. In a front, opposite-dir impact, the mean closing speed was over 90 mph. Similarly, where the impact was an opp direction sideswipe, the relative velocities were 89.2 and 64.7 for left and right side impa respectively. Relative velocities are lowest in same-direction collisions. In front, same-di collisions (rear-end collisions in which the truck is the striking vehicle) the relative veloc 39.4 mph. In rear impacts (in which the truck was struck in the rear), the relative velocity 46.4 mph.

Table 11. Mean relative velocity of impacts in light vehicle/tractor-semitrailer fatal involvements by crash type (Sandia collision data, 1994-1997)

Truck impact	N	Mean relative velocity (mph)	Std. Dev.
front same direction	18	39.4	17.6
front opposite direction	57	90.7	31.4
front perpendicular	33	43.2	13.6
rear	29	46.4	18.0
sideswipe same direction	9	37.0	14.1
left sideswipe opposite direction	10	89.2	27.6
right sideswipe opposite direction	7	64.7	18.5
left side perpendicular	13	58.1	17.1
right side perpendicular	3	57.0	15.7
other crash type	15	51.6	31.7
unknown crash type	1	105.0	.

These data should be taken primarily as suggestive, as the sample sizes for most crash types are quite small. Note that the standard deviations of the estimates are large. For example, the relative velocity in front opposite direction impacts ranged from 11 to almost 150mph. Appendix C contains a set of histograms showing the distribution of relative velocities for each impact point.

CHAPTER 4: COLLISION AND INJURY MODELS

Methods of estimating the injury causing potential of a vehicle crash are typically based on the values of physical quantities (such as acceleration, velocity, and displacement) to which the occupants of the vehicle are subjected during the impact. These values are determined primarily by the initial velocity of the vehicles involved in the collision, the nature of the collision (direct, off-set, oblique etc.), and the physical properties of the vehicles and their structures (mass, moments of inertia, structural stiffness, damping, crush distance etc.). A number of studies have attempted to analyze the behavior of colliding vehicles using a variety of models ranging in complexity from simple one-dimensional lumped models to detailed finite element models with thousands of degrees of freedom. A review of the relevant literature in this area has been present in Chapter 2 of this study.

Collision Models

This section presents an analysis of collision physics using lumped parameter models to analyze the dissipation of the collision energy, the velocity change undergone by the vehicles, and the acceleration profiles through which this velocity change is accomplished. The analysis will be particularly focused for use with the injury models presented later in this chapter to suggest and evaluate the benefits of various truck structural countermeasures that decrease the injury potential of light vehicle/truck collisions. In many of the calculations it will be assumed that one of the colliding vehicles (the light vehicle) is considerably lighter than the other (the truck).

Velocity Changes (ΔV)

The most fundamental measure of collision severity is the velocity change undergone by the colliding vehicles. This velocity change occurs in the short timeframe of the collision and results in forces that deform the vehicles and inflict injuries on the occupants of those vehicles. Smith (1998) examined the change in velocity (Δv) of the vehicles involved in a collision, taking into consideration the fact that the collision may be offset (i.e., the line of action of the collision forces does not pass through the line drawn through the center of masses of the two vehicles). These calculations will not be repeated here, but result will be described and used to derive a relationship between the initial closing velocity and the change in velocity Δv undergone by the vehicles. Furthermore, the result will demonstrate the fundamental cause of heavy truck aggressivity, namely the mass mismatch.

If the mass of the light vehicle and the truck is denoted as m_c and m_t and their respective changes in velocity are denoted as Δv_c and Δv_t, the following equations can be written (Smith, 1998):

$$\Delta v_c = \sqrt{\frac{2Em_t}{m_c\left(m_c\delta_c + m_t\delta_t\right)}} \tag{3}$$

and

$$\Delta v_t = \sqrt{\frac{2Em_c}{m_t\left(m_c\delta_c + m_t\delta_t\right)}} \tag{4}$$

Here, $\delta = 1 + \frac{h^2}{k^2}$ and h is the offset of the line of action of the contact force between the vehicle from the center of mass of the vehicle, k is the radius of gyration of the vehicle, and E is the total energy dissipated in the collision. Therefore:

$$\frac{\Delta v_c}{\Delta v_t} = \frac{m_t}{m_c} \tag{5}$$

Assuming a perfectly inelastic collision (the coefficient of restitution in automobile collisions drops below 0.1 and decreases steadily as the closing velocity increases above 10 mph; Smith and Noga, 1982) the vehicles achieve a common velocity v_f after the collision. The relative velocity of the two vehicles can be written as:

$$v_r = v_c - v_t \tag{6}$$

and

$$\Delta v_c = v_f - v_c \tag{7}$$

$$\Delta v_t = v_f - v_t \tag{8}$$

Then, from conservation of momentum:

$$m_c * v_c + m_t * v_t = (m_c + m_t) * v_f \tag{9}$$

From Equations 5 through 9, the following can be derived:

$$\Delta v_c = \frac{m_t}{(m_t + m_c)} v_r \tag{10}$$

Figures 9 and 10 show the velocity changes undergone by the light vehicle and the truck as a percentage of the initial relative velocity between the two vehicles before the collision.

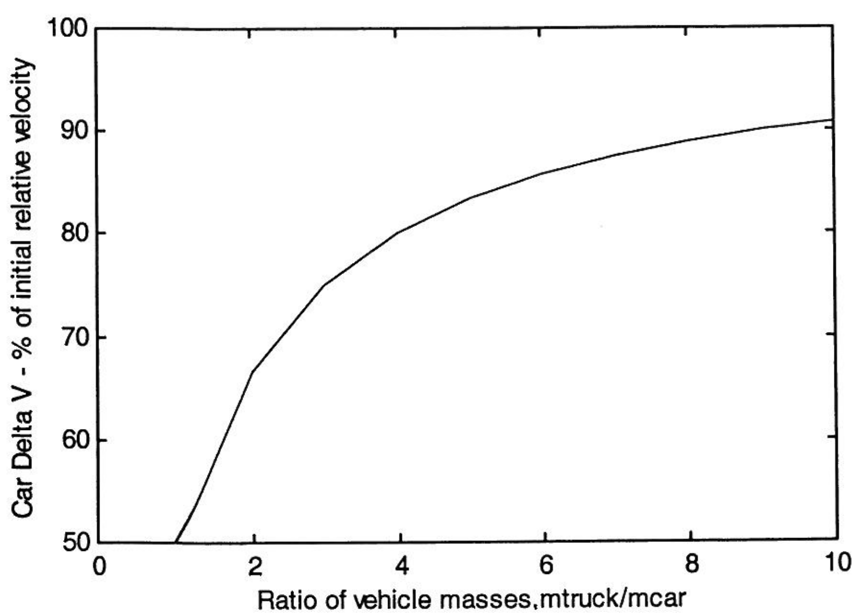


Figure 9. Relationship between Light vehicle Δv and initial relative velocity

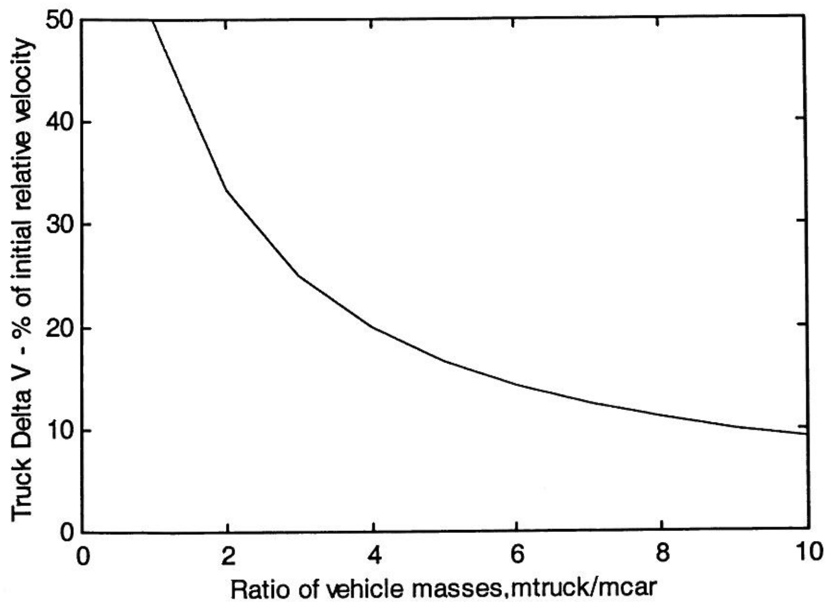


Figure 10. Relationship between Truck Δv and initial relative velocity

The figures show that as the ratio of the truck and light vehicle masses increases, a greater and greater proportion of the initial relative velocity is dissipated in the lighter vehicle. This is also shown as the ratio exceeds 10, $\Delta v_c > 0.90 * v_r$. Conversely, as the mass mismatch increases, the velocity of the truck undergoes very little change and essentially the truck continues its initial motion through and after the collision, with the light vehicle simply being swept along. This mass-related mismatch contributes greatly to the aggressivity of heavy trucks, and by definition very little can be done to alleviate it. Therefore it is necessary to examine the collision process in greater detail in order to devise countermeasures that manage the dissipation of collision energy and reduce the severity of the damage done to the lighter vehicle and its occupants.

Energy Dissipation

In any collision the forces, damage, and injury severity are all related to the dissipation of the kinetic energy of the colliding vehicles. The kinetic energy of a vehicle can be very simply represented by the formula $\frac{1}{2}MV^2$ where M is the mass of the vehicle and V is its velocity. The other factor that determines the severity of the collision is the arresting distance or crush zone available to decelerate the vehicle to a stop. Given an initial velocity V and a stopping distance s, the average acceleration of the vehicle may be computed from:

$$a = \frac{V^2}{2s} \tag{11}$$

Figure 11 shows the relationship between available stopping distance and the average acceleration required to dissipate all the kinetic energy of the impacting vehicle. In general, decelerations of greater than 20g result in severe or possibly fatal injuries. Thus, Figure 11 indicates that for a closing velocity of 25mph, the crush distance must be greater than approximately 0.35m to keep the average acceleration below this threshold; this number goes up to about 1.3m for a 50mph closing velocity. Of course this crush or stopping distance can be met through the deformation of the structures of both the impacting light vehicle and the truck, though with current truck designs the structure of the truck is considerably stiffer than that of the light vehicle and deforms by a significantly lesser amount. The above analysis assumes a constant deceleration of the impacting vehicle and thus a constant structural crush force. However, the crush strength of real life structures is not constant with deformation and instead peaks quickly and then tends to decline.

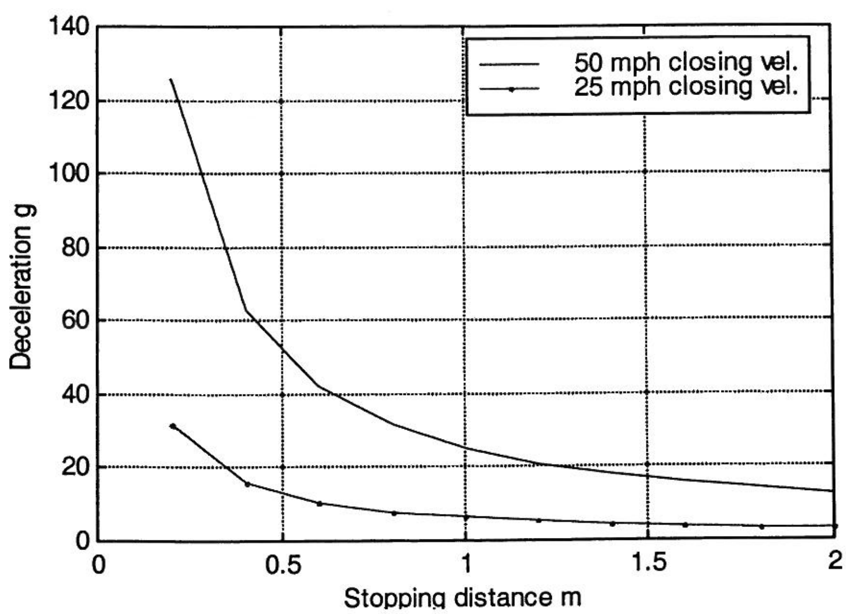


Figure 11. Relationship between vehicle acceleration and stopping distance

Figure 12 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; these 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 peak force and the peak accelerations of a real structure are necessarily greater than that in the case of the constant acceleration based analysis.

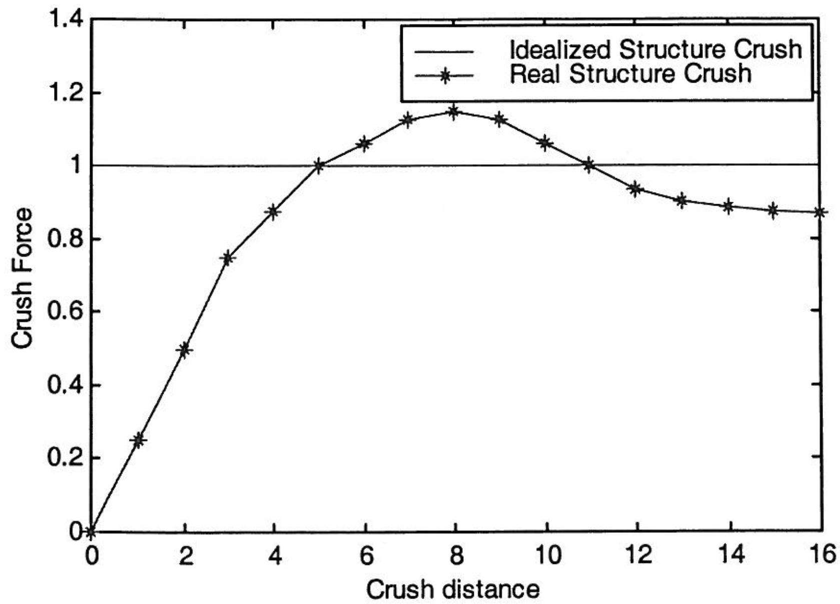


Figure 12. Relationship between vehicle acceleration and stopping distance

A vehicle collision model has been developed and used to explore the effect of various parameter changes on the collision variables. In addition, it also suggests and analyzes the feasibility of making structural modifications that serve as countermeasures for reducing the truck aggressivity.

2-D (In Plane) Vehicle Collision Model

In developing the collision model, it is assumed that all vehicle motion (before, during, and after the collision) takes place in the X-Y (horizontal) plane and that any motion in the Z or vertical direction may be neglected. The mass of the truck is significantly greater than that of the impacting light vehicle and, as was seen from the earlier analysis of the change in relative velocities (Figures 9 and 10), the motion of the truck is mostly unaffected by the collision. It is therefore assumed that the truck acts effectively as a fixed barrier with which the light vehicle collides. The light vehicle will be modeled as a simple rigid body with mass and yaw moment of inertia. Of course, the light vehicle structure is not rigid and has significant compliance, but the structural compliance of both the light vehicle and the truck will be assumed to be concentrated in the truck structure and will be modeled as an idealized spring-damper combination, for the purposes of this analysis. Carney et al. (1996) demonstrated the validity of this assumption and showed that it provides excellent agreement with considerably more complicated finite-element models and with crash test data. Further, this model structure will provide a clear means of analyzing the effect of changes in parameters and their relative significance in modifying crash severity.

Figures 13, 14 and 15 show a schematic representation of the model and the three collision types (direct, offset, and oblique) that may be analyzed using the model.

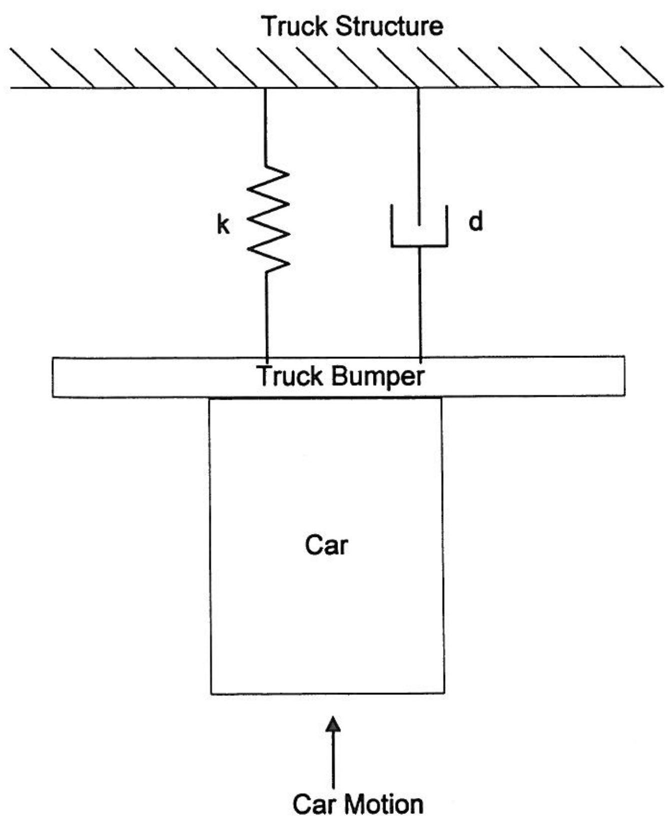


Figure 13. Light Vehicle/Truck Collision, Direct Impact

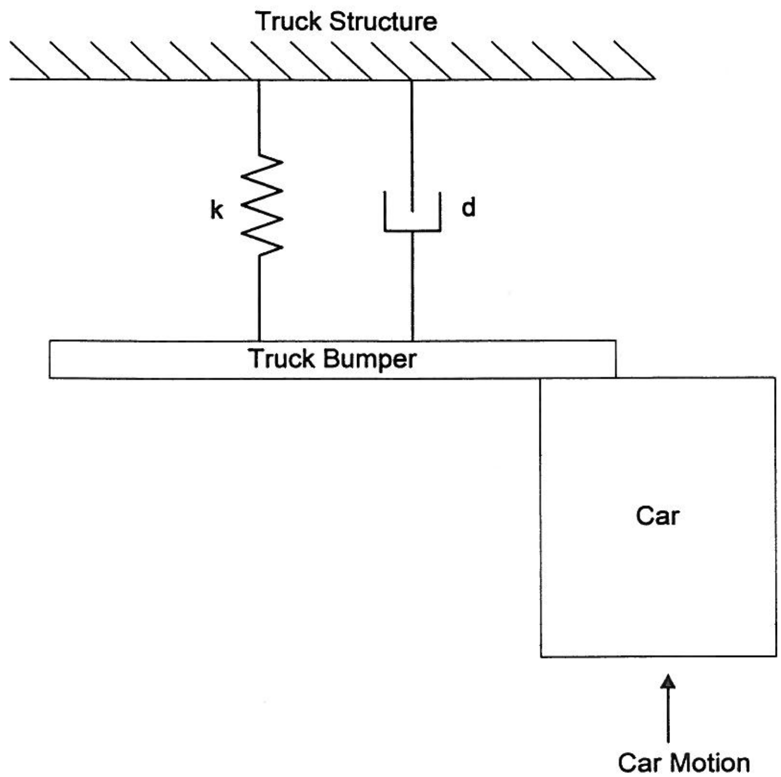


Figure 14. Light Vehicle/Truck Collision, Offset Impact

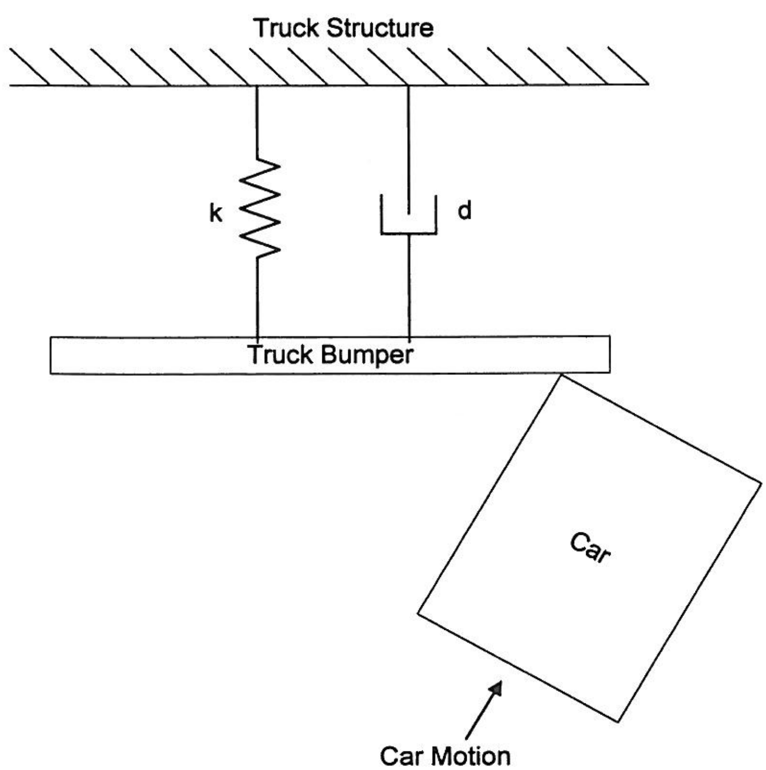


Figure 15. Light Vehicle/Truck Collision, Oblique Impact

In all three cases, the contact force between the two vehicles is assumed to act normal to the surface of the truck bumper (which is assumed to be of negligible mass compared to the impacting light vehicle), and the force due to the friction between the colliding vehicles acts parallel to the surface. In real crashes the contact force between the two vehicles acts in a distributed fashion over the entire contacting surface of both vehicles. This will be modeled as a single effective force acting normal to the truck front surface, through a point on the light vehicle surface, offset from the center by a distance, a, and at an angle to the light vehicle front that depends upon the yaw rotation, ϕ, of the light vehicle. The friction force is assumed to be related to the normal force by the proportionality constant, μ (coefficient of friction). The model simulates the motion of the light vehicle immediately after contact with the truck front structure. It is assumed that the contact points on the truck and the light vehicle move together. The free body diagram of the light vehicle is shown below in Figure 16.

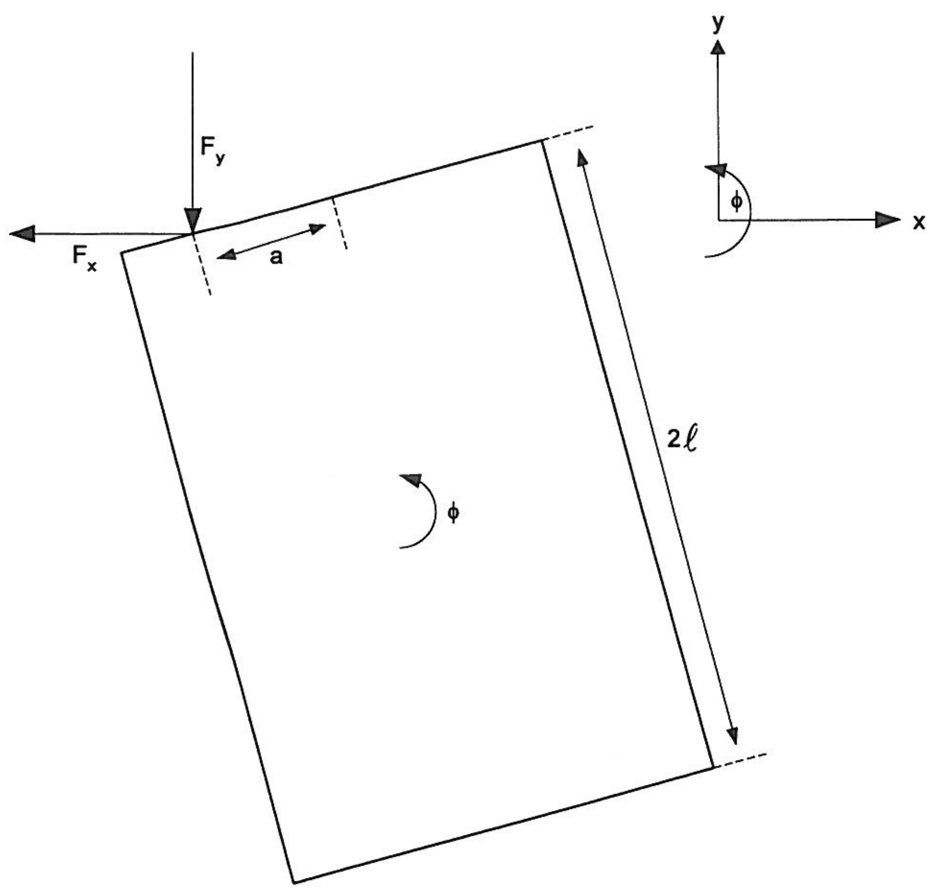


Figure 16. Free body diagram for light vehicle collision model

This model was then implemented in the rigid body dynamics simulation program AutoSim®. The program automatically generates the differential equations describing the forces on and the resulting motion of, the impacting vehicle. The resulting equations are:

$$F_y = k*(y_c + l*\cos(\phi) + a*\sin(\phi)) + d*((\dot{y}_c + a*\dot{\phi})*\cos(\phi) + (\dot{x}_c - l*\dot{\phi})*\sin(\phi)) \quad (12)$$

$$F_x = \mu*(k*(y_c + l*\cos(\phi) + a*\sin(\phi)) + d*((\dot{y}_c + a*\dot{\phi})*\cos(\phi) + (\dot{x}_c - l*\dot{\phi})*\sin(\phi))) \quad (13)$$

$$\dot{x}_1 = x_2 * \cos(x_5) - x_4 * \sin(x_5) \quad (14)$$

$$\dot{x}_2 = -(m_c * x_4 * x_6 + F_x * \cos(x_5) + F_y * \sin(x_5)) / m_c \quad (15)$$

$$\dot{x}_3 = x_4 * \cos(x_5) + x_2 * \sin(x_5) \quad (16)$$

$$\dot{x}_4 = (-m_c * x_2 * x_6 - F_y * \cos(x_5) + F_x * \sin(x_5)) / m_c \quad (17)$$

$$\dot{x}_5 = x_6 \quad (18)$$

$$\dot{x}_6 = (-F_y * (a*\cos(x_5) - l*\sin(x_5)) + F_x * (l*\cos(x_5) + a*\sin(x_5)) \quad (19)$$

Here, $x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6]$ is the system state vector, $x_c = x_1$ and $y_c = x_3$ are respectively the displacement of the center of mass of the light vehicle in the X and Y directions, and $\phi = x_5$ is the yaw rotation of the light vehicle around a vertical axis passing through the center of mass. The following values are assumed for the vehicle and collision properties: mass of the light vehicle m_c = 1500 kg, I_{zc} =2000 kg-m^2, l =1.5m and coefficient of friction between the colliding vehicles μ =0.35.

Optimizing the Truck Structure

Earlier analysis demonstrated the close relationship between crush or stopping distance and the level of acceleration experienced by the vehicle and its occupants. At the same time it was recognized that the acceleration of the vehicle is not a constant but is time varying, thus peak levels of acceleration can be considerably higher than the average value. In terms of occupant safety it is important to fully utilize the available crush distance and minimize these peak acceleration levels. For the purposes of the model, a simple spring mass damper combination has been chosen to represent the vehicle structure. While real structures exhibit nonlinear and considerably more complex crush behavior, this model structure will serve to clearly demonstrate the considerations involved in selecting the stiffness and damping properties of the vehicle structure and the feasibility of achieving a given level of occupant protection corresponding to an available crush space.

Figures 53 and 54 in Appendix C show the distribution of closing velocities in fatal front, same-direction and front, opposite-direction light vehicle/truck crashes. It can be seen that the median closing velocity is approximately 100km/h (62.5mph). Therefore, this velocity will be used as a reference in further discussions. Figure 17 shows is the relationship between average acceleration and stopping distance for this velocity.

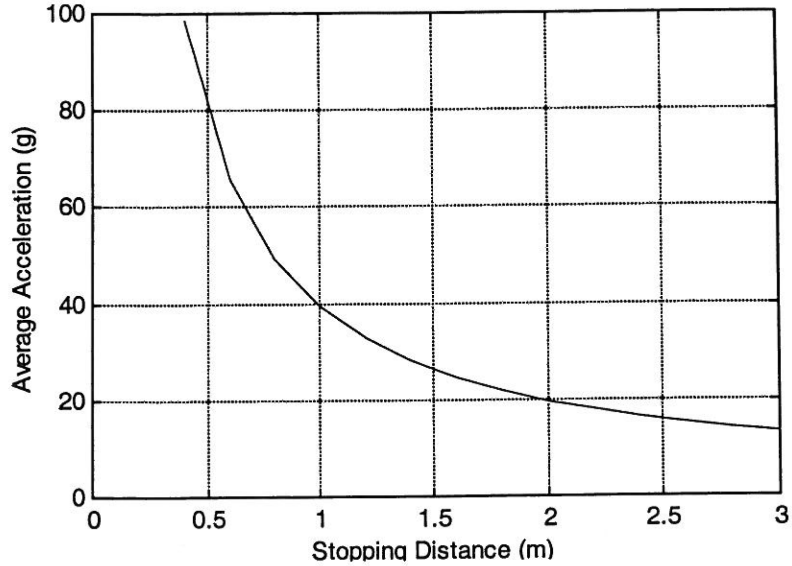


Figure 17. Acceleration vs. stopping distance (100km/h crash)

The typical crush distance available in light vehicles is approximately 1m. For that stopping distance, the average acceleration is about 40g. This level of acceleration usually results in severe occupant injuries if not fatality. NCHRP guidelines (Ross et al., 1993) recommend a maximum occupant acceleration of 20g in 100km/h crashes for vehicle and highway occupant protection features. This level of acceleration requires a minimum crush length of 2m. However, real structures do not exhibit constant crush strength and therefore the required crush space is likely to be greater. The optimum values of the stiffness and damping parameters, k and d, are calculated in a model that minimizes the stopping distance while satisfying the requirement that the peak acceleration is below 20g.

For this purpose, a constrained optimization routine was implemented in MATLAB® using the vehicle parameters listed earlier. A direct collision with no initial lateral or yaw velocity was assumed. Under these assumptions, the resulting values are k = 1.0343e5N/m and d = 1.0075e4Ns/m. Figures 18 and 19 show the acceleration profile and corresponding vehicle displacement for a collision.

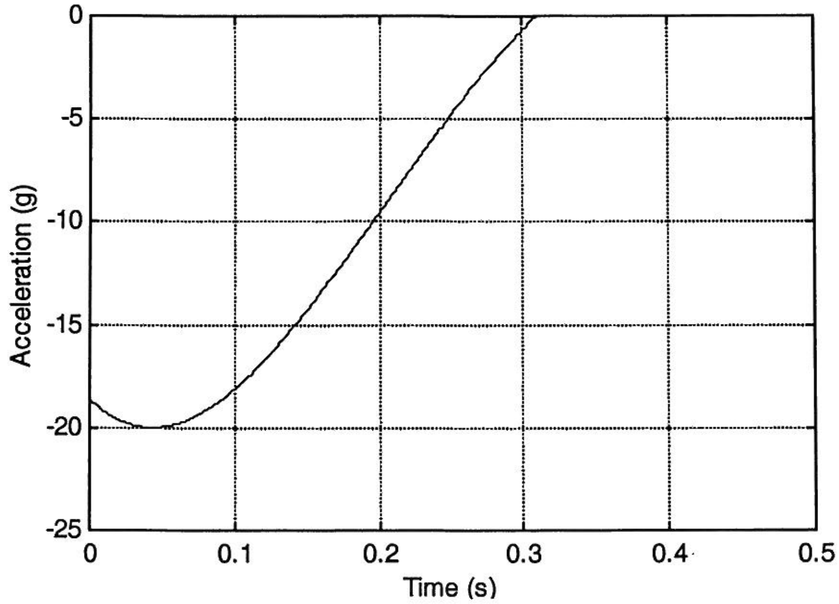


Figure 18. Acceleration profile for optimized structural parameters

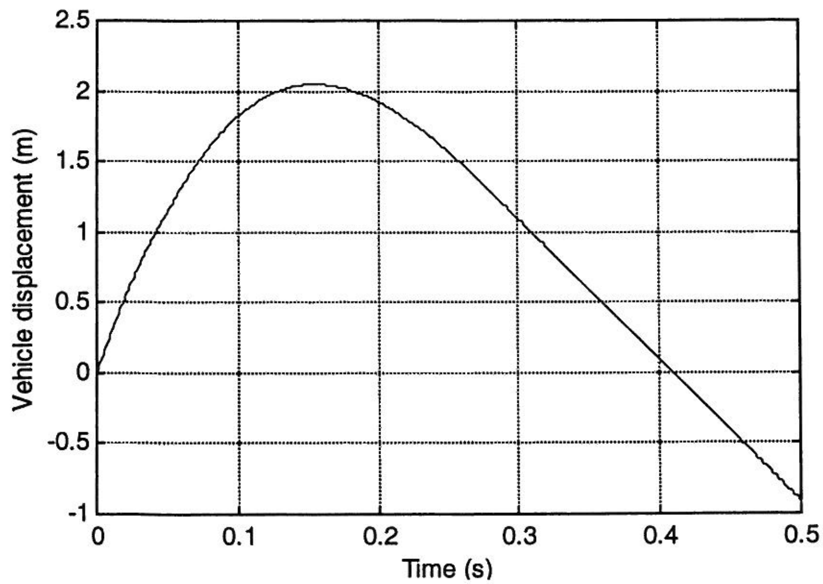


Figure 19. Vehicle displacement for optimized structural parameters

It can be seen that the magnitude of the peak acceleration is almost exactly equal to 20g and the peak displacement of the vehicle is a little over 2m (2.05m). At a little over the 0.3 second point, the vehicle loses contact with the truck front structure and the contact force between the vehicles is then 0. Thus, with a relatively simple structure it is possible to select parameters that come close to the ideal of a constant crush strength and provide attenuation of the g-forces generated by the collision.

The values chosen for the stiffness and damping are optimal only for the set of conditions assumed above. Figures 20, 21, 22 and 23 show the effect of changes in closing velocity and vehicle mass on the acceleration and displacement profiles. Increases or decreases in vehicle initial velocity result in corresponding changes in vehicle acceleration levels and displacement. Similarly, an increase or decrease in vehicle mass results in correspondingly lower or higher accelerations and increased or decreased displacement. This last point is particularly important, as design of the truck structure is dependent upon which class of vehicle is chosen to be protected. Some considerations in making this choice will include the degree of protection each class of vehicle affords its occupants (with larger, heavier vehicles needing less accommodating truck structures to ensure occupant survival), the distribution of vehicles in the general population, and the likely ranges of speeds at which any particular class of vehicle is used. This will be further analyzed (quantitatively) in the section on countermeasures the level of benefit achievable through such attenuation of the crash pulse.

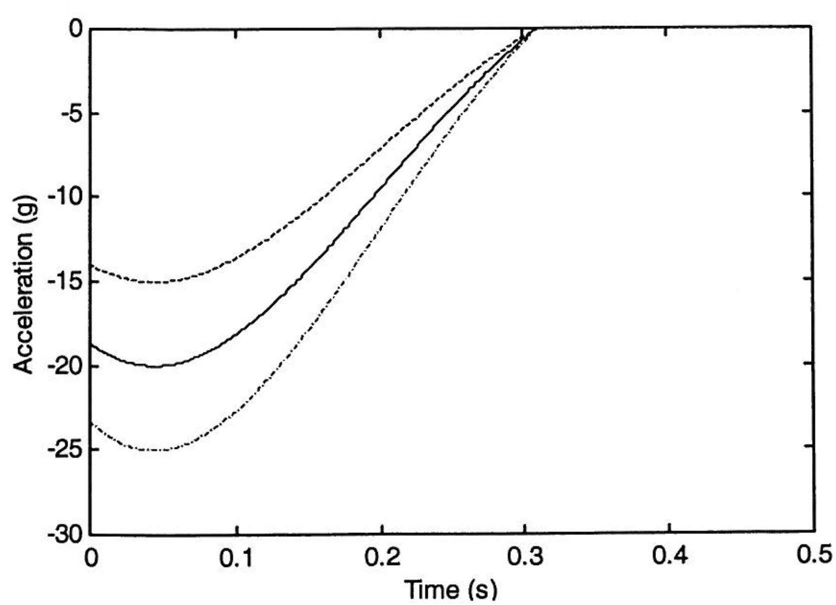


Figure 20. Variation in vehicle acceleration with closing velocity

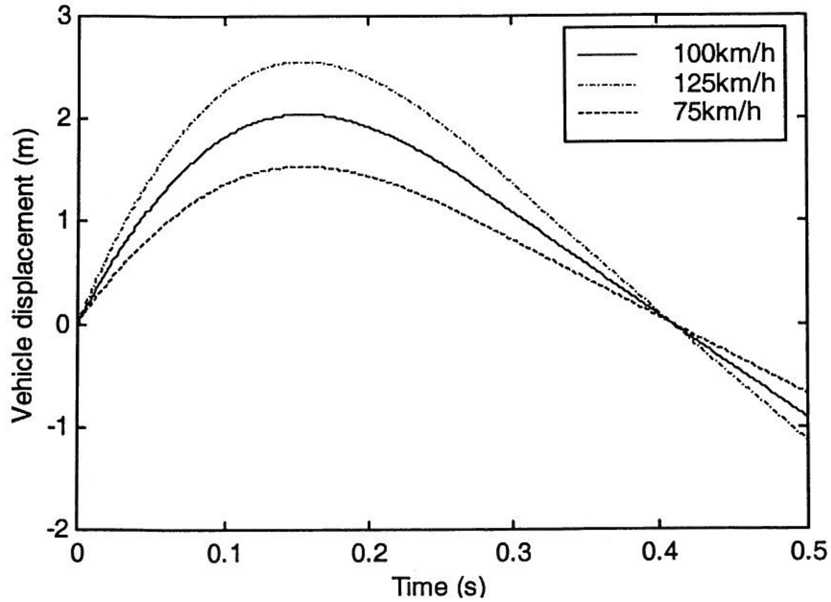


Figure 21. Variation in vehicle displacement with closing velocity

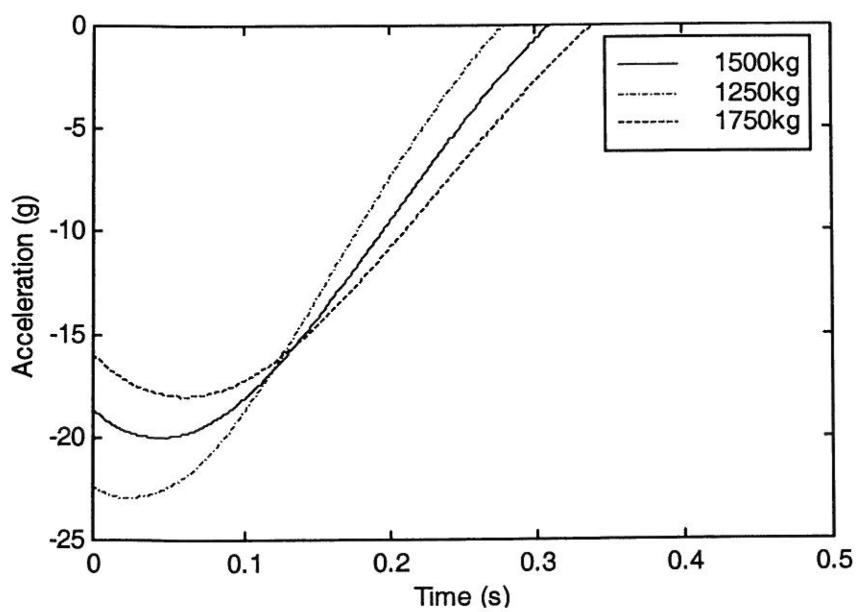


Figure 22. Variation in vehicle acceleration with closing velocity

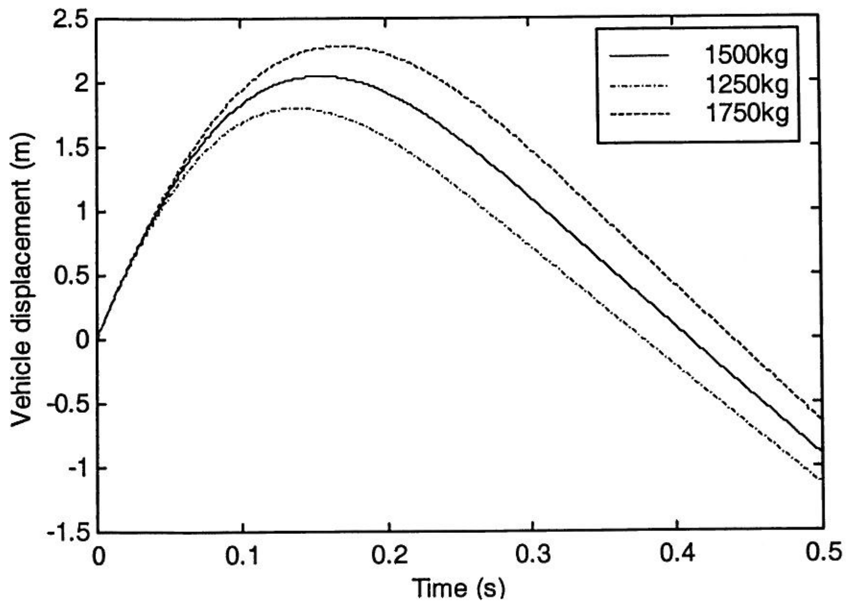


Figure 23. Variation in vehicle displacement with closing velocity

Oblique/Offset (Deflection Type Crashes)

The previous section considered the case of attenuation of the crash pulse in direct or head-to-head collisions. In a large proportion of crashes, however, the line of contact between the colliding vehicles is significantly offset from the vehicles' centers, or the direction of travel of the colliding vehicles is at an angle to the line passing through the center of either vehicle. More importantly, for the purposes of this study, the Δv and the acceleration levels undergone by the vehicles in such crashes are lower than those in direct collisions. This leads to the possibility of intentionally designing truck structures that deflect or redirect the impacting light vehicle, thus lowering the amount of energy that must be dissipated during the collision.

The case of an offset collision with no lateral velocity is considered. In this case, it is assumed that the frictional force between the vehicles is 0. This is not particularly significant from the countermeasure design point of view since it is difficult to imagine a device or structural modification that can create a specific collision offset on demand. However, this model will still serve to demonstrate the reduction in Δv (and hence reduced energy dissipation) that results from the collision being offset from the center of the vehicle, and this model will serve to lead into the more complicated case of the oblique collision.

Three different offsets are considered (0.2, 0.4, and 0.6m). The initial velocity of the impacting light vehicle is assumed to be 27.7782m/s (100km/h) in the Y direction. The initial yaw angle and rotation rate are both assumed to be 0.

Figure 24 shows the contact force between the vehicles for each of the four cases (0m offset, 0.2m offset, 0.4m offset, 0.6m offset). As the offset increases, the peak force during the collision decreases; furthermore, the force acts upon the light vehicle for a shorter duration.

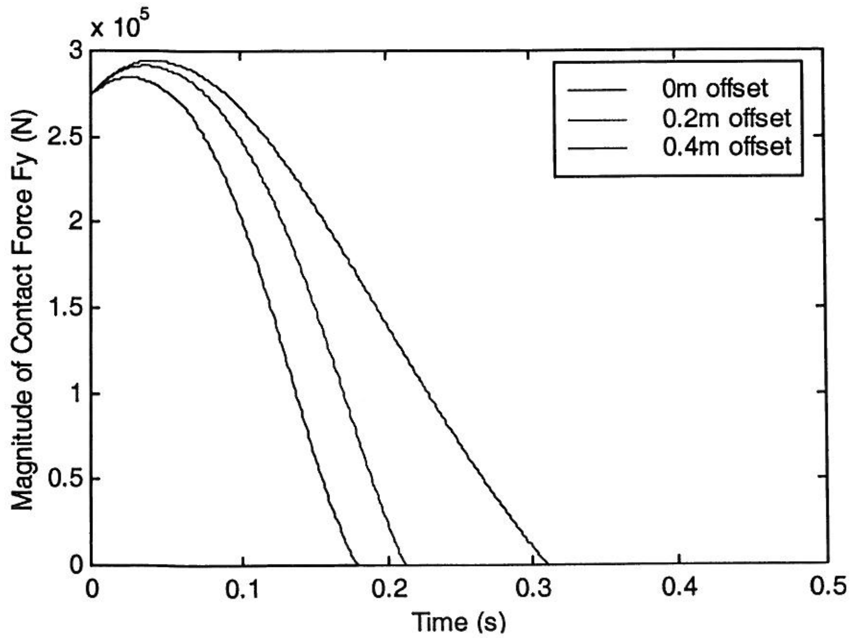


Figure 24. Variation in contact force with offset

Figure 25 shows the vehicle Y velocities for each case. It can be seen that the largest Δv takes place in the no offset case and then the magnitude of velocity change declines with increase in offset, making the collision less severe.

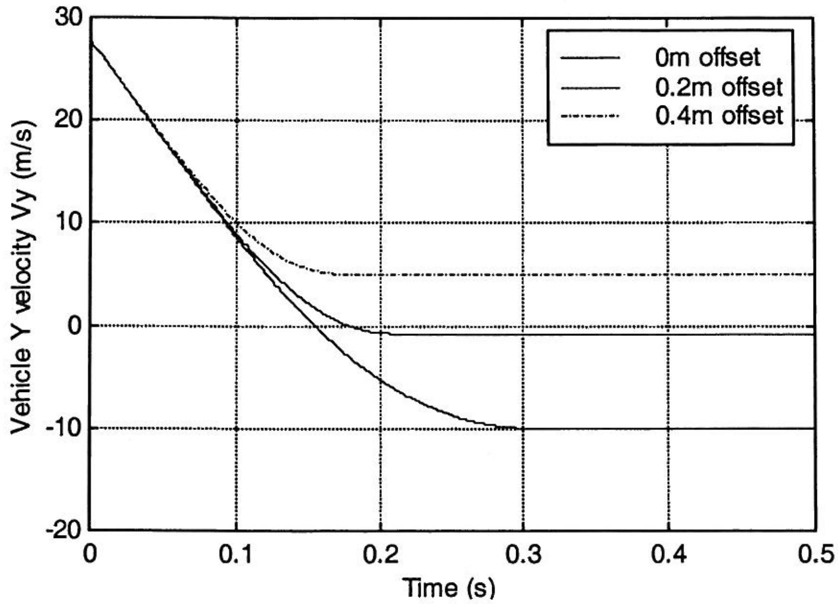


Figure 25. Variation in Vy with offset

An oblique collision is when the impacting vehicle is traveling in a direction that is at an angle to the front surface of the truck and is deflected rather than completely stopped during the collision. This crash mode is of particular interest for the design of a crash severity countermeasure since it manages the collision energy through intentionally deflecting the impacting vehicle, thus reducing the amount of energy that has to be dissipated or absorbed by the vehicle structure.

For this case, the light vehicle's direction of travel is rotated away from the perpendicular through an angle θ, making the travel direction oblique to the front surface of the truck. It should be noted that the yaw ϕ of the light vehicle is independent of θ. Where the yaw angle is 0, the first point on the light vehicle that contacts the truck is the corner of the light vehicle (see Figure 15). This means that the line of action of the contact force is offset from the light vehicle center by a distance equal to half the width of the light vehicle. The width is assumed to be 1.5m (i.e., a=0.75m). It is also assumed that μ=0.35. If the assumption is maintained that the light vehicle is perfectly rigid, after the initial contact, the light vehicle rotates about the point of contact until the entire front surface of the light vehicle is parallel to that of the truck, it then continues rotating so that the other front corner is now the point through which the contact force acts is the other front corner of the light vehicle. This results in a discontinuity in the moment acting on the light vehicle in the simulation. In real world crashes, however, considerable deformation of the vehicle surfaces occurs and the contact force is distributed over a finite surface area rather than concentrated at a point. Therefore, this situation will be modeled by postulating that as the light vehicle rotates, the effective line of action of the contact force moves along the front of the light vehicle such that the offset a varies according to the following equation:

$$a = 0.75 * \tanh(\phi * 8) \tag{20}$$

The hyperbolic tangent function varies between -1 and 1, and Equation 20 results in a proceeding smoothly from -0.75m (contact taking place at the left front corner of the light vehicle) to 0.75m (contact at the right front corner) as ϕ varies from -45° to + 45°. For yaw angles of greater magnitude than 45°, $|a|$ is uniformly equal to 0.75m. This is shown in Figure 26.

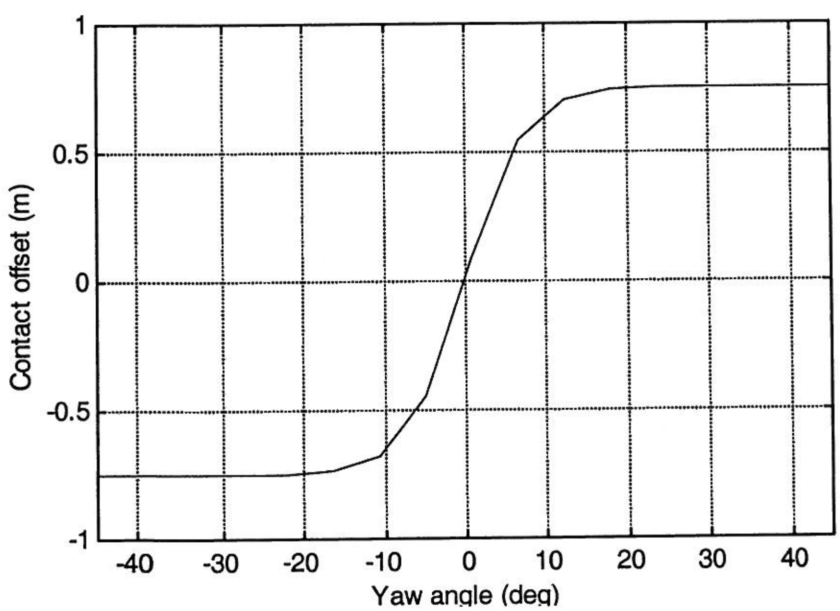


Figure 26. Variation in contact offset with yaw angle

Three different values of θ are considered: 15°, 30°, and 45°. Figure 27 shows the resulting acceleration of the light vehicle for each of these cases and for the case of a direct collision. The peak acceleration magnitude in each of the oblique impacts is less than that for the direct impact.

For the 15° case, the peak acceleration is nearly equal to that for the direct impact. This is due to the fact that the Y component of the acceleration is only a bit lower than that in the direct impact case and the acceleration has an X component (due to friction between the two vehicles). However, the 15° collision is still much less severe than the direct impact since the acceleration quickly drops below that for the direct impact, and the total duration for which the collision forces act on the vehicle (non-zero acceleration time) is also less. The peak acceleration magnitude decreases as the collision becomes more oblique.

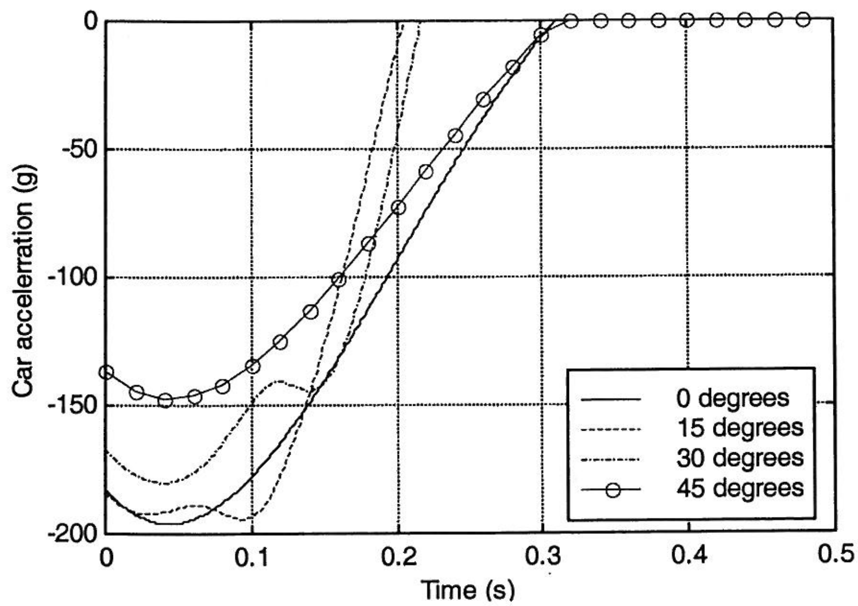


Figure 27. Comparison of acceleration magnitudes for oblique collisions

Figure 28 shows the magnitude of the change in vehicle velocity for each collision.

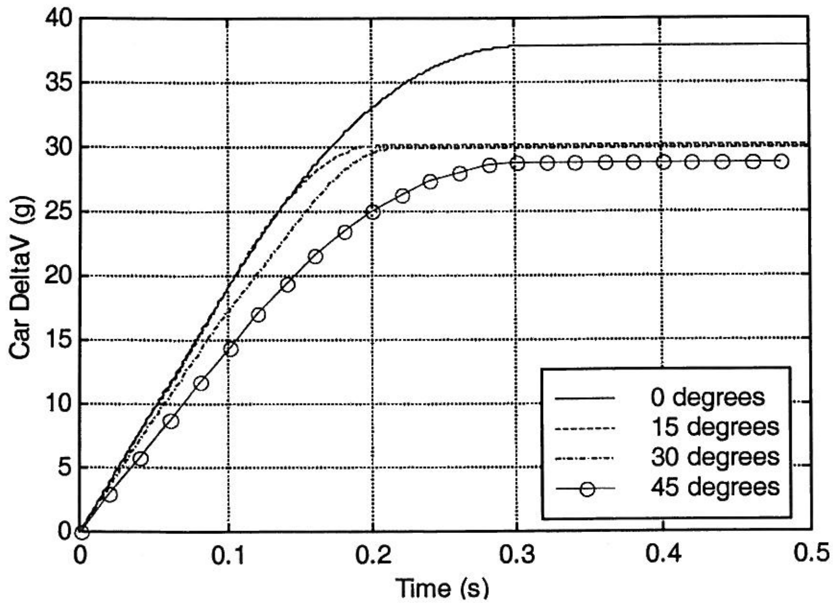


Figure 28. Comparison of vehicle Δv for oblique collisions

Similar to the acceleration results, the Δv for each of the oblique impacts is less than that for the direct impact. In addition, Δv magnitude decreases as the collision becomes more oblique, though the decrease is not very large as the angle increases from 15° to 30°. The reason for this can be understood by examining the X and Y components of the velocity separately.

Figures 29 and 30 show the change in the X and Y components of the velocity of the impacting light vehicle. In each figure a constant has been subtracted from the velocities so that they have a common initial value of 0 to make the graphs easier to understand. The Y component of the vehicle velocity is simpler to interpret, with the change in velocity decreasing with increase in collision angle. In the case of the X component of the velocity, things are more complicated. Of course, the X component of the velocity is uniformly zero for the direct impact case. For oblique impact, the velocity changes most for the 30° case. This is because for the 15° impact, no further change is possible once the velocity becomes 0 (even though the friction force is higher due to greater normal contact force, which can be seen in the greater slope of the velocity graph). For the 30° and 15° impacts, the final X component of the velocity does not go to 0, hence the intuitive expectation that there is a lower velocity change in a more oblique impact is satisfied.

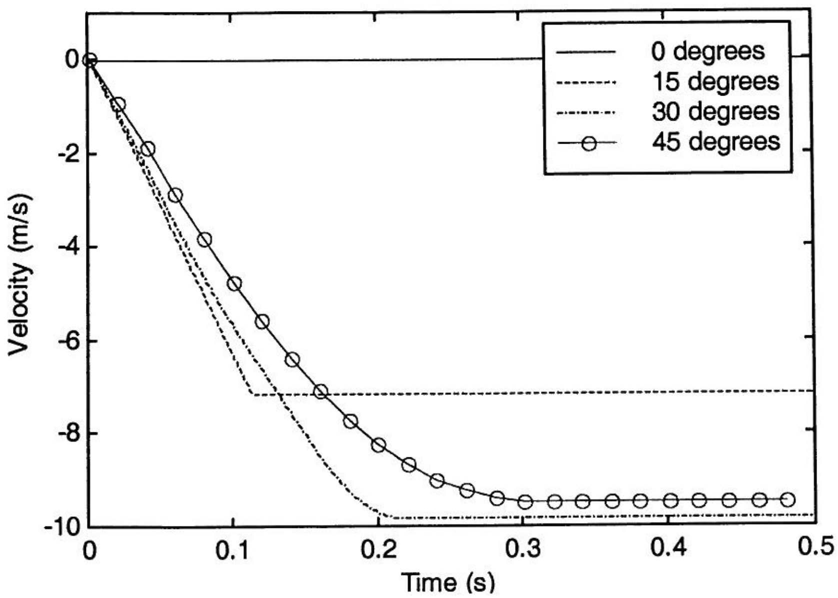


Figure 29. Comparison of vehicle v_x change for oblique collisions

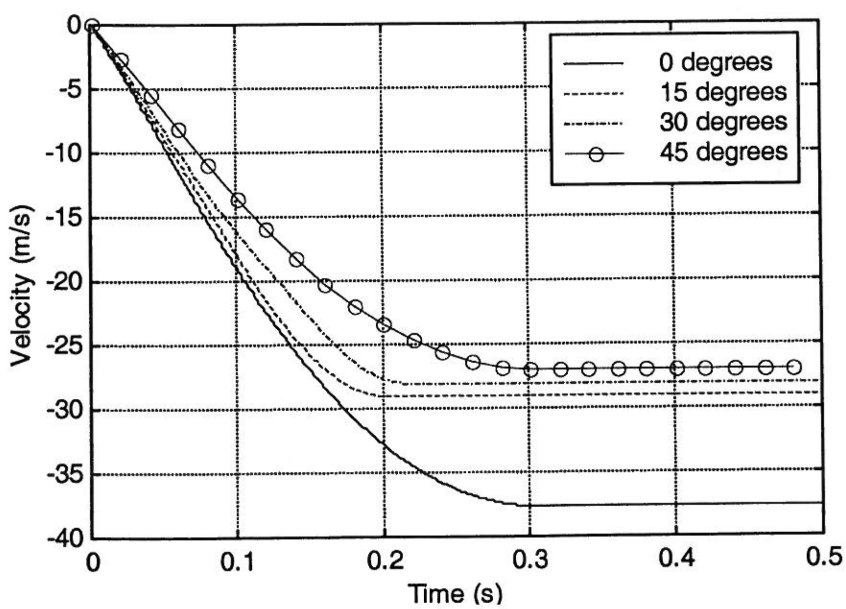


Figure 30. Comparison of vehicle v_y change for oblique collisions

From the above analysis, it is clear that oblique impacts are less severe than head-to-head collisions due to both lower peak accelerations and Δv. The benefits of converting a direct impact into an oblique one will be analyzed further in the section on countermeasures and injury models presented later in this chapter, and quantitative estimates for the improvement in injury outcomes will be derived.

Crash Injury Models

Overview of Injury Risk Factors

It is has been well-established from crash-investigation research and laboratory testing that the risk of serious and fatal injuries to occupants of motor vehicles is a function of several key crash, occupant, vehicle, and restraint factors. Dominant crash factors include the severity, direction, and location of the impact to the occupants' vehicle. Crash severity has two basic components. One is the change in speed of the case vehicle at the moment of impact, which is also referred to as the Δv or Equivalent Barrier Speed (EBS). The other is the deceleration or acceleration history over which the change in speed takes place. If the Δv takes place over a longer period of time because of more crush zone external to the occupant compartment, then the overall deceleration level is reduced, the forces on the occupants will be lower, and the risk of injury will probably be reduced as well.

The direction of the impact to the case vehicle is a critical factor in terms of the patterns and causes of injury, as well as the types of countermeasures that are effective. In frontal crashes, the key to effective occupant protection is to couple the occupant to the vehicle as much as possible by belt and airbag restraint systems so that the occupant will "ride down" the vehicle deceleration pulse with little or no contact with interior components. In an impact to the side of a vehicle where an occupant is seated (referred to as a near-side impact for that occupant), belt restraints offer little or no protection since the primary cause of serious injury is the vehicle sidewall or door moving at high speed into the seated occupant with the mass of the striking vehicle behind it. Similarly, in rear impacts, seat belts and airbags offer little or no protection in most crashes. Rather, the design and impact performance of the vehicle seatback and headrest are important factors in preventing spinal injuries, as well as preventing head injury from ramping up the seatback and contacting vehicle components behind the seat. However, there still is much controversy over the most effective design for seatbacks and headrests for protecting occupants of widely varying size and mass.

The most critical *occupant factors* that affect injury outcome in light vehicle crashes are age and gender, although occupant weight and stature clearly have some effects on some types of injury. In general, young adults have a much higher tolerance to injury than elderly adults, and elderly females are particularly prone to serious skeletal injuries in moderate to severe crashes from all directions. In addition, an elderly occupant is less likely to recover, or to recover as quickly, from serious injuries than is a young person. This is especially true for injuries to the head, chest, and pelvis.

Beyond restraint-system and seat design, *vehicle factors* that have a significant influence on injury outcome include vehicle mass, geometry, and stiffness. Vehicle mass has a significant effect on the crash severity, particularly in crashes with other vehicles. When two vehicles of significantly different mass are involved in a head-on collision, the vehicle with the larger mass experiences a lower crash severity, or Δv, than the smaller vehicle. Thus, the primary effects of vehicle mass are largely accounted for by Δv.

Vehicle geometry primarily affects the location of the impact and damage to the case vehicle, and impact location can therefore have a significant influence on the likelihood, type, and severity of occupant injuries. If a sport utility vehicle (SUV) with a high bumper height strikes a sedan with a lower bumper height in a head-on collision, the damage to the sedan will be primarily above the bumper and the main longitudinal structural members of the vehicle will probably not absorb the bulk of the impact loading. This can have positive effects on occupant injuries because of the greater amount of vehicle crush from softer, above-bumper components. This increases the time over which the Δv occurs and lowers vehicle deceleration levels, which then lowers the forces on the occupants. However, the major concern is that an override situation will result in a greater likelihood and extent of rearward intrusion of case vehicle interior components such as the instrument panel, A-pillars, windshield headers, and steering wheel. These intrusions reduce the available occupant space and increase the likelihood of serious injury from contact with vehicle components. In addition, if the impact is severe enough and the override is significant, the occupant can make contact with the hood of the case vehicle, or even with the exterior of the striking vehicle, which has a high probability of causing serious or fatal injuries.

In *side impacts* with a near-side occupant, the concern over vehicle geometry is even greater than for frontal impacts. The ideal situation in a side impact is for the bumper of the striking vehicle to load primarily down low at the sill, so that the loading and inward intrusion of the door next to the occupant is minimized. If the bumper of the striking vehicle is significantly above the door sill, the door structure, and perhaps the centers of the A- and B-pillars, will be required to deal with energy of the impacting vehicle. Although manufacturers of later-model vehicles have been adding structural reinforcements to increase door strength and comply with FMVSS 213, it is difficult to make a door that is strong enough to deal with the force of a striking vehicle without being impractical in terms of size and weight.

Relative *vehicle stiffness* can also be a significant factor in injury outcome. In a frontal impact, a stiffer vehicle front structure will increase the deceleration of the impact event since the amount of crush and time of crushing are reduced. This can be a negative factor in impacts with larger vehicles or in single-vehicle impacts with large objects such as bridge abutments or large trees. However, most stiff vehicles are also heavier (e.g., pickup trucks and SUVs), and the combination of stiffness and mass is probably a positive factor for the occupants of the stiffer vehicle in collisions with other vehicles of similar or lesser mass. As previously noted, stiffening the side of a vehicle is a positive factor for occupants in near-side impacts since it reduces door intrusion and transfers more of the impact energy into moving the total mass of the struck vehicle (i.e., into the vehicle Δv). With more of the energy used to move the whole vehicle, less energy goes into displacing the side of the vehicle inward, and the speed of this inward displacement is lower, thereby reducing the likelihood of injury to the near-side occupant.

Considerations for Injury Countermeasures in Light Vehicle Impacts with Heavy Trucks

In considering all of the factors that can have a significant affect on occupant injury severity and frequency in motor vehicle crashes, the primary variables that can be addressed from the heavy-truck side of the problem are crash severity and geometry. The geometry issue is one of improving the match-up between structural members of light vehicles and structures of large trucks to reduce intrusions and locations of intrusions into the occupant space of the light vehicle during different types of collisions. Underride bars on the rear ends of truck trailers are aimed at the latter concern for frontal impacts of light vehicles into the rear end of truck trailers, but many of these bars are not strong enough and/or low enough to be very effective, and significant improvements in design are possible.

With regard to affecting the crash severity experienced by a light vehicle in a collision with a large truck, the parameter that can probably be most easily influenced is the deceleration level of the light vehicle. For example, in a head-on crash between a light vehicle and a large truck, the peak and/or average deceleration of the light vehicle might be reduced by pre-crash sensing and deployment of external airbags on the front of the truck. These airbags would increase the time over which the change in speed of the light vehicle takes place by reducing the effective stiffness of the front of the truck. The light vehicle might experience about the same Δv with or without the truck airbag, but the deceleration level might be reduced significantly, and this could have an important effect on reducing injuries to the occupants of the light vehicles.

Unfortunately, the relationship between vehicle deceleration and injury outcome for a given crash Δv is a topic that is not well studied, and there is little in the literature that directly answers this question. A preliminary indication of the effects of changing the light vehicle deceleration pulse on occupant injury outcome for different levels of Δv can be obtained using computer simulations, crash dummy testing, or a combination of the two. Results of these tests and simulations (such as resultant head accelerations, chest compression, spine acceleration, and neck forces and moments) can be used in combination with established injury-risk curves for different body regions based on biomechanical research to estimate the change in injury risk for different crash pulses. Although a comprehensive study of the effects of reducing the magnitude of the peak deceleration experienced by the light vehicle in an impact with a heavy truck is beyond the scope of the current program, a preliminary investigation of these effects has been conducted using a computer model of an optimally restrained driver in a typical passenger sedan. The methods and results of this exercise are described in Section 3.2.4.

Effects of Changing Δv on Injury Outcome in Frontal Crashes

<u>Overview and Sources of Data</u>

In light vehicle/truck collisions, the Δv is greatly influenced by the mass ratio of the two vehicles and therefore is not easily or practically modified. However, this does not mean that countermeasures aimed at reducing the Δv of light vehicles involved in collisions with trucks should not be considered. Because Δv is a measure of the energy delivered to the occupants of the case vehicle, and because energy is proportional to $(\Delta v)^2$, there is much to be gained by reducing the Δv by as much as 10mph. For example, reducing the Δv from 40 to 30mph reduces the crash energy by 44%. Similarly, reducing the Δv from 30 to 20mph reduces the crash energy by 56%. Thus, devices that would cause the light vehicle to be deflected to one side or the other, rather than loaded directly in a head-on crash, could result in significant reductions in crash Δv for the light vehicle. This could reduce injury likelihood as long as this deflection does not result in other impact events or vehicle rollovers that might also be the cause of serious and fatal injuries.

The Δv of light vehicles involved in real-world crashes can often be estimated quite accurately using vehicle crush profile measurements in various reconstruction computer programs, such as WinSmash. Therefore, values for Δv (or EBS in the case of a vehicle striking a rigid object) of the case vehicle are available in established crash/injury databases along with rather detailed documentation about occupant injuries, restraint usage, and other occupant and vehicle factors. The National Automotive Sampling System (NASS) database is perhaps the most widely used source of data for determining relationships between independent variables (crash, occupant, vehicle, and restraint factors) and dependent variables (maximum injury severity to different body regions). This is because the NASS database contains data from a relatively large number of real-world crashes that have been sampled in a manner that allows estimation of the distributions of crash, vehicle, and injury data for the total population. However, it is not necessary to use a probabilistic sample of cases to establish relationships between independent and dependent variables; other databases, such as the in-depth crash-injury database at UMTRI, could also be used for this purpose.

Estimating Effects of Reducing Δv on Injuries Using the Urgency Algorithm

In the NASS database, injury severities are coded using the Abbreviated Injury Scale (AIS). An AIS score from 1 to 6 is assigned to each injury and is associated with the potential threat to life of that injury, as shown in Table 12.

Table 12. Injury severity codes

AIS Code	Level of Injury
0	no injury
1	minor
2	moderate
3	serious - not life threatening
4	severe - life threatening, survival probable
5	critical - survival uncertain
6	maximum - not treatable

The maximum AIS (MAIS) for all injuries sustained by an injured occupant is often used to establish the overall severity of the occupant's injuries.

In recent years, researchers at George Washington University (GWU) have been analyzing the NASS database to develop an injury-prediction model for use in emergency medicine. The model determines the likelihood of injury to occupants of light vehicles for different injury severity levels as a function of different crash, vehicle damage, occupant restraint, and occupant age factors. This tool is called the "Urgency Algorithm" (UA) because the initial version of the UA program was developed in by Malliaris et al. (1997) for the purpose predicting the maximum likelihood of MAIS2+, MAIS3+, MAIS4+, and fatal injuries for frontal crashes. The algorithms have since been refined and updated using larger and more recent sets of cases in the NASS database.

Because the UA program provides the ideal tool to answer the question about the relationship between Δv and injury severity, it has been used for that purpose in the current study. Analyses have been conducted for frontal crash events with a principle direction of force (PDOF) between 10 and 2 o'clock, and the primary area of damage to the front of the vehicle. These analyses have also been conducted for side impacts to the occupant compartment with a near-side occupant.

Probability of Injury Versus Crash Δv in Frontal Impacts

Overview

The UA program has been used to investigate the probability of sustaining MAIS > 2, MAIS > 3, MAIS > 4, and fatal injuries in frontal crashes for front-seat adult drivers and passengers of sedans, pickup trucks, vans, and SUVs when fully restrained by a three-point belt plus airbag, and when restrained by only an airbag in 30-mph, 40-mph, and 50-mph delta-V frontal crashes. In these analyses, injured body regions are those for which occupant restraints in frontal crashes are most effective and include the head, face, neck, chest, abdomen, and spine. In other words, injuries to the upper and lower extremities and pelvis are not considered. These analyses have been conducted for occupants of all ages as well as for occupants aged 20, 40, 60, and 80 years. By comparing the probabilities of injury to the head, face, neck, chest, abdomen, and spine for the different Δv s, the effects of reducing the crash Δv from 50 to 40mph or 40 to 50mph are estimated.

To perform the UA analysis, NASS cases from years 1995-2000 were used. Following data conditioning and variable definition, multivariate logistic regression procedures were used to develop a relational model of the raw data. The coefficients of this model, or weighting factors, were then used to define the probability of injury at a particular severity level based on a series of crash conditions. More specifically, regression coefficients and event information were combined to produce the following relation:

$$w= A_0 + A_1 * \text{Predictor1} + A_2 * \text{Predictor2} + A_3 * \text{Predictor 3} \tag{21}$$

For this analysis, Predictors 1 though 3 are values for Δv, belt usage, and airbag deployment respectively. Δv is a continuous variable input in miles per hour (mph) while belt usage is a dichotomous variable that may be answered as "yes" or "no" for fully restrained or airbag-only restrained, respectively. These A values are coefficients derived using least squares fitting techniques, where A_0 is an intercept value and A_1 through A_3 are coefficients for each included model variable. The value for w is then used to predict the probability of a specified injury outcome using the maximum likelihood relation shown below:

$$P=1/[1 + \exp(-w)] \tag{22}$$

Regression coefficients derived for this analysis are shown in Table 13.

Table 13. Regression coefficients for drivers

Injury Level	Intercept	Δv	Belt	Belt and Airbag
MAIS 2	-3.888	0.131	-0.726	-0.381
MAIS 3	-5.286	0.145	-1.071	-1.021
MAIS 4	-6.507	0.129	-1.295	-1.894
Fatal	-8.178	0.199	-0.834	-1.387

Results for All Drivers

The complete results of these analyses are tabulated in Appendix A, while pertinent results for drivers are described and summarized graphically in this section. Figure 31 shows the probability of different injury levels for fully restrained (belt plus airbag) drivers, with an average age of 35.5 (SD 1.13) years, in frontal impacts at different Δv s. As noted, the probability of injury is higher for lower injury severities, and the probabilities of drivers sustaining MAIS 4 and higher injuries are quite low (< 5%), even for Δv s of 40 and 50mph. However, at all injury levels, the likelihood of injury decreases significantly with decreasing Δv.

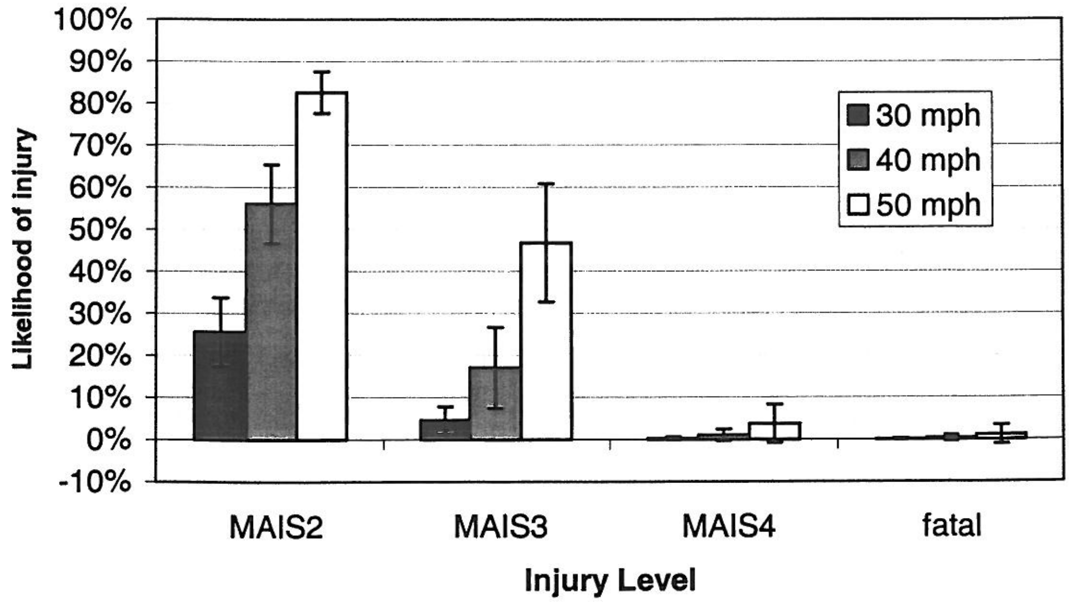


Figure 31. Likelihood of different injury levels for the head/neck/chest/abdomen/spine of fully restrained drivers in frontal crashes of 30, 40, and 50mph Δv

Figure 32 shows the percent reductions in the probability of injury at the different injury levels for fully restrained drivers when the frontal-crash Δv is reduced from 50 to 40mph, and from 40 to 30mph. Importantly, reducing Δv from 50 to 40mph or from 40 to 30mph reduces the likelihood of MAIS > 3 and greater injuries to fully restrained drivers by 60 to 70% or more.

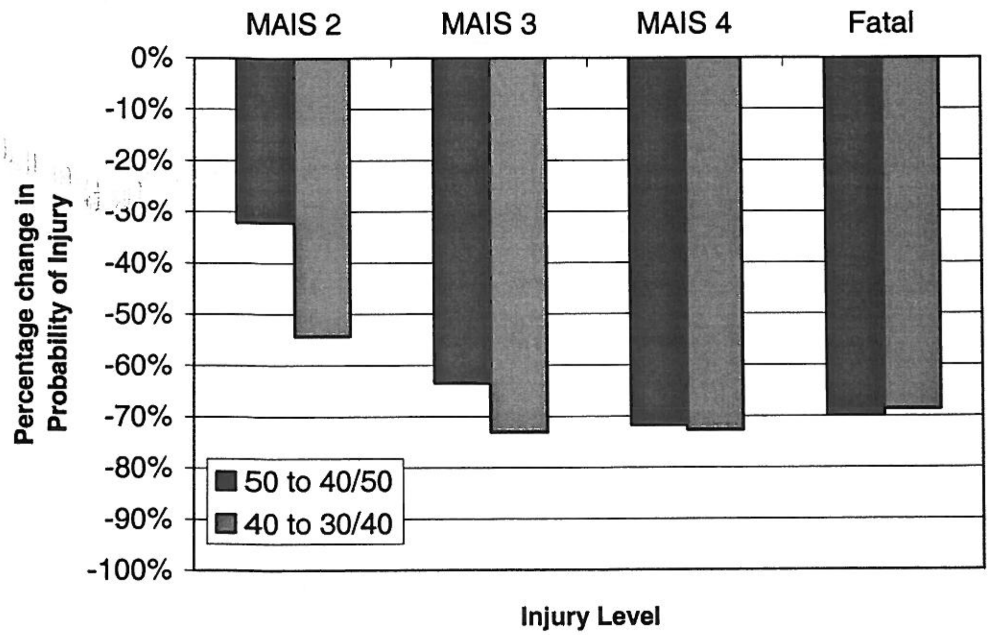


Figure 32. Percentage change in probability of injury for the head/neck/chest/abdomen/spine when Δv is reduced for fully restrained drivers in frontal impacts

The probabilities of injury at different MAIS levels were also calculated for airbag-only-restrained drivers for which the mean age is 32 years (SD = 1.81); these are shown in Figures 33 and 34. The reductions in injury likelihood are similar to those for fully restrained drivers, but the magnitudes of injury probabilities are significantly higher for airbag-only-restrained drivers, especially for the higher injury levels.

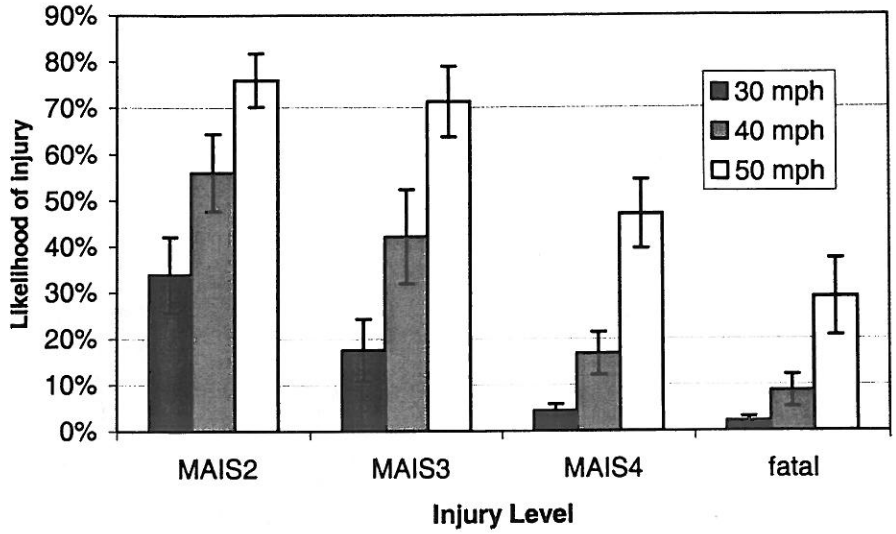


Figure 33. Likelihood of different injury levels for the head/neck/chest/abdomen/spine for airbag-only-restrained drivers in frontal crashes of 30, 40, and 50mph Δv.

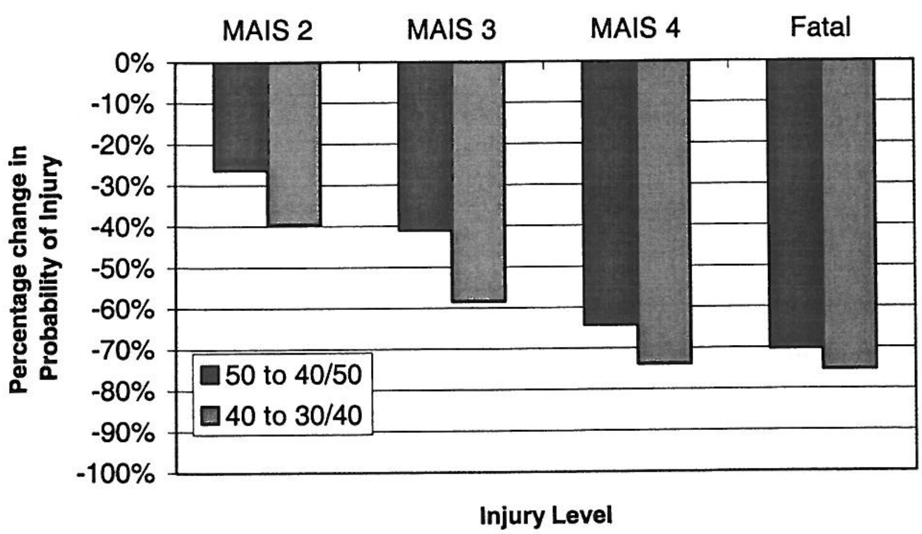


Figure 34. Percentage change in probability of injury for the head/neck/chest/abdomen/spine when Δv is reduced for airbag-only-restrained drivers in frontal impacts.

Figure 35 shows the ratio of the injury risks for airbag-only-restrained drivers in frontal crashes relative to the injury risks for belt-plus-airbag-restrained drivers in frontal crashes. The significant benefit of belt-restraint use is seen for all injury levels and crash severities, but is particularly beneficial at MAIS 4 and fatal injury levels, where injury risk for airbag-only-restrained drivers is 12 to 25 times higher than for drivers restrained by both the airbag and a three-point belt.

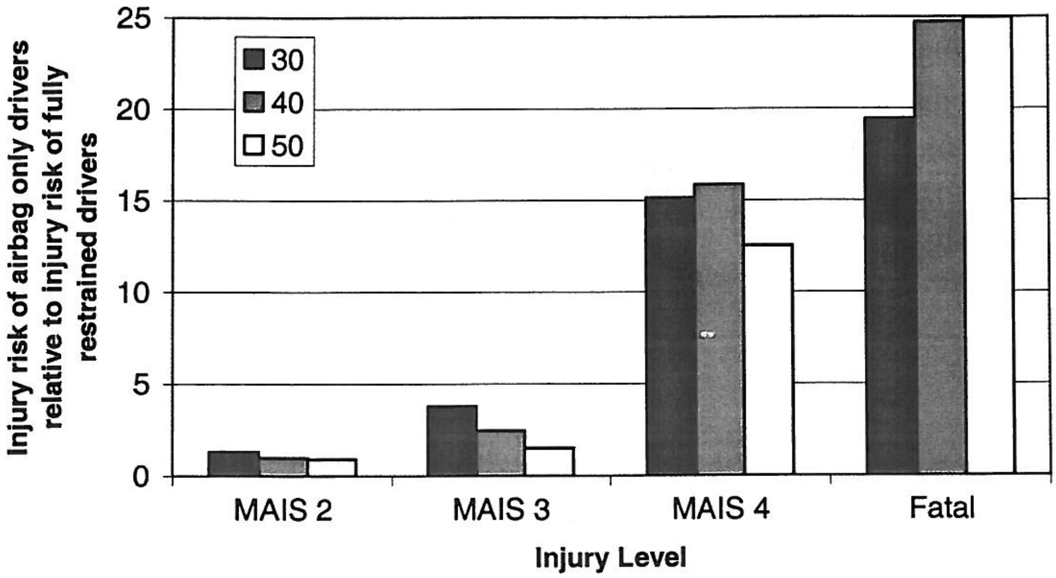


Figure 35. Ratio of the injury risk of airbag-only-restrained drivers compared to injury risk of fully restrained drivers.

Effects of Driver Age

Analysis of crash databases have typically shown that injury likelihood is strongly related to occupant age. As an example, Figure 36 shows the injury likelihood in frontal crashes at different AIS levels at Δv of 40mph for 20, 40, 60 and 80-year-old fully restrained drivers. At all injury levels, the probability of injury increases with increasing occupant age. Similar trends are seen for Δv s of 30 and 50mph.

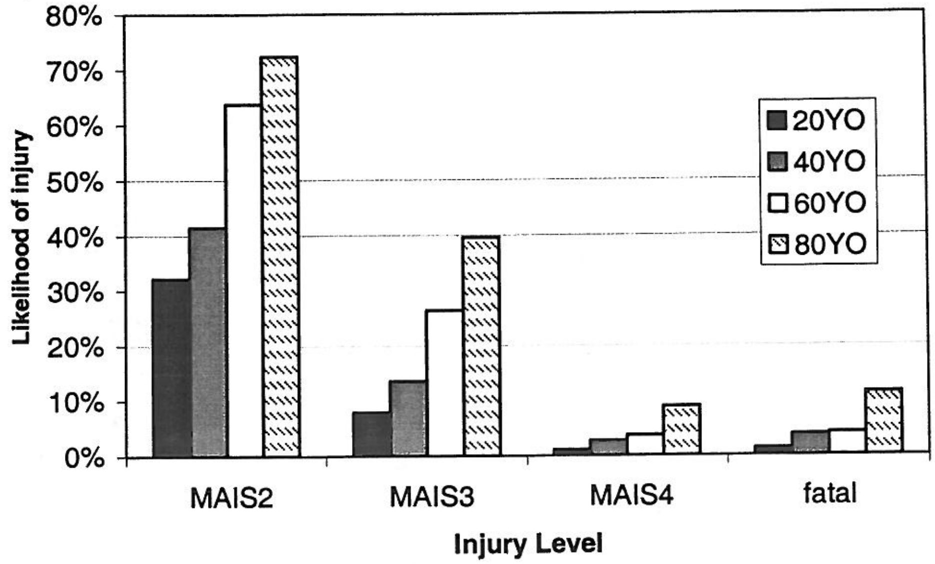


Figure 36. Differences in injury likelihood for 40mph frontal impact as a function of age for fully restrained drivers.

The percentage change in probability of injury (shown in 0) expected to result from decreasing Δv was also calculated for fully-restrained drivers of different ages in frontal impacts. Figure 37 shows the results when Δv is changed from 50 to 40mph, and Figure 38 shows the results when Δv goes from 40 to 30mph. In general, the reduction in injury likelihood is similar for all ages and ranges from about 60 to 70% for MAIS > 3. The reductions are lower for MAIS = 2 injuries, especially going from 50 to 40mph Δv, and are seen to be lower for older drivers at this injury level.

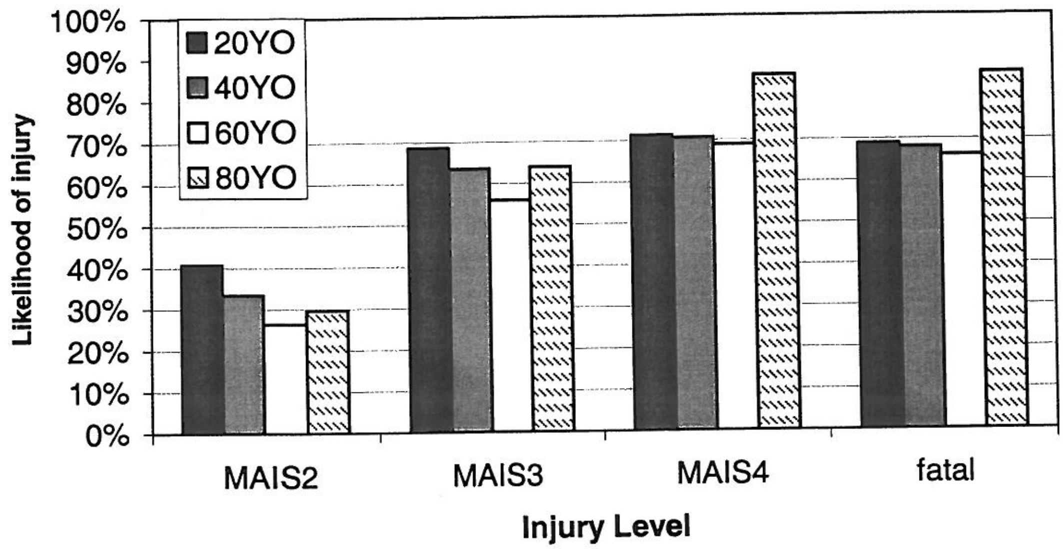


Figure 37. Percentage change in probability of injury for fully restrained drivers when Δv is reduced from 50 to 40mph, controlling for driver age.

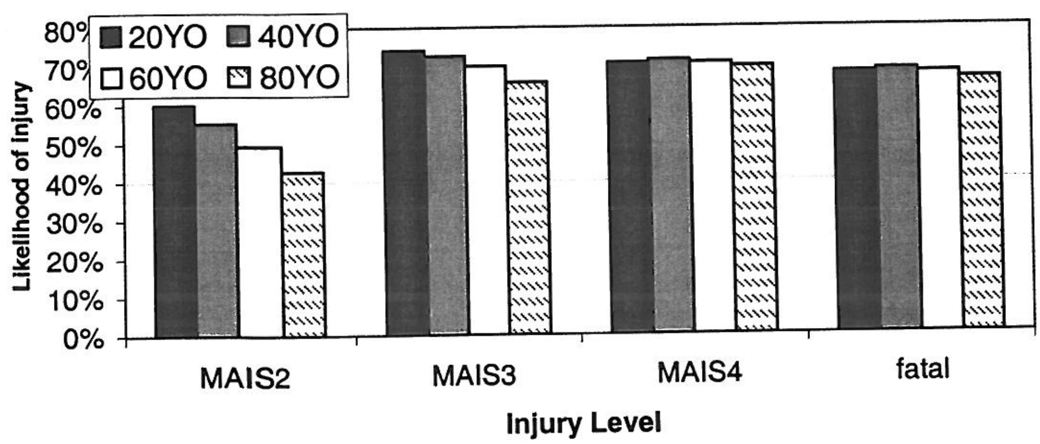


Figure 38. Percentage change in probability of injury for fully restrained drivers when Δv is reduced from 40 to 30mph, controlling for driver age.

Summary of Effects of Reducing Δv in Frontal Impacts

The results of the Urgency Algorithm analysis of NASS on the relationship between injury risk and Δv in frontal impacts indicate that:

1. The likelihood of injury at all MAIS levels decreases significantly with decreases in Δv from 50 to 40mph and from 40 to 30mph for both fully-restrained and airbag-only-restrained drivers.
2. At MAIS > 4, injury risk for airbag-only-restrained drivers is 12 to 25 times higher than the injury risk of drivers restrained by both the airbag and three-point belt.
3. Reducing Δv by 10mph reduces injury probability at the MAIS > 3 by about 60 to 70% for fully restrained drivers and for airbag-only-restrained drivers.
4. Reducing Δv from 50 to 40mph generally reduces injury risk by a greater percentage than reducing Δv from 40 to 30mph for fully restrained or airbag-only-restrained drivers.
5. The risk of injury increases with age for all Δv s and injury levels, but the effects of reducing Δv are similar for all ages at MAIS > 3.

Relationship Between Vehicle Deceleration and Injury Risk

As previously noted, the relationship between vehicle deceleration level and injury outcome for a given crash Δv is not well studied and answers are not readily available in the injury-biomechanics literature. However, the effects of reducing the magnitude of vehicle deceleration on occupant injury outcome for different levels of Δv can be explored using computer simulations and/or crash dummy testing. Results of these tests or simulations can be used with established injury-risk curves for different body regions to estimate the change in injury risk for different crash pulses.

Today, vehicle frontal crash testing is conducted using Hybrid III anthropomorphic test dummies, or ATDs. ATDs have been designed to represent human occupants in 30mph frontal crashes, and instrumentation is provided to measure response parameters, such as head and chest accelerations, that can be associated with the probability of injury to humans. While most testing uses an ATD representing an adult mid-size male with a stature of 5' 9" and a weight of about 170lbs, other Hybrid III dummies are available that represent large (90th percentile) adult males, small (10th percentile) adult females, and 10, 6, and 3-year-old children. Computer model versions of the Hybrid III mid-size male dummy have also been developed, and are used in a crash-victim simulation program called MADYMO. This program can be used to explore the kinematics (movement) and kinetics (accelerations and forces) of ATDs under different impact and occupant-restraint conditions and thereby estimate the likelihood of injury to motor-vehicle occupants in different types and magnitudes of impacts.

Injury Predictors

Different injury measures are used with both ATD testing and computer simulations to estimate the risk of injury to different regions of the body. For head injuries, the HIC or head injury criterion is used. This value is computed by moving a 15ms window of integration time over the resultant of X-, Y-, and Z-axis head accelerations raised to the 2.5 power to that portion of time that produces the highest HIC value. The relationship between the probability of head injury of AIS > 4 as a function of HIC is shown in Figure 39. A HIC value of 1,000 corresponds to an 18% risk of severe (AIS> 4) head/brain injury (Eppinger et al., 2000).

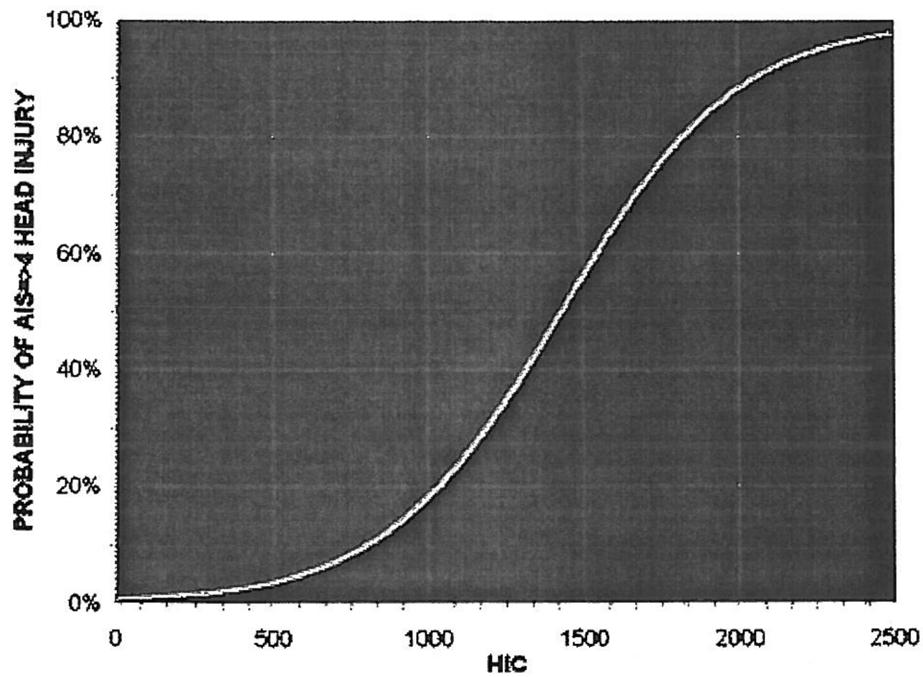


Figure 39. Probability of severe or greater head injury (AIS > 4) as a function of 15ms HIC.

To estimate the likelihood of thoracic injury, ATD thoracic-spine acceleration and chest compression are calculated. Currently, only an estimated injury risk curve for chest (i.e., spine) acceleration (Figure 40) is used in federal safety requirements. A chest acceleration of 60g for 3ms (i.e., 3ms chest-g clip) corresponds to a 20% risk of severe thoracic injury (Eppinger et al., 2000). For chest compression, separate injury risk curves have been estimated for belt loading and distributed loading (i.e., airbag loading). For a mid-size male, a deflection at the sternum under distributed loading of 47.7mm corresponds to a 5% risk of AIS > 3 injury, while a deflection of 64.3mm corresponds to a 5% risk of AIS > 4 injury. For belt loading, a sternum deflection of 47.7mm corresponds to a 48% risk of AIS > 3 injury, while 64.3mm corresponds to 80% risk of AIS > 3 injury (Mertz 2002).

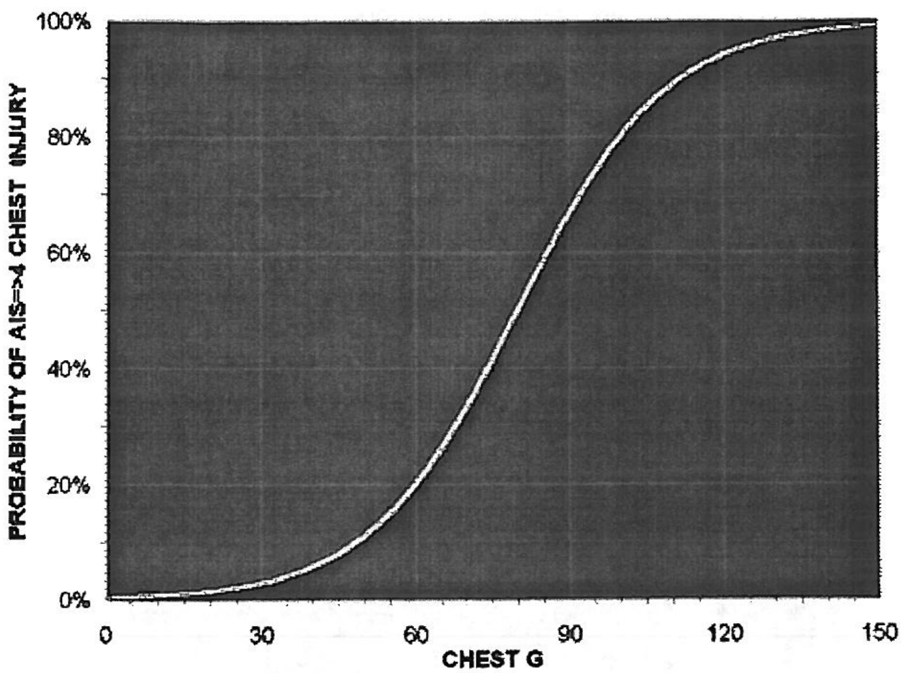
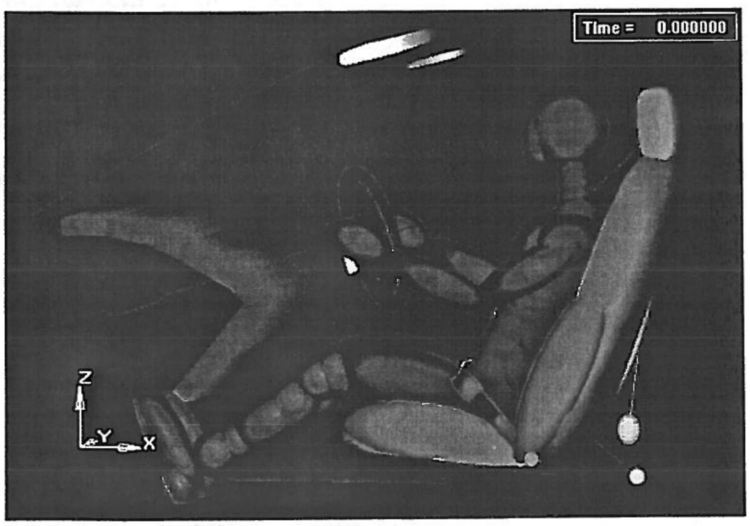


Figure 40. Probability of severe thoracic injury as a function of chest acceleration.

To evaluate neck injury potential, moments and forces at the junction between the ATD head and neck are often measured using a six-axis upper-neck load cell. A measure to evaluate injury potential under combined bending and axial loading, called Nij, was developed by NHTSA (Eppinger et al., 2000), where the i subscript corresponds to tension or compression, and the j signifies bending in flexion (forward) or extension (rearward). An Nij value of 1.0 corresponds to a 15% probability of serious injury (i.e., AIS > 3). Injury risk curves for pure axial tension and compression are not used by NHTSA in federal regulatory testing, but values of 4170 N and –4000 N, respectively, are considered to be maximum limits. Analysis by Mertz (2000) suggests that this tension value corresponds to a 55% risk of AIS > 3 neck injury. Examples of AIS 3 neck injury include vascular injury, minor spinal cord contusion, and vertebral fracture without cord damage.

Model Configuration and Inputs

A preliminary examination of the effect of changing peak deceleration while holding Δv constant was conducted using computer simulations of frontal crashes. Figure 41 illustrates the MADYMO model used to perform the simulations. The model consists of a multi-segment representation of the Hybrid III midsize male ATD restrained by a three-point belt and airbag in the driver position of a typical sedan-type vehicle. The model also includes a shoulder-belt load limiter that prevents shoulder belt loads from exceeding 3.5 - 4.0kN, and a belt pretensioner that snugs the belts on the occupant prior to forward movement.



(a) MADYMO model at time zero.

(b) MADYMO model at 50ms.

(c) MADYMO model at 100ms.

Figure 41. MADYMO Crash simulation.

Figure 42 shows the three pairs of vehicle frontal-crash deceleration pulses used in the study, while Figure 43 shows the corresponding changes in velocity or Δv s. As indicated, peak vehicle deceleration levels of 30 and 20g were used with Δv s of 30, 40, and 50mph. The duration of the deceleration pulse is necessarily increased 50 to 80ms when the peak deceleration value is decreased from 30 to 20g at each Δv .

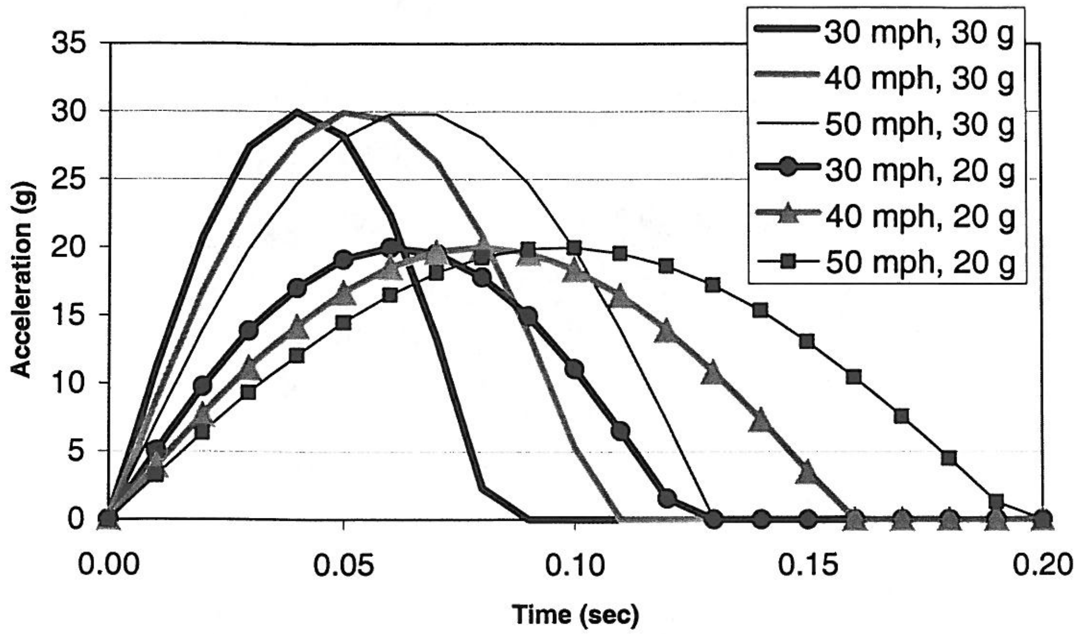


Figure 42. Vehicle deceleration pulses used in MADYMO analysis.

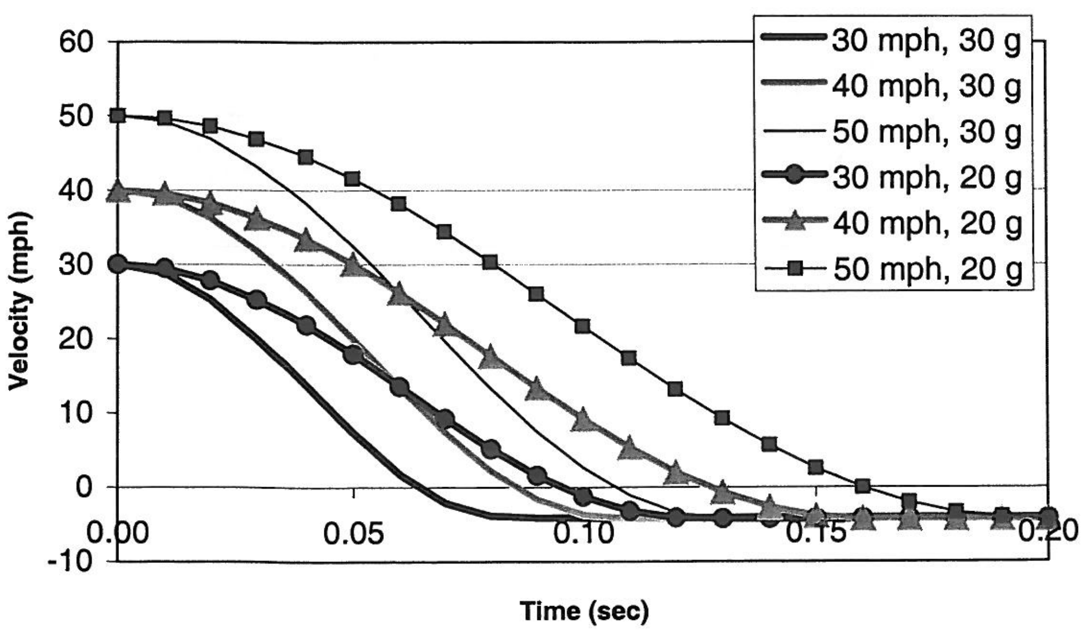


Figure 43. Vehicle velocity profiles used in MADYMO analysis.

Effects of Changing Δv on Injury Outcome in Side-Impact Crashes

As previously noted, when a vehicle is struck in the side, the Δv of the vehicle center of mass caused by the impact has less correspondence to injury risk than it does in a frontal impact. This is because injuries in side impacts are largely due to direct contact with a near-side occupant by the vehicle door or side wall, and it is the speed of the door or side wall that is most important. Even so, the NASS database can be used to gain some insights into the effects of countermeasures that might reduce the struck vehicle Δv when the vehicle is impacted in the side by a large truck.

The effect of Δv on injury likelihood in side impacts was therefore calculated using the Urgency Algorithm described previously for frontal-impact analysis. Since near-side occupants are the most likely to be injured whether or not they are wearing a belt restraint, this analysis used both belt-restrained and unbelted drivers in near-side crashes in which the striking vehicle contacted the left side of the case vehicle. In addition, the type of crash was limited to the T-type configuration, where the striking vehicle contacts the vehicle in a manner that results in direct-contact damage to the occupant compartment. The analysis was performed for Δv s of 20, 30, and 40mph since the distribution of Δv s at which serious injuries occur tend to be lower than for frontal impacts.

The mean age of drivers in these near-side crashes is 36.2 (SD = 0.90) years. The results for drivers at different injury levels are shown in Figure 44. As indicated, injury likelihood increases dramatically with increasing Δv at all injury levels.

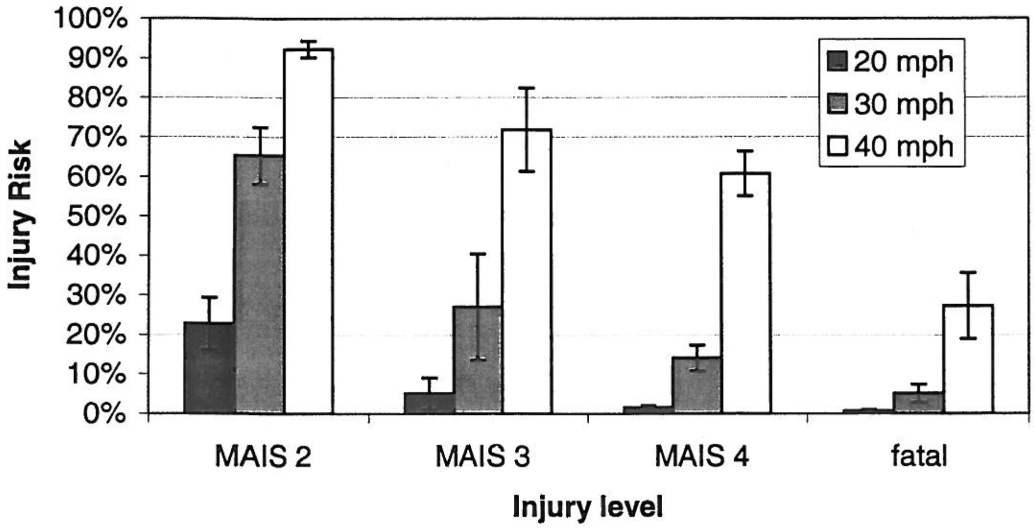


Figure 44. Likelihood of different injury levels for drivers in T-type near-side 20, 30, and 40mph delta-V crashes.

Figure 45 shows the possible reduction in injury risk that results from reducing Δv in near-side impacts. As a percentage of the initial likelihood, reducing Δv by 10mph leads to significant reduction in injury likelihood over all injury levels. Reducing Δv from 40 to 30mph reduces the likelihood of MAIS > 3 injuries from 60+ to almost 90%. Thus, the results from the analysis of NASS for T-type side impacts to near-side drivers suggest that any truck countermeasure that reduces the side-impact Δv to light vehicles would lead to a substantial decrease in injury risk to near-side occupants at all injury levels.

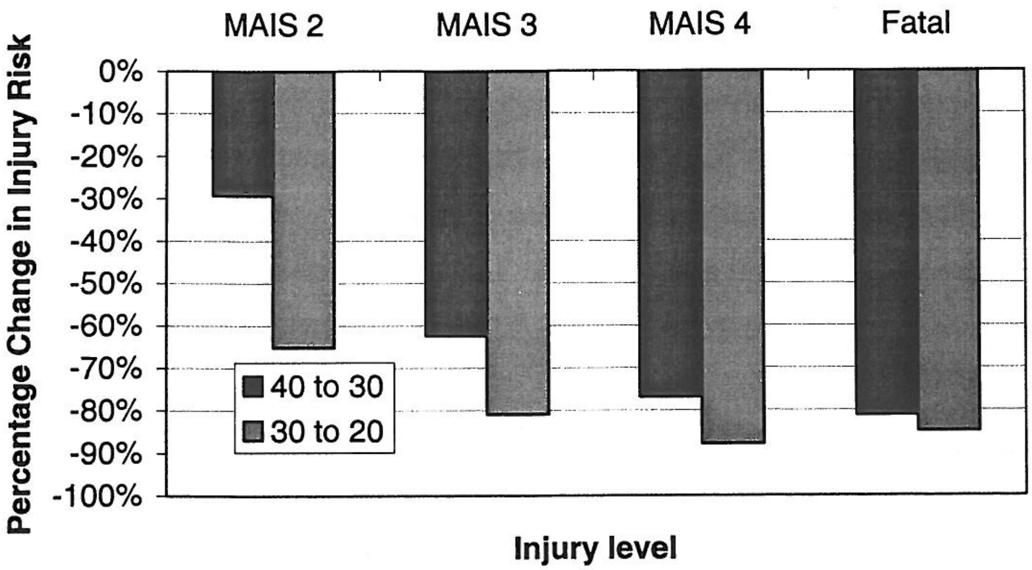


Figure 45. Percentage change in probability of injury when Δv is reduced in side impacts.

Summary and Discussion

Analysis of real-world crash/injury data from the NASS database as well as computer simulations have been used to estimate the potential benefits of countermeasures that would reduce the crash severity to light vehicles involved in frontal and side impacts with heavy trucks. The Urgency Algorithm developed by Malliaris (1997) and improved by researchers at GWU has been used to examine the benefits of reducing the change in light vehicle speed during a crash, or Δv, while computer simulations have been used in an attempt to determine the benefits of reducing the magnitude of the light vehicle deceleration.

The computer simulations used to investigate the separate effects of reducing the deceleration levels of light vehicles involved in frontal collisions used a driver occupant with optimal restraint conditions of three-point belt plus airbag, with the belt restraint having both pretensioner and load-limiter features. The results of these simulations agree with the NASS analysis in showing that the probabilities of belt-plus-airbag restrained drivers sustaining serious and severe injuries to the head, neck, and chest are quite low. In spite of low probabilities for these conditions of the simulations, the results also show that significant reductions in the likelihood of serious and severe injuries result by reducing the magnitude of the vehicle deceleration.

Although the modeling results agree with the real-world data in predicting low probabilities of serious and severe injuries, they differ from the NASS data in that they do not show significant reductions in the likelihood of serious and severe head, chest, and neck injuries with reductions in Δv. It is believed that this is partly because of the optimal restraint conditions used, such that the loading on the chest, neck, and head were not significantly affected by higher Δv s as long as the deceleration levels were maintained constant. Additional simulations should be conducted with different restraint conditions to more closely examine this issue.

In the analysis of the NASS data for the effects of reducing Δv, the noted reductions in injury likelihood are probably also due to the accompanying reductions in vehicle deceleration. In the real world, frontal crashes with higher Δv s also have higher deceleration levels so that in analyzing the NASS data for the effects of reducing Δv, one is also including the effects of reducing deceleration.

To examine this relationship between deceleration and Δv further, the NHTSA database of staged vehicle crashes was queried to find barrier crash data from FMVSS 208 compliance tests (30mph) and NCAP tests (35mph) performed on the same model vehicle. Results are available for both types of tests for seven different vehicles with model years 1997 or later.

Table 14 lists the vehicles and the peak decelerations from the compliance and NCAP tests. The peak decelerations range from 22.6 to 35.2g in the 30mph compliance tests and from 23.7 to 40g in the 35mph NCAP tests. The mean value for these seven vehicles is 28.3g for 208 tests and 32.9g in NCAP tests. The differences between the two tests for a given vehicle range from 2.1g in a Pontiac Grand Am to 9g in a Saturn SL1. The mean difference is 4.6g. These data exhibit a range of 12 to 16g for a given change in velocity due to different vehicle stiffness.

Table 14. Vehicle Decelerations from FMVSS 208 Compliance and NCAP Tests.

	Peak Acceleration (g)		
	Compliance	NCAP	Difference
97 Pontiac Grand Am	25.8	27.9	2.1
98 Chevrolet Venture	20.7	23.7	3
97 Mitsubishi Galant	28	31.1	3.1
98 Jeep Grand Cherokee	35.2	39.6	4.4
98 Nissan Altima	31.2	36.6	5.4
97 Ford F150	34.5	40	5.5
99 Saturn SL1	22.6	31.6	9
Mean	28.3	32.9	4.64

Since both compliance and NCAP tests involve impacting the vehicle into a rigid barrier, the decelerations are entirely dependent on the stiffness and mass characteristics of the vehicle. If the assumption is made that the decelerations of these seven vehicles approximate the range of deceleration levels that occur in real-world 30mph impacts, the mean peak deceleration of 30mph NASS frontal crashes would be about 28g. If the mean change in deceleration is 4.6g for an increase in Δv of 5mph, the mean deceleration at 40 and 50mph Δv s would be about 37 and 48g, respectively. This suggests that much of the increase in injury risk with increasing Δv from the NASS analysis is due to increases in vehicle decelerations. These observations also suggest that the deceleration levels used in these initial simulations are unrealistically low for the 40 and 50mph runs.

Conclusions and Recommendations

The results from analyzing real-world crash/injury data and from performing computer simulations indicate that significant reductions in the likelihood of severe and fatal injuries to restrained front-seat occupants of light vehicles can be appreciated by implementing countermeasures on large trucks. These countermeasures will reduce the Δv and/or the deceleration of the light vehicle. Because of the relationship between Δv and deceleration level in real-world crashes and the absence of deceleration data in crash database, it is not possible to determine the benefits of countermeasures that reduce only the Δv of the light vehicle. However, it is likely that any countermeasure that reduces Δv will also produce the expected reduction in deceleration. While the results for the computer simulations conducted are preliminary and for relatively optimal driver restraint conditions, they suggest that the benefits to countermeasures that reduce the deceleration of the light vehicle without reducing the Δv would be significant. However, further exploration of this issue through additional modeling with less-than-optimal restraint conditions and deceleration levels that are more appropriate to the Δv levels should be conducted.

CHAPTER 5: COUNTERMEASURES

It is clear that the relative aggressivity of heavy trucks in collisions with light vehicles arises from three types of mismatches between the heavy truck and the light vehicle: (ii) mass, (ii) geometric (where the truck structure is at a greater height than that of the light vehicle resulting in over/underride), and (iii) structural (the greater stiffness of the truck structure results in the bulk of the collision energy being dissipated through crush of the lighter vehicle). By definition, little can be done about the mass disparity. However, the other types of mismatches can be decreased resulting in corresponding decreases in the severity of the damage inflicted upon the lighter vehicle and its occupants.

The preceding chapters of this document presented detailed analyses of the types and frequencies of heavy truck/light vehicle crashes, the severity and numbers of injuries suffered by the occupants of those vehicles, the physics of the collision process, and the mechanisms that relate the collision variables to the injury levels of the vehicle occupants. Based on these analyses, this chapter will focus on proposing and evaluating countermeasures that have the potential to provide the greatest benefit in terms of improving crash injury outcomes.

Front Underride Prevention

The analysis of heavy truck/light vehicle crash data shows clearly that the greatest number and crash severity outcome occurs in cases involving collisions with the front of the heavy truck. Such collisions account for almost 57% of fatal injuries and 35% of A injuries, in spite of making up less than 25% of all collision types. Further, it is clear that the incidence of underride in collisions between heavy trucks and light vehicles is substantial. Whether the data are from Australia, Great Britain, Indiana, Michigan, Texas, the U.S. as a whole, or a sample of cases from New York, every study found significant incidence of underride regardless of the side of the truck the light vehicle struck. (A summary of results from these studies has been presented in the review of truck crash related literature.) Many of these studies also concluded that substantial gains could be made in improving crash outcomes by preventing underride, with estimates ranging from 21 to 39% reduction in the number of fatalities. In this section, the benefits of preventing front underride in heavy truck/light vehicle collisions on the U.S. road system will be calculated. It should be noted that some elements of the data are not directly available (e.g., GES does not code for the occurrence of underride) and have to be estimated or inferred from other information or studies. However, the calculations presented here will demonstrate the basic methodology and provide an estimate of the reduction in crash severity possible through the use of underride guards.

Table 15 summarizes the estimates of the incidence of underride. There is some variation from study to study. But it is clear that underride occurs in a very substantial fraction of fatal truck involvements. To calculate the effect of front underride on aggressivity directly from crash data, knowledge of the incidence of front underride is required in crashes of all severities. This estimate is not available in GES data (or from other sources). However, an estimate can be made of this contribution to aggressivity (or conversely the reduction) through the use of the heavy truck/light vehicle crash data that was presented earlier in this document. The cases of the front same direction and front opposite direction crashes will be successively considered. For the purposes of these calculations, the median estimate of 62% will be used for fatal front underride incidence (Table 15).

Table 15. Summary of underride incidence by truck area involved.

Study	Rear	Side	Front
Blower, 2001	60-70%	N.E.**	N.E.
Minahan and O'Day, 1977	90%	75%	N.E.
Ranney, 1978*	63%	22%	N.E.
Riley and Bates, 1980	80%	44%	51%
Braver, 1998	79%	65%	62%
Thomas and Clift, 1991	N.E.	N.E.	88%

* Ranney included crashes with all injury outcomes. Other studies are for fatal crashes only.

** No estimate

Table 5 (Chapter 2) shows that there were 693 fatal front same-direction crashes in the three-year period from 1996 to 1998. The 62% underride incidence implies that approximately 430 of these had underride as a contributing factor in the crash outcome.

Figures 53 and 54 in Appendix C show estimates of relative velocity in fatal heavy truck/light vehicle collisions from a study performed by UMTRI for Sandia National Laboratories. It should be noted that the estimates cover only a small number of collisions (75) and thus are subject to the problems associated with small sample sizes. However, these estimates represent the best available and serve to demonstrate the calculations. In crashes with a large mass mismatch between the colliding vehicles, the Δv of the lighter vehicle is a large proportion of the relative velocity (Chapter 4, Collision Models Section). Therefore, it is assumed that this is the velocity change undergone by the light vehicle in these collisions. This slightly overestimates the Δv, which in turn underestimates the benefit of underride prevention (which has the advantage of making the calculations presented here somewhat conservative or cautious). It is further assumed that when underride is prevented, the resulting crash is simply transformed into an equivalent head-on barrier crash (again, this a conservative assumption since some proportion of these crashes will be offset or oblique resulting in less severe collisions).

The Crash Injury Models Section of Chapter 4 presented the relationship between vehicle Δv and the likelihood of fatalities. In Appendix D, Tables D-9 and D-10 present this relationship (in the form of probability of fatality for a given Δv). Using the data from Tables 5, D-8, and D-9 and Figure 54, Tables 16 and 17 can be constructed. These two tables compare the number of fatalities that actually occurred at a given Δv to the number that would be predicted to occur if underride were prevented and the resulting crash was assumed to then become a barrier impact. For belted and airbag restrained occupants, the results show that 1,119 fatalities could be prevented, while a reduction of 807 fatalities is predicted in the case of occupants who do not use their seatbelts but are protected only by the airbag. In percentage terms this ranges from 27 to 37% of the total number of fatalities in front opposite-direction crashes. It should be noted that the calculations probably overestimate the reduction in fatalities at low velocities (0-30mph) since the low number of fatalities in that range in the crash database results in a likelihood that is rounded down to zero. However, since the number of fatalities at these velocities is likely to be small, this overestimate is not likely to be very great. In all likelihood, the predicted savings are underestimated at the higher velocities since the assumption is made that all the relative velocity is manifested as vehicle Δv, while some proportion of the crashes are likely to be offset or oblique crashes. As can be seen from the crash model analysis (Chapter 4), this results in significantly less severe crash outcomes.

The collision and injury models and the crash data indicate that significant reductions in fatalities could be achieved through preventing underride of the impacting light vehicle.

Table 16. Actual fatalities vs. predicted fatalities if underride is prevented (front opposite-direction crashes) and occupant is restrained by both three point belt and airbag.

Δv	Percent of collisions	P(fatal)	Fatalities with underride	Predicted fatalities without underride
0-10	0.0	0.00	0	0
10-20	1.5	0.00	28	0
20-30	1.5	0.00	28	0
30-40	3.0	0.01	56	1
40-50	9.5	0.04	176	7
50-60	4.0	0.08	74	6
60-70	13.0	0.13	241	31
70-80	4.0	0.21	74	16
80-90	5.0	0.29	93	27
90-100	11.0	0.38	204	78
100-110	16.0	0.49	297	146
110-120	11.0	0.61	204	125
120-130	14.5	0.74	269	199
130-140	4.0	0.88	74	65
140-150	2.0	1.00	37	37
Total	100		1857	738

Table 17. Actual fatalities vs. predicted fatalities if underride is prevented (front opposite-direction crashes) and occupant is restrained by only airbag.

Δv	Percent of collisions	P(fatal)	Fatalities with underride	Predicted fatalities without underride
0-10	0.0	0.00	0	0
10-20	1.5	0.00	28	0
20-30	1.5	0.00	28	0
30-40	3.0	0.08	56	4
40-50	9.5	0.18	176	32
50-60	4.0	0.29	74	22
60-70	13.0	0.40	241	97
70-80	4.0	0.49	74	36
80-90	5.0	0.57	93	53
90-100	11.0	0.64	204	131
100-110	16.0	0.70	297	208
110-120	11.0	0.74	204	151
120-130	14.5	0.79	269	213
130-140	4.0	0.89	74	66
140-150	2.0	1.00	37	37
Total	100		1857	1050

Managing Collision Energy

In heavy truck/light vehicle collisions, the burden of dissipating the energy of the vehicles involved in the collision is mostly borne by the lighter and less stiff vehicle. This results in the occupants of the light vehicle undergoing a large Δv with associated high levels of acceleration. In addition, the occupants of the light vehicle have only a small space or no survival space due to crushing of the light vehicle structure. If some means other than the deformation of the light vehicle structure could be provided to dissipate a portion of the collision energy, the survival prospects of the occupants could be greatly improved. Two primary means of such energy dissipation or management in heavy truck/light vehicle collisions are: (i) attenuation of the collision forces (or acceleration levels) by increasing the time over which the collision Δv takes place through the use of softer (less stiff), energy absorbing truck structures; and (ii) deflection of the striking automobile such that not all the energy of the light vehicle is dissipated in the collision. The possible benefits of these approaches will be estimated for managing the collision energy in the context of the U.S. road system.

Reducing Vehicle Deceleration Through Energy Absorbing Truck Structures

As discussed in the section on collision models (Chapter 4), the fundamental physical process that takes place during the collision is that the colliding vehicles are brought to a stop through the dissipation of their kinetic energies. This dissipation takes place through the crush of the vehicle structures; this can take place over different time intervals depending on the vehicle structural stiffness and crush space available. A short time interval results in high deceleration levels, which in turn result in correspondingly high forces and occupant injury severity. In contrast, longer intervals allow for a more gradual deceleration of the colliding vehicles. The collision analysis (see Figure 17 and associated text) further showed the relationship between the stopping distance available and the levels of deceleration experienced by the impacting light vehicle. Thus, increasing the crush space by making the truck structure less stiff offers the possibility of significantly improving injury outcomes. NCHRP Report 350 (Menges et al., 1997) uses 20g as a threshold level of peak deceleration for a collision to be considered survivable. This threshold is of significance in the analysis presented below based on the MADYMO models developed in the section on injury models (Chapter 4).

Using the MADYMO simulations, head, chest, and neck injury criteria were calculated for two levels of deceleration (20 and 30g). Results are listed in Table 18. In addition, the estimated risks of injury for each measure were determined using the injury risk curves described previously, and are shown in Table 19. For HIC, chest acceleration, and the Nij measures, the risks of injury (MAIS ≥ 4 for head and chest and MAIS ≥ 3 for neck) were calculated using NHTSA's injury-risk equations. For chest deflection, neck tension, and neck compression (for which injury thresholds rather than injury risk curves are generally used), the value of the simulation is presented as a percentage of the maximum allowable value. For chest deflection the reference value of 64.3mm was used.

Table 18. Head, chest, and neck injury measures from 20 and 30g simulations of 30, 40, and 50mph frontal impacts.

Pulse			Chest		Neck					
Velocity	Peak G's	HIC	Decel.	Comp.	Nte	Ntf	Nce	Ncf	Tension	Comp.
30	30	422	45	39	0.17	0.23	0.25	0.36	974	34
30	20	224	23	32	0.19	0.12	0.28	0.19	826	59
40	30	593	45	39	0.17	0.27	0.26	0.38	918	35
40	20	246	26	34	0.18	0.15	0.28	0.21	790	69
50	30	721	43	39	0.18	0.32	0.27	0.28	888	296
50	20	229	28	42	0.17	0.14	0.27	0.21	754	75

Neck tension and compression are in N.

Table 19. Probabilities of severe head and chest injury and serious neck injury from 20 and 30g simulations of 30, 40, and 50mph frontal impacts.

Pulse			Chest		Neck					
Velocity	Peak G's	HIC	Decel.	Comp.*	Nte	Ntf	Nce	Ncf	Tension*	Comp.*
30	30	2.8%	8.1%	52.0%	2.8%	3.2%	3.4%	4.2%	23.4%	0.9%
30	20	1.4%	1.9%	42.7%	3.0%	2.5%	3.6%	3.0%	19.8%	1.5%
40	30	5.0%	8.1%	52.0%	2.8%	3.5%	3.4%	4.4%	22.0%	0.9%
40	20	1.5%	2.3%	45.3%	2.9%	2.7%	3.6%	3.1%	18.9%	1.7%
50	30	7.7%	7.1%	52.0%	2.9%	3.9%	3.5%	3.6%	21.3%	7.4%
50	20	1.5%	2.6%	56.0%	2.8%	2.7%	3.5%	3.1%	18.1%	1.9%

* HIC, chest decel, and Nij are estimated injury risk values; chest compression and neck tension and compression are expressed as a proportion of injury threshold value.

<u>Head Injury</u>

The estimated probability of severe head injury from these simulations is shown in Figure 46. The injury risk in the most severe condition (50mph, 30g) is estimated to be less than 8% for a fully restrained (belts plus airbag), mid-size male driver. However, by decreasing the vehicle deceleration level by 10g, the risk of severe head injury is reduced from 50 to 80%. Also, the head injury risks for all three 20g tests are nearly identical, while risk increases with Δv in the simulations conducted at the 30g acceleration level.

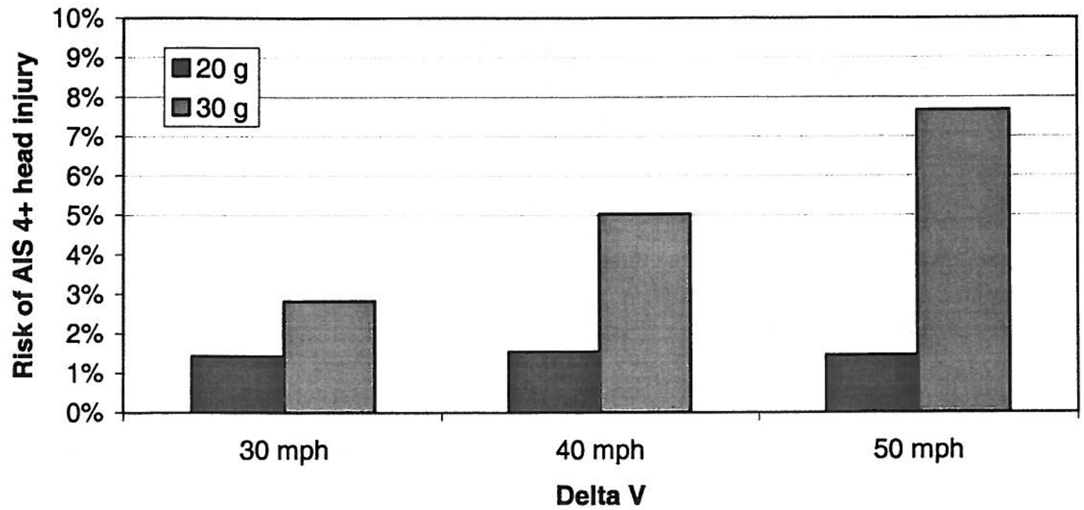


Figure 46. Estimated risks of severe head injury for a fully restrained mid-size adult male in 30, 40, and 50mph frontal impacts with 20 and 30g peak decelerations.

Thoracic Injury

Figure 47 shows the estimated risk of severe thoracic injury based on chest acceleration. Decreasing the vehicle deceleration level from 30 to 20g reduces injury risk by 63 to 77% depending on the Δv levels. However, the highest estimated injury risk of any of these simulations is just over 8%, and the injury risk based on chest deceleration is almost constant with increasing velocity at both 20 and 30g deceleration levels. This may be because these simulations have used an ideal restraint system with pretensioners to tightly couple the occupant to the vehicle and a load limiter to limit the loading on the chest. As a result, chest acceleration has a greater dependence on the crash deceleration rather than changes in Δv.

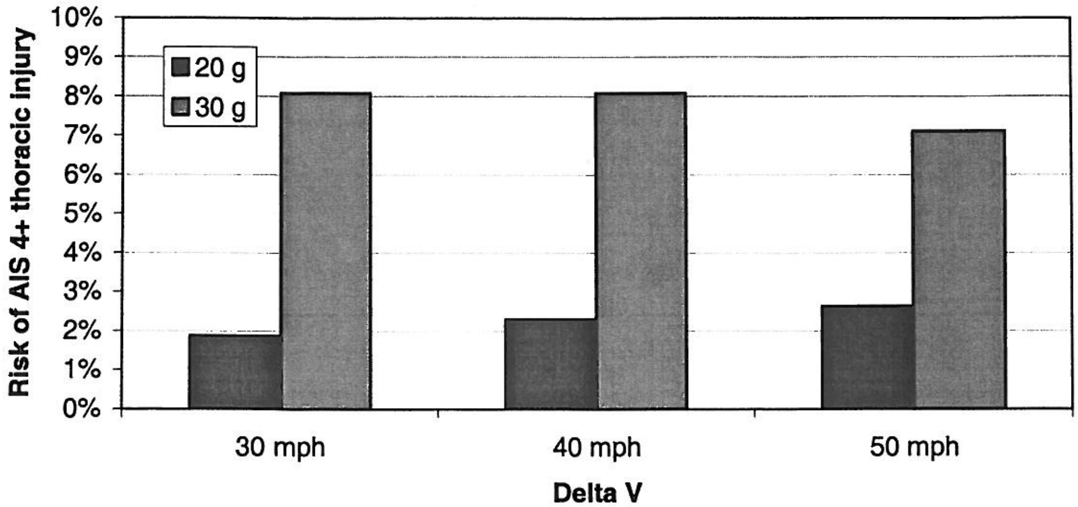


Figure 47. Estimated risk of serious thoracic injury in simulations performed with Δv of 30, 40, and 50mph at 20 and 30g acceleration levels.

The chest deflection from each simulation is shown in Figure 48 and is expressed as a percentage of the threshold injury deflection of 64.3mm. All simulations produced chest deflections from 43 to 56% of the injury threshold. Chest deflection is the same for all three 30g simulations and increases slightly with Δv in the 20g simulations. These results suggest that with belt-plus-airbag restraint, reducing Δv from 50 to 30mph and/or reducing the peak vehicle deceleration from 30 to 20g has little effect on chest deflection. However, these results are limited to the optimal restraint conditions of a belt pretensioner with a load limiter in the shoulder belt plus an airbag.

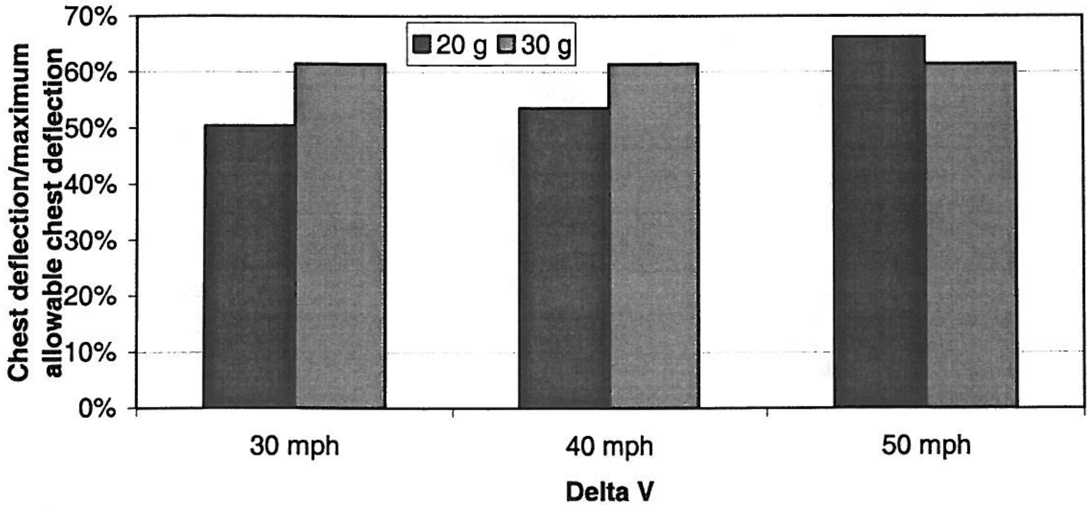


Figure 48. Chest deflection as a proportion of threshold chest deflection in simulations performed with Δv of 30, 40, and 50mph at 20 and 30g acceleration levels.

Neck Injury

The probability of serious neck (MAIS $\geq$ 3) injury for each simulation is shown in Figure 49. The plot shows the maximum values of the injury risks estimated from the four Nij combinations of neck bending and axial loading. All simulations produced neck measures that represented a risk between 3 and 5%. The 20g simulations are slightly lower than the 30g simulations, but at both acceleration levels, the risks are nearly identical for all Δv levels. For the 20g simulations, the compression/extension condition corresponds to the highest risk, and the compression/flexion mode has the highest risk for the 30g simulations. This shift likely occurred because of slight changes in kinematics regarding the position of the occupant relative to the airbag and steering wheel.

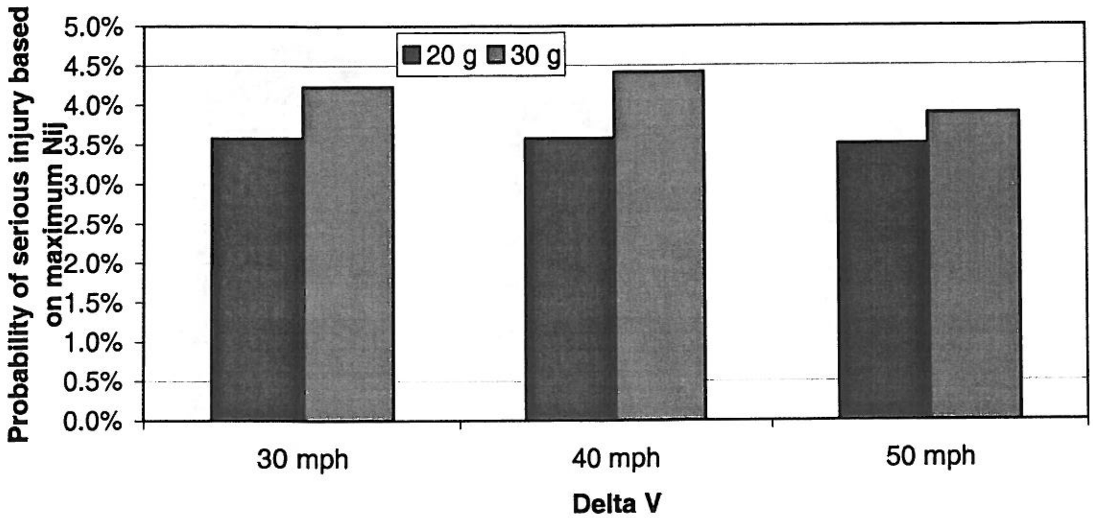


Figure 49. Estimated risk of serious neck injury based on combined axial neck loading and bending in simulations performed for 30, 40, and 50mph Δv s at 20 and 30g deceleration levels.

Figures 50 and 51 show peak neck tension and neck compression, respectively, expressed as a percentage of the injury threshold value. The tension values are 15 to 25% of the injury threshold values; most of the compression values are near 2% of the threshold, except for the 50mph, 30g test for which compression is approximately 8% of the threshold value. If the Mertz (2000) criteria are used, the neck tension values correspond to less than 0.1% risk of serious neck injury. The tension measures are about 15% lower in the 20g cases relative to the 30g simulations for all three Δv levels. Neck tension is almost constant with Δv at both acceleration levels. The very small injury risk values for neck compression are essentially the same for each Δv and deceleration level.

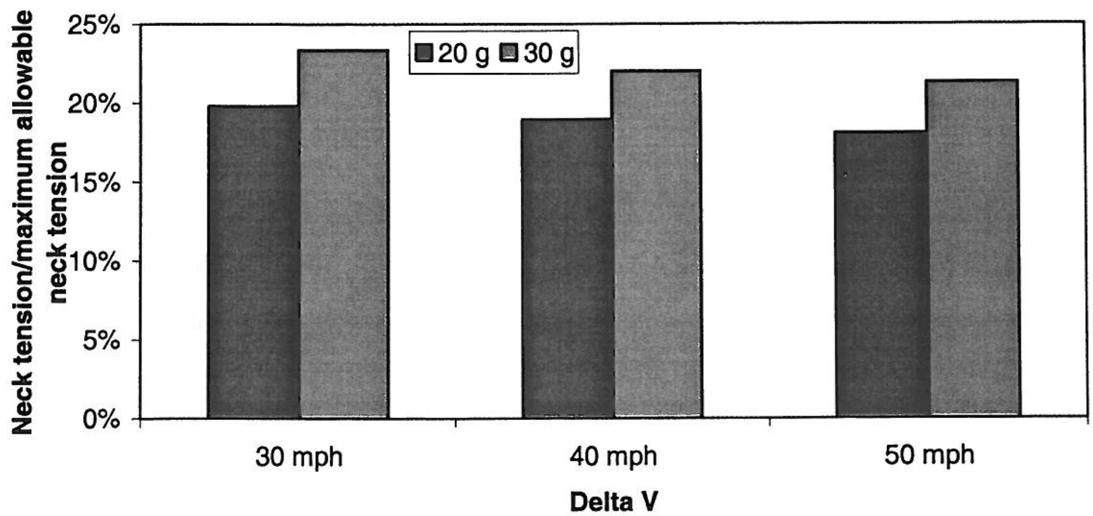


Figure 50. Neck tension expressed as a proportion of threshold neck tension in simulations performed with Δv of 30, 40, and 50mph at 20 and 30g acceleration levels.

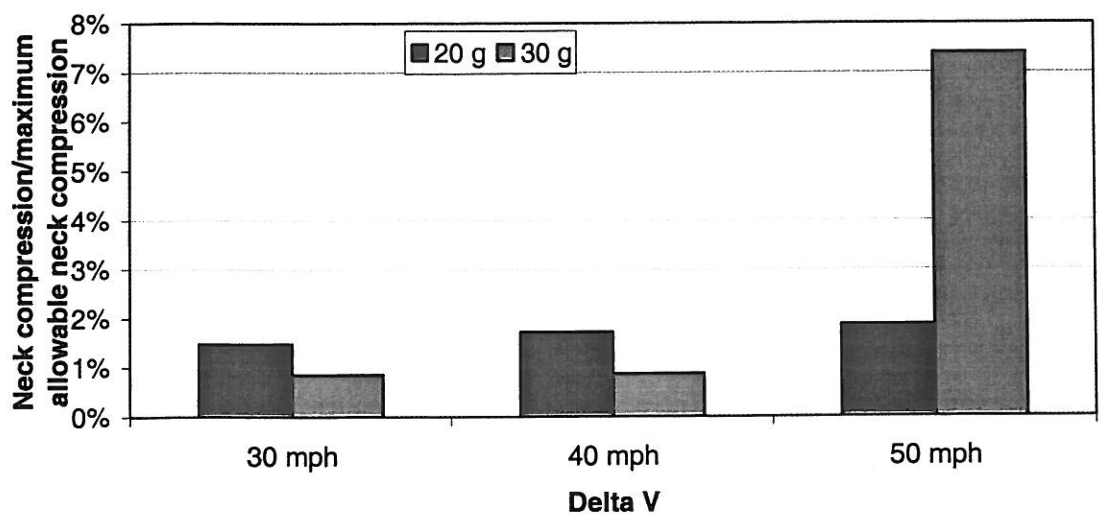


Figure 51. Neck compression expressed as a percentage of threshold neck compression in simulations performed with Δv of 30, 40, and 50mph at 20 and 30g acceleration levels.

<u>Summary of Modeling Results</u>

The results show that all six combinations of frontal-impact vehicle decelerations and Δv s produce injury measures associated with low probabilities of severe injury when the driver is restrained by both airbags and belt restraints (the latter includes a belt pretensioner and shoulder-belt load limiter). These results are consistent with the Urgency Algorithm results shown in

Equation 21, which shows that for deltaV's of 30, 40, and 50mph, drivers fully restrained by three-point belts and airbags have less than a 5% chance of severe injury to the head, face, neck, chest, abdomen, and spine.

The primary findings from the computer simulations are as follows:

1. All simulations performed at 20 and 30g and Δv s of 30, 40, and 50mph using a belt-and-airbag restrained driver with belt-pretensioner and load limiter produced injury measures associated with less than a 10% chance of severe head and chest injury, and serious neck injury.
2. Reducing the peak vehicle deceleration from 30 to 20g resulted in reductions in injury risk for all injury measures except neck compression and chest compression, where in one instance results for the 50mph were nearly identical.
3. The most important observation is that for each of the two acceleration levels (20 and 30g), the simulations show almost constant injury likelihoods or injury criterion levels irrespective of the crash Δv used in the simulation (this is especially true for the 20g level). This can be seen from Tables 18 and 19 and Figures 46 through 51. While more detailed simulations (and experimental studies) for a wider range of crash conditions would be desirable (which are beyond the scope of this study), this result seems to indicate that injury outcomes are much more dependent on the deceleration level than on the vehicle Δv.

Evaluating the Benefits of Attenuating Crash Decelerations

Based on the collision analysis presented earlier, Figure 52 can be derived, which shows the relationship between Δv and the truck crush space (assuming a 1m crush of the impacting light vehicle) required to keep the light vehicle deceleration below the 20g threshold. From the quantitative simulation results presented above, it is reasonable to assume that the probability of a fatality is approximately 3.5% for a 20g maximum deceleration crash. It should be noted that this is a conservative assumption (the simulation results are for AIS 4 level injuries, which are serious but not necessarily fatal injuries), and the fatality probability is likely to be lower.

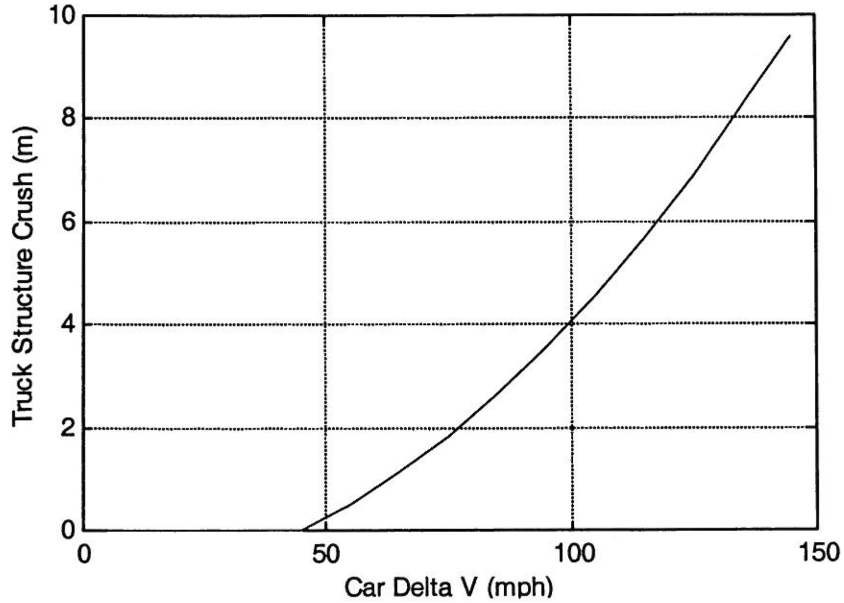


Figure 52. Δv threshold for 20g maximum deceleration vs. truck crush space.

Using the previously presented data on fatality probabilities in truck frontal collisions and the relative velocity distribution in fatal collisions, Table 20 can be produced. This table shows the possible reduction in fatalities if the truck had sufficient crush space (assuming a 1m crush of the impacting light vehicle) to keep the maximum deceleration of the impacting vehicle below 20g. While it is clearly unreasonable to expect truck designs to accommodate a 10m crush space that would result in virtually all collisions becoming survivable, a more feasible 2.6m (approximately 8ft) crush space results in saving almost 25% of the lives lost. This can be raised to nearly 50% with about 4.0m (approximately 12ft) of available crush.

Table 20. Predicted fatality reduction with truck crush (1m light vehicle crush space) to maintain 20g max deceleration.

Collision Δv (mph)	Truck crush space (for 20g max) (m)	Percent of collisions	Predicted savings as percent of total fatalities
5	0	1.3	0.0
15	0	5.1	0.0
25	0	7.1	0.3
35	0	15.1	1.5
45	0.0194	25.1	3.2
55	0.5228	32.5	7.6
65	1.1268	44.3	9.9
75	1.8316	47.9	13.4
85	2.6370	51.9	23.3
95	3.5431	60.8	42.0
105	4.5499	73.8	58.0
115	5.6574	82.7	83.4
125	6.8655	94.4	91.8
135	8.1743	97.6	96.5
145	9.5838	100.0	99.7

Deflection of the Striking Automobile

The analysis of oblique collisions in Chapter 4 showed that such collisions are significantly less severe (both in terms of vehicle Δv and deceleration levels) than direct or head-on collisions. This is due to the fact that, in oblique collisions, not all the energy of the impacting vehicle is dissipated during the crash. Thus, truck structures that are designed to deflect the impacting vehicle can convert a head-on collision into a less severe oblique collision. Mendis et al. (1996) and Prasad et al., (1995) presented an experimental study of a truck front end that was designed to swivel to deflect an oncoming automobile. The study concluded that the design reduced the severity of the collision, though no quantitative evaluation of this improvement was provided. Here, the benefits of this type of deflection will be analyzed based on the collision and injury models and the crash data presented earlier in the study.

While the specific design of the truck structure that results in deflection of the striking vehicle can vary, such deflection can be simply modeled as an oblique collision in which the light vehicle enters the collision traveling at a particular velocity and exits the collision without having lost all its initial speed (i.e., after dissipating only a portion of its kinetic energy) in a direction that is at an angle to the original line of travel. The analysis of oblique collisions showed that the Δv of the light vehicle is relatively insensitive to the collision angle (angle between the normal to the truck surface and the line of travel of the automobile) for angles of 15 to 45° (see Figure 28). Therefore, it is assumed in this analysis that the initial collision angle is 45°.

Again using the data presented earlier on collision speed distributions and injury likelihoods, Tables 21 and 22 can be generated. These tables show the predicted reduction in fatalities per 1,000 collisions (if converted from head-on to deflected collisions). If it is assumed that all the light vehicle occupants were restrained by both seat belts and airbags, 294 out of 397 fatalities can be prevented if head-on collisions are converted into deflections, which is approximately a 72% reduction in fatalities. In the case where the occupants are not using seatbelts and are protected only by the airbags, the corresponding numbers are 262 and 565, which is a reduction of 46%. However, it should be noted that these estimates do not take into account what happens to the light vehicle after it exits the collision and the possible results of secondary collisions with the traffic stream or other roadside structures.

Table 21. Fatalities in direct vs. deflected collisions (front opposite-direction crashes) if occupant is restrained by both three-point belt and airbag.

Direct Collision Δv (mph)	Percent of Collisions	Distribution of Collisions (per 1,000)	Deflected Collision Δv (mph)	Predicted Fatalities Direct Collision	Predicted Fatalities Deflected Collision
5	0.0	0	4.55	0	0
15	1.5	15	13.15	0	0
25	1.5	15	19.92	0	0
35	3.0	30	26.42	0	0
45	9.5	95	32.64	4	1
55	4.0	40	38.58	3	1
65	13.0	130	44.25	17	5
75	4.0	40	49.64	8	2
85	5.0	50	54.75	14	4
95	11.0	110	59.59	42	11
105	16.0	160	64.16	78	20
115	11.0	110	68.45	67	17
125	14.5	145	72.46	107	27
135	4.0	40	76.21	35	9
145	2.0	20	1.00	20	5
Total	100	1000		397	103

Table 22. Fatalities in direct vs. deflected collisions (front opposite direction crashes) if occupant is restrained by only airbag.

Direct Collision Δv (mph)	Percent of Collisions	Distribution of Collisions (per 1,000)	Deflected Collision Δv (mph)	Predicted Fatalities Direct Collision	Predicted Fatalities Deflected Collision
5	0.0	0	4.55	0	0
15	1.5	15	13.15	0	0
25	1.5	15	19.92	0	0
35	3.0	30	26.42	2	0
45	9.5	95	32.64	17	6
55	4.0	40	38.58	12	5
65	13.0	130	44.25	52	22
75	4.0	40	49.64	20	9
85	5.0	50	54.75	28	14
95	11.0	110	59.59	70	37
105	16.0	160	64.16	112	62
115	11.0	110	68.45	81	47
125	14.5	145	72.46	115	68
135	4.0	40	76.21	36	20
145	2.0	20	1.00	20	11
Total	100	1000		565	303

CHAPTER 6: CONCLUSION

Trucks are significantly more aggressive than light vehicles in collisions. For example, the damage suffered by a light vehicle struck by a truck is considerably greater (in terms of velocity or collision energy) than when a light vehicle is struck by another vehicle of similar size and structural characteristics. Overall, a collision of a light vehicle with a truck is more than twice as likely to produce a K or an A-injury in the light vehicle than a collision with another light vehicle. The higher aggressivity of trucks is related to the greater mass, geometric mismatch between vehicle structures, and greater stiffness of trucks in comparison with light vehicles.

This document presented the results of a project to identify opportunities to reduce heavy truck aggressivity by changes to the structure of the truck. Three main tasks were performed as part of this study: (i) a detailed analysis of heavy truck/light vehicle crash data from the U.S. road system, (ii) derivation of collision and injury models that predicted crash outcomes (for the occupants of the lighter vehicle) from fundamental collision variables, and (iii) truck structural countermeasures for reducing aggressivity were proposed and evaluated.

This chapter presents a discussion of the results of the study and, based upon those results, a set of recommendations for reducing the aggressivity heavy trucks.

Discussion of Results

An essential first step in considering structural changes to trucks is to identify the areas on the truck to be addressed and measure the size of the problem. To do so, existing crash data have been used to calibrate the injury probability around the perimeter of the truck in the event of a crash, as well as to determine the prevalence of deaths and injuries in light vehicles by area of the truck involved in a collision. Relative motion is part of the definition of crash type and further characterizes the types of collisions any changes in truck structure will have to deal with.

The types of crashes addressed here, two-vehicle truck/light vehicle crashes, account for 65% of all truck crash involvements and 60% of fatal truck involvements. There are about 250,000 such crashes annually. While almost 75% of the crash involvements produce no injury in the light vehicle, there are almost 3,000 fatalities, 10,000 A-injuries, and 16,000 B-injuries to occupants of light vehicles in these crashes.

Crashes involving the truck's front have the highest probability of a K or A-injury and account for most fatal and serious injuries. Fifty-seven percent of fatal truck/light vehicle involvements and 59% of light vehicle fatalities occur in crashes involving the front of the truck. A fatal or A-injury in the light vehicle occurs in 24.7% of front opposite-direction crashes and in 12.5% of front perpendicular crashes. These are the highest injury rates of the crash types studied.

Collisions with the side of a truck account for about the same number of K or A-injuries as frontal collisions, but injury probability is somewhat lower and depends critically on the mode of the collision. Same-direction sideswipes have the lowest K/A injury probability at 2.1% of all crash types examined, while opposite-direction sideswipes have a much higher probability (10.7%). Crashes in this mode can be similar to frontal crashes if the light vehicle underrides the truck and engages the axles. When the angle of impact is perpendicular, injury probabilities are lower when the front of a light vehicle strikes the side of a truck than if the front of a truck strikes the side of a light vehicle, 8.1% to 12.5% respectively. In side perpendicular collisions, energy absorbing structures on the light vehicle can work if the light vehicle strikes the cab or axles, but there is much less structure on the light vehicle to protect its occupants when the truck is the striking vehicle.

Same direction crashes involving the front or rear of the truck point out the crucial role of geometrical mismatch between trucks and light vehicles. In these crashes, light vehicle K/A injury probabilities are higher if the light vehicle strikes the rear of the truck than if the truck is the striking vehicle, 5.4% to 3.9% respectively. Comparison with light vehicle/light vehicle collisions indicates that underride contributes to higher injury probabilities in collisions with the rear of a truck. When a light vehicle is struck in the rear, injury probabilities are higher by about a factor of three if the striking vehicle is a truck. But when a light vehicle strikes the rear of another vehicle, the probability of a K or A-injury is about six times greater if the vehicle strikes a truck than if it strikes another light vehicle.

Underride likely accounts for this disparity. Truck fronts are generally lower than their rear structures, so the front of the truck is more likely to engage the rear of the light vehicle before it gets into the passenger compartment. However, it should be noted that there is no data to test this hypothesis directly. The data used in this study does not reliably identify underride. In fact, reliable data on the incidence of underride has come only from special studies, usually limited fatal crashes. But recent studies have indicated that underride is common in fatal collisions. Moreover, a recent study of underride in fatal rear-end collisions showed that cargo bed heights and axle set-back distances provide ample opportunity for underride if a truck is struck in the rear.

In summary, truck fronts are a primary target for any effort to reduce truck aggressivity in collisions with light vehicles. Collisions involving truck front-ends account for 60% of light vehicle fatalities as well as the highest probability of a fatality in the light vehicle. Reducing frontal aggressivity would provide the greatest gains, though likely also the greatest challenge.

Results of the collision and injury modeling effort using both real world data and simulation studies are consistent in showing that the likelihood of fully restrained (three-point belts plus airbags) drivers sustaining severe or fatal injuries to the head, face, neck, thorax, abdomen, or spine in frontal crashes up to 50mph Δv is surprisingly low, generally less than 5%. However, results from analysis of NASS data show that the likelihood increases significantly for drivers who are not using the available belt restraints, and are therefore restrained only by the airbag. Most importantly relative to the issue of truck countermeasures is the finding that, for both restraint conditions, reducing the Δv by 10mph (i.e., from 50 to 40mph or from 40 to 30mph) reduces the likelihood of severe and fatal injuries by 60 to 70%.

These results indicate that any countermeasure that reduces the Δv of a light vehicle involved in a frontal collision with a heavy truck will significantly reduce the probability of severe and fatal injuries to light vehicle occupants. While the primary analysis on the effects of Δv has been performed for frontal crashes of light vehicles, similar results were found for side impacts and similar conclusions apply.

Based on the data analysis and the modeling efforts, collisions with the truck front were identified as most important in terms of the number and severity of injuries and the potential benefits from application of aggressivity reduction countermeasures. The first step in improving the crash outcome of the light vehicle and its occupants is to prevent underride through the use of suitably designed guards. Analysis of the crash data along with use of the collision and injury models shows that a reduction of 27 to 37% in fatality counts is possible when underride is prevented, depending upon the availability and use of occupant restraint systems (3-point seat belts, seat belt load limiters and pretensioners, and air bags) in the light vehicle.

Once underride is prevented, occupant injury outcomes can be improved through the appropriate management of the collision energy to reduce occupant Δv and deceleration levels. Two methods of such energy dissipation or management in truck/light vehicle collisions or strikes are: (i) attenuation of the collision forces or acceleration levels by increasing the time over which the collision Δv takes place through the use of softer (less stiff) or energy absorbing truck structures, and (ii) deflection of the striking vehicle such that not all the energy of the light vehicle is dissipated in the collision.

Attenuation of the collision through the use of energy absorbing structures requires the availability of crush space in the truck structure. Truck structural designs that can accommodate 2.6m (approximately 8ft) crush result in a saving of almost 25% of lives lost. This can be raised to nearly 50% with about 4.0m (approximately 12ft, though such a large crush space may not be feasible given current truck design and economic constraints) of available crush.

Truck structures that deflect the impacting vehicle greatly reduce the severity of the collision due to the fact that not all the energy of the impacting vehicle is dissipated during the crash. Thus, the occupants of the lighter vehicle undergo a lower Δv and experience improved injury outcomes. This countermeasure seems to offer the greatest potential benefits with possible fatality reductions ranging from 46 to72%, depending again on the use of the restraint systems in the light vehicle. However, these estimates do not take into account what happens to the light vehicle after it exits the collision and the possible results of secondary collisions with the traffic stream or other roadside structures.

Recommendations

Based on the results of the analysis conducted in this study, some specific measures to reduce heavy truck aggressivity can be suggested.

1. *Front underride prevention*: It is clear (both from crash data, observation of crash damage, and from collision and injury modeling analysis) that when the impacting light vehicle underrides the front of the truck, the injuries to its occupants are likely to be severe, with a high probability of a resultant fatality. Further, the largest number of fatal crashes results from collisions with the front of the truck. Thus, the first line of defense in reducing heavy truck crash severity must be the prevention of front underride. This may be accomplished either through changes in the truck front structure to ensure that these structural members are low enough engage the crash absorbing mechanism of the light vehicle or through the use of properly designed underride guards added to the existing truck structure. The analysis in this study showed that a reduction of 27 to 37% in fatalities is possible through prevention of front underride.

2. *Crash attenuating truck front structure*: Once underride is prevented, crash outcomes can be improved through proper management and dissipation of the collision energy. The literature reviewed in this study presented several examples of innovative truck structures that can perform such an energy dissipating function. These include, front underride guards that are designed to deflect and absorb collision energy, truck fronts built of collapsible structural members, an add-on (mounted on existing truck structure) crash attenuator, etc. All of the above work with existing truck designs and by providing up to 8ft of crush space, offer potential reductions in fatalities of approximately 25%. With more radical changes in truck design (changes in position of the truck engine, cab and associated structural members) it may be possible to achieve crush distances of as great as 12' and in this case the as much as a 50% reduction in fatalities can be achieved.

3. *Deflecting front structure*: Another method of managing the collision energy is to deflect the impacting vehicle through the use of an appropriately designed truck structure. This produces large reductions in the collision energy absorbed by the light vehicle and greatly improves (46 to 72% fatality reduction) the resulting injury outcomes. The greatest

drawback of this countermeasure is the possibility of secondary collisions, and further analysis of this aspect must be undertaken before adoption.

4. *Layered application of countermeasures*: All the countermeasures suggested here were analyzed independently; however, they can be used simultaneously to in a layered system of aggressivity reduction (and of course in conjunction with other non-structural countermeasures) to provide greater improvements in crash outcomes.

In conclusion, this study provides a detailed analysis of the truck aggressivity problem in the context of the U.S. road system, presents techniques and models for analyzing collisions and injury outcomes, and shows that significant improvements in injury outcomes are possible through the use of appropriately designed truck structural countermeasures.

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APPENDIX A

Routine to generate truck impact variable in GES data:

`acc_type` is GES accident type variable

`man_col` is GES manner of collision variable

`impact` is GES-coded impact point on the truck

`impact2` is GES-coded impact point on the other vehicle

```
if acc_type in(20,24,28,34,36,38,40) then tr_imp=1;
else if acc_type in(32,33,42,44,45,46,47,48,49,70,71,72,73,76,77,78,79,93)
      and impact=1 then tr_imp=1;
else if acc_type=98 and man_col=1 then tr_imp=1;
else if acc_type in(50,51,52,54,55,56,57,58,59,60,61) then tr_imp=2;
else if acc_type in(64,65,66,68,69,80,81) and impact=1 then tr_imp=2;
else if acc_type=98 and man_col=2 then tr_imp=2;
else if acc_type in(82,83,86,88,90) and impact=1 then tr_imp=3;
else if acc_type in(74,84,85,98) and man_col=4 and impact=1 and impact2
      in(2,3,12) then tr_imp=3;
else if acc_type in(21,22,23,25,26,27,29,30,31,35,37,39,41) then tr_imp=10;
else if acc_type in(32,33,42,45,46,48,65,66,68,74,76,78,83,90,92,93) and
      impact=4 then tr_imp=10;
else if acc_type=98 and man_col=3 then tr_imp=10;
else if acc_type=98 and man_col=4 and impact=4 then tr_imp=10;
else if acc_type in(45,48,49) and impact in(2,3,6,11,12,13,14,99) then
      tr_imp=20;
else if acc_type in(44,46,70,73,76,79) and impact in(2,6,11,13,99) then
      tr_imp=20;
else if acc_type in(47,71,72,77,78) and impact in(3,6,12,14,99) then
      tr_imp=20;
else if acc_type in(92,93) and impact in(2,11,13) and impact2 in(1,3,12) then
      tr_imp=20;
else if acc_type in(92,93) and impact in(3,12,14) and impact2 in(1,2,11,13)
      then tr_imp=20;
else if acc_type in(74,75,84,98) and man_col=4 and impact in(2,11,13) and
      impact2 in(3,12,14) then tr_imp=20;
else if acc_type in(74,75,84,98) and man_col=4 and impact in(3,12,14) and
      impact2 in(3,11,13) then tr_imp=20;
else if acc_type in(74,84,98) and man_col=5 then tr_imp=20;
```

```
else if acc_type in(64,65,66,67,68,69,80,81) and impact in(3,12,14) then
      tr_imp=30;
else if acc_type in(92,93) and impact in(3,12,14) and impact2 in(2,4,11,13)
      then tr_imp=30;
else if acc_type in(74,84,98) and man_col=4 and impact in(3,12,14) and
      impact2 in(3,12,14) then tr_imp=30;
else if acc_type in(64,65,66,68,69,80,81) and impact in(2,11,13) then
      tr_imp=31;
else if acc_type in(92,93) and impact in(2,11,13) and impact2 in(3,4,12,14)
      then tr_imp=31;
else if acc_type in(74,98) and man_col=4 and impact in(2,11,13) and impact2
      in(2,11,13) then tr_imp=31;
else if acc_type in(64,65,66,67,68) and impact in(6,99) then tr_imp=98;
else if acc_type in(82,83,86,89,90) and impact in(3,6,12,14,99) then
      tr_imp=40;
else if acc_type in(74,84,85,98) and man_col=4 and impact in(3,12,14) and
      impact2=1 then tr_imp=40;
else if acc_type in(82,83,87,88,90) and impact in(2,4,11,13) then tr_imp=41;
else if acc_type in(74,75,85,98) and man_col=4 and impact in(2,11,13) and
      impact2 in(1,4) then tr_imp=41;
else if acc_type=99 then tr_imp=99;
else tr_imp=98;
```

Routine to generate truck impact variable in the TIFA data:

v1059 is TIFA-coded accident type variable

v135 is FARS initial impact point on the truck

impact1 is FARS initial impact point on the other vehicle

v23 is FARS first harmful event variable

v24 is FARS manner of collision variable

```
if v1059
      in(20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42
      ,71,73,77,79)
 and v135 in(1,11,12) then tr_imp=1;
else if v1059 in(45,47,48,49,70,72,73,76) and v135=12 then tr_imp=1;
else if v1059=99 and v24=1 and v135 in(11,12) then tr_imp=1;
else if v1059 in(50,51,52,53,54,55,56,57,58,59,60,61,62,63,65,69,81) and v135
      in(1,11,12) then tr_imp=2;
else if v1059 in(64,66,67,68) and v135=12 then tr_imp=2;
```

```
else if v1059 in(98,99) and v24=2 and v135=12 then tr_imp=2;
else if v1059<20 and v23=12 and v24=2 and v135=12 then tr_imp=2;
else if v1059 in(82,83,86,87,88,89,90,91) and v135=12 then tr_imp=3;
else if 19<v1059<43 and v135 in(5,6,7,14) then tr_imp=10;
else if v1059 in(45,48,52,68,74,76,82,84,90,91,92,98,99) and v135=6 then
      tr_imp=10;
else if v1059 in(45,46,47,70,72,76,78) and v135 in(1,2,3,4,5,7,8,9,10,11)
      then tr_imp=20;
else if v1059 in(48,49,74,75,84,85,92,93) and v135 in(7,8,9,10,11) and
      impact1 in(1,2,3,4,5,6,12) then tr_imp=20;
else if v1059 in(48,49,74,75,84,85,92,93) and v135 in(1,2,3,4,5) and impact1
      in(6,7,8,9,10,11,12) then tr_imp=20;
else if v1059
      in(20,21,22,23,24,25,26,27,28,29,30,31,32,34,35,36,37,38,39,40,41,42,77
      ,79)
 and v135 in(2,3,4,8,9,10) then tr_imp=20;
else if v1059 in(98,99) and v24=5 and v135 in(9,10) then tr_imp=20;
else if v1059 in(98,99) and v24=4 and v135 in(1,2,3,4,5) and impact1
      in(7,8,9,10,11) then tr_imp=20;
else if v1059 in(98,99) and v24=4 and v135 in(7,8,9,10,11) and impact1
      in(1,2,3,4,5) then tr_imp=20;
else if v1059<20 and v23=12 and v135 in(1,2,9) then tr_imp=20;
else if v1059 in(51,54,55,56,57,58,59,60,61,81) and v135 in(7,8,9,10) then
      tr_imp=30;
else if v1059 in(52,62,63,64,65,66,68,69) and v135 in(7,8,9,10,11) then
      tr_imp=30;
else if v1059 in(74,75,92) and v135 in(7,8,9,10,11) and impact1
      in(7,8,9,10,11) then tr_imp=30;
else if v1059 in(98,99) and v24=6 and v135=9 then tr_imp=30;
else if v1059 in(98,99) and v24=4 and v135 in(7,8,9,11) and impact1
      in(9,10,11) then tr_imp=30;
else if v1059 in(50,51,54,55,56,57,58,59,60,61,81) and v135 in(2,3,4) then
      tr_imp=31;
else if v1059 in(52,62,63,64,65,66,68,69) and v135 in(1,2,3,4,5) then
      tr_imp=31;
else if v1059 in(74,75,92) and v135 in(1,2,3,4,5) and impact1 in(1,2,3,4,5)
      then tr_imp=31;
else if v1059 in(98,99) and v24=6 and v135=5 then tr_imp=31;
```

```
else if v1059 in(98,99) and v24=4 and v135 in(1,2,3,4,5) and impact1
      in(1,2,3,4,5) then tr_imp=31;
else if v1059 in(82,83,86,87,88,89) and v135 in(7,8,9,10,11) then tr_imp=40;
else if v1059 in(84,90,91) and v135 in(7,8,9) and impact1=12 then tr_imp=40;
else if v1059 in(86,87,88,89) and v135 in(1,2,3,4,5) then tr_imp=41;
else if v1059 in(84,90,91) and v135 in(1,2,3,4,5) and impact1=12 then
      tr_imp=41;
else if v1059=99 then tr_imp=99;
else tr_imp=98;
```

APPENDIX B

This Appendix shows the histograms of the probability of injury in collisions between trucks and light vehicles by collision type.

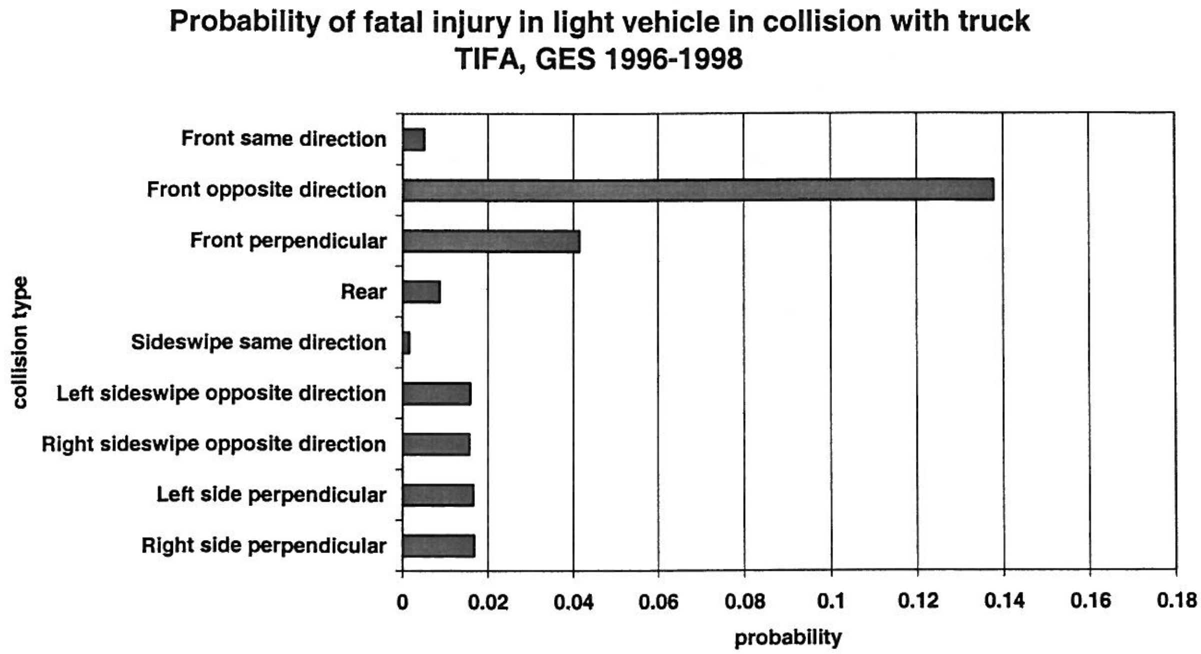


Figure B-1. Probability of fatal injury in light vehicle.

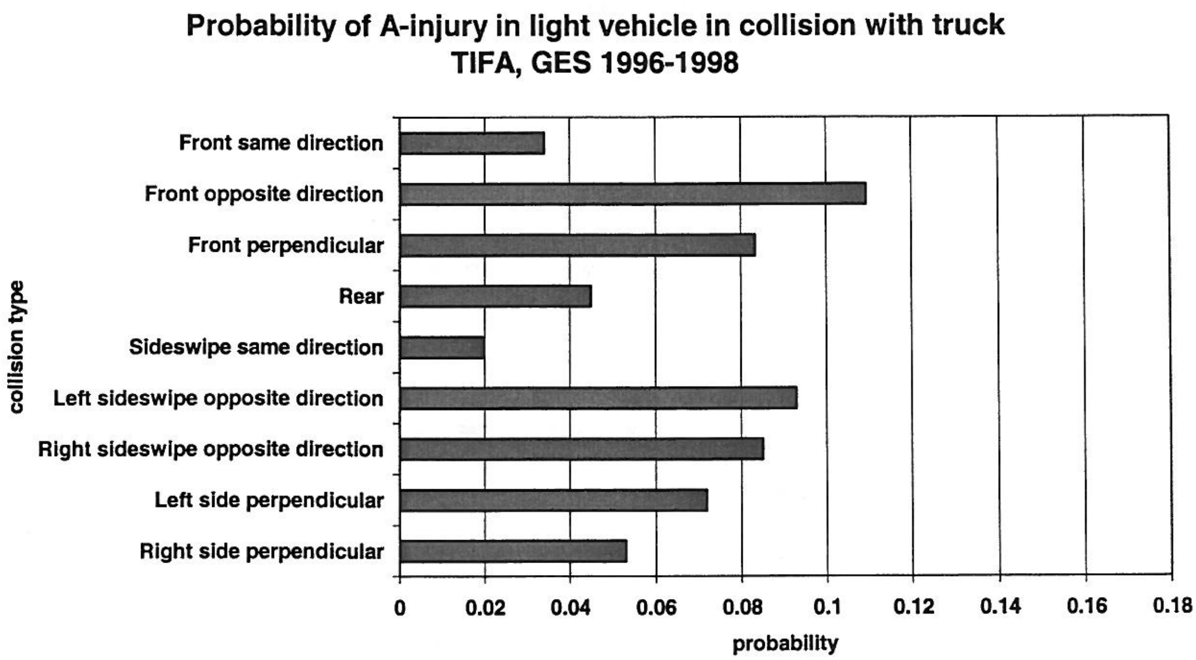


Figure B-2. Probability of A-injury in light vehicle.

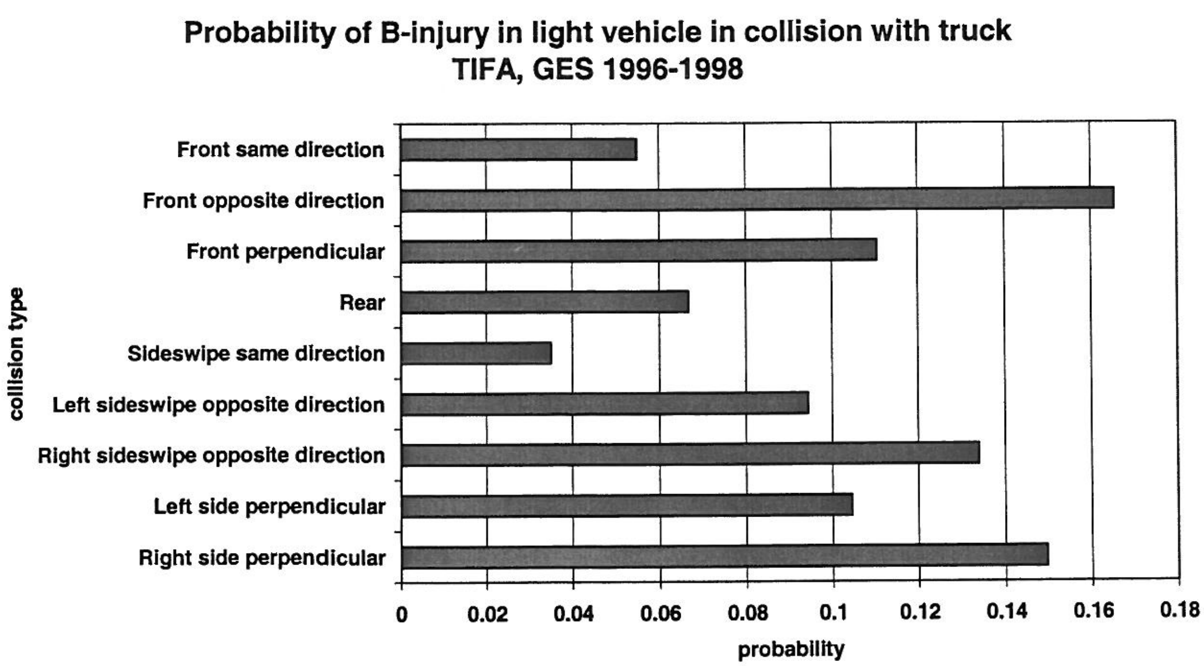


Figure B-3. Probability of B-injury in light vehicle.

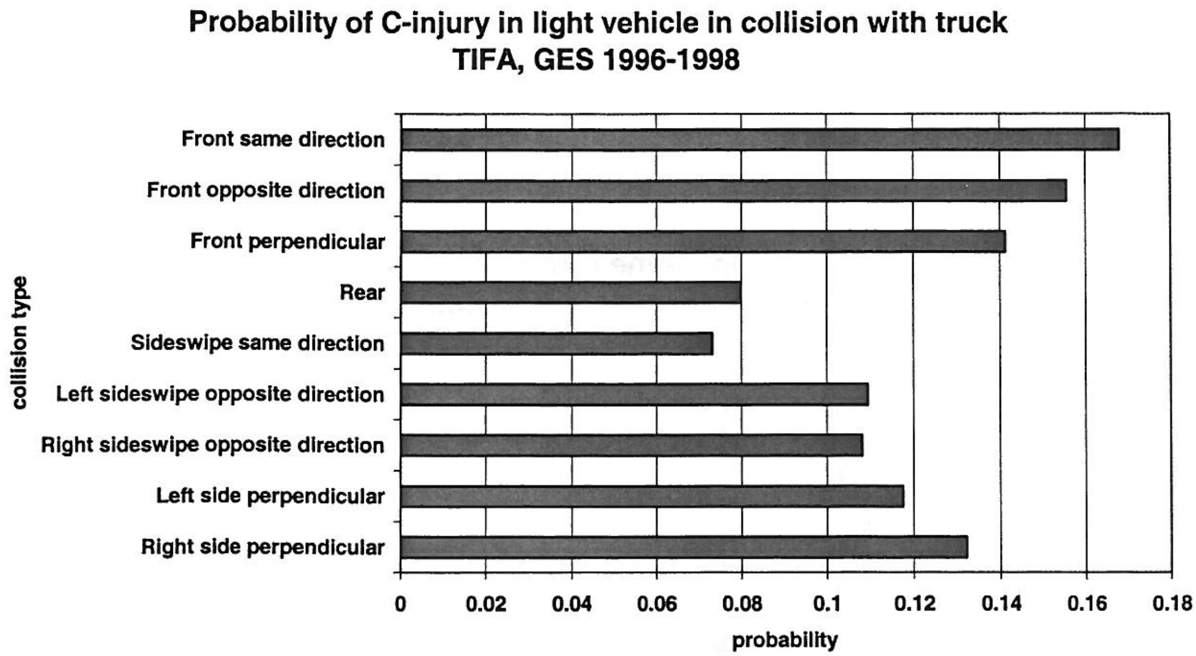
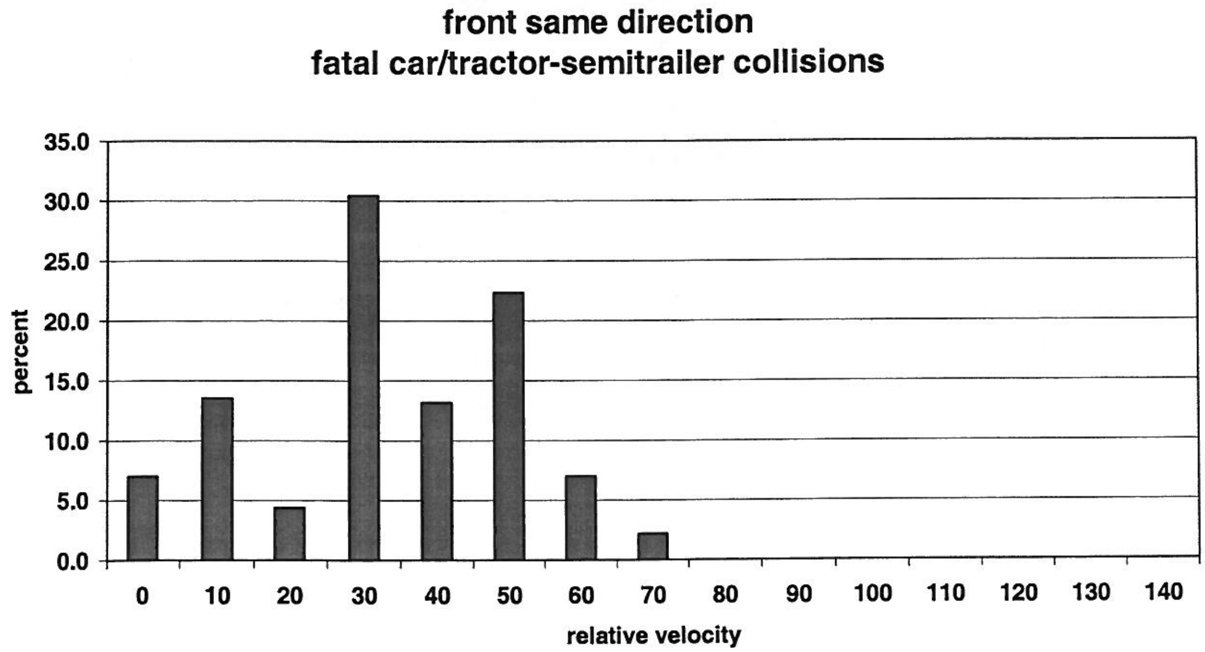


Figure B-4. Probability of C-injury in light vehicle.

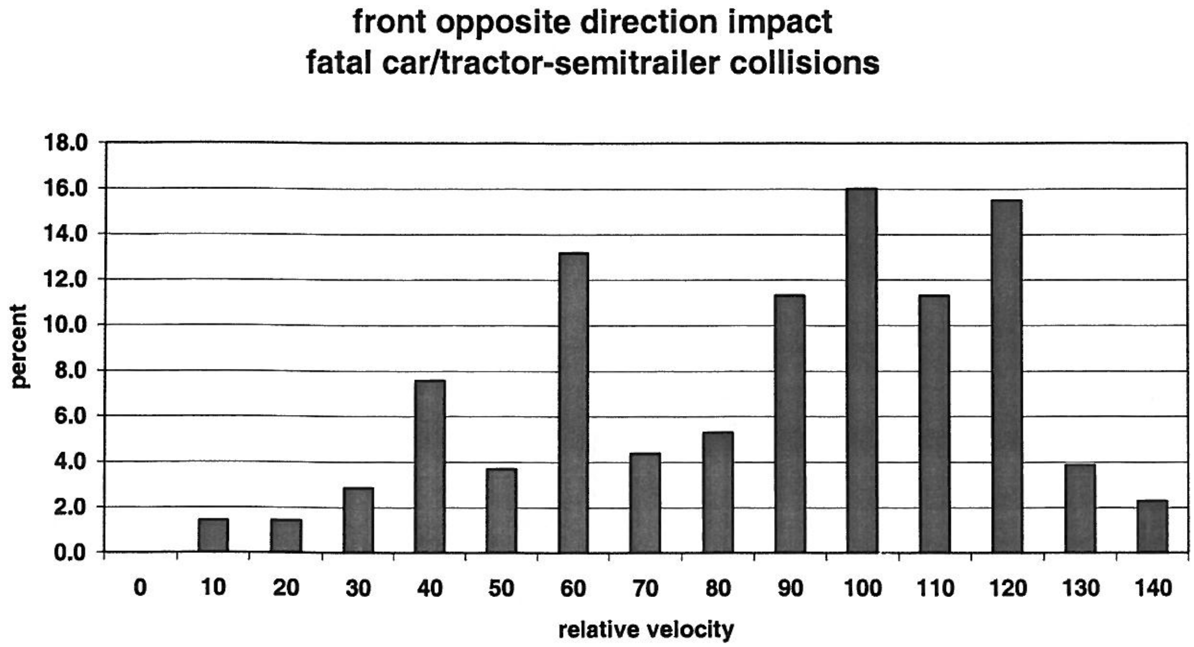
APPENDIX C

This Appendix shows the histograms of relative velocity in fatal collisions between tractor-semitrailers and light vehicles (data developed for Sandia National Laboratories, 1994-1997).



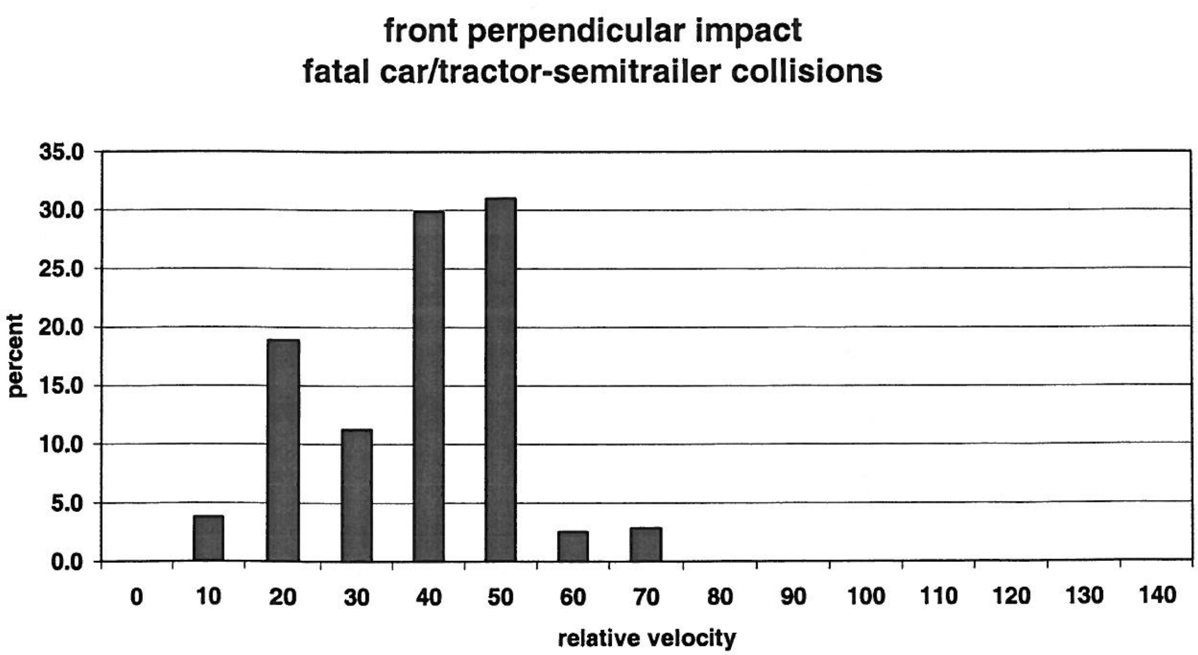
N=18

Figure C-1. Velocity distribution for front-same direction collisions.



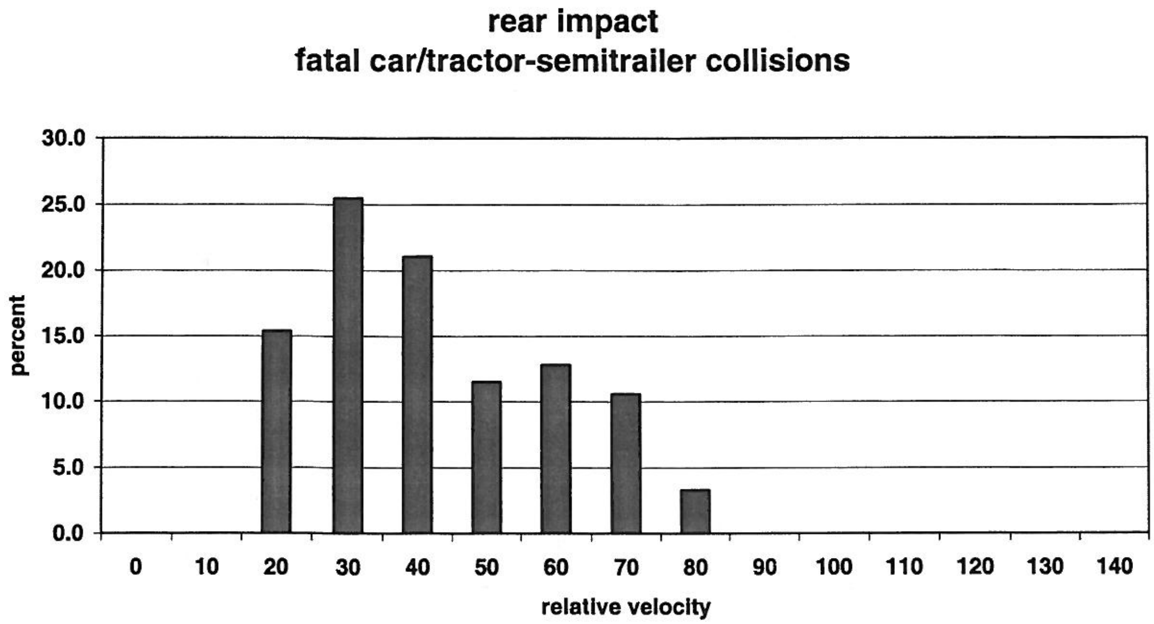
N=57

Figure C-2. Velocity distribution for front-opposite direction collisions.



N=33

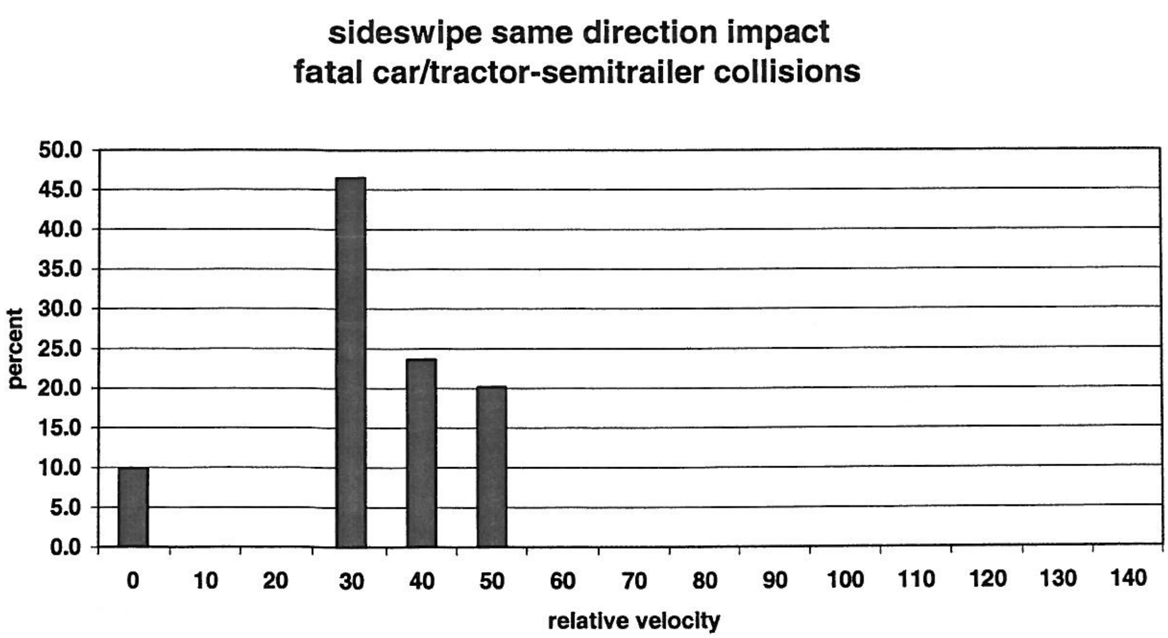
Figure C-3. Velocity distribution for front perpendicular collisions.



N=

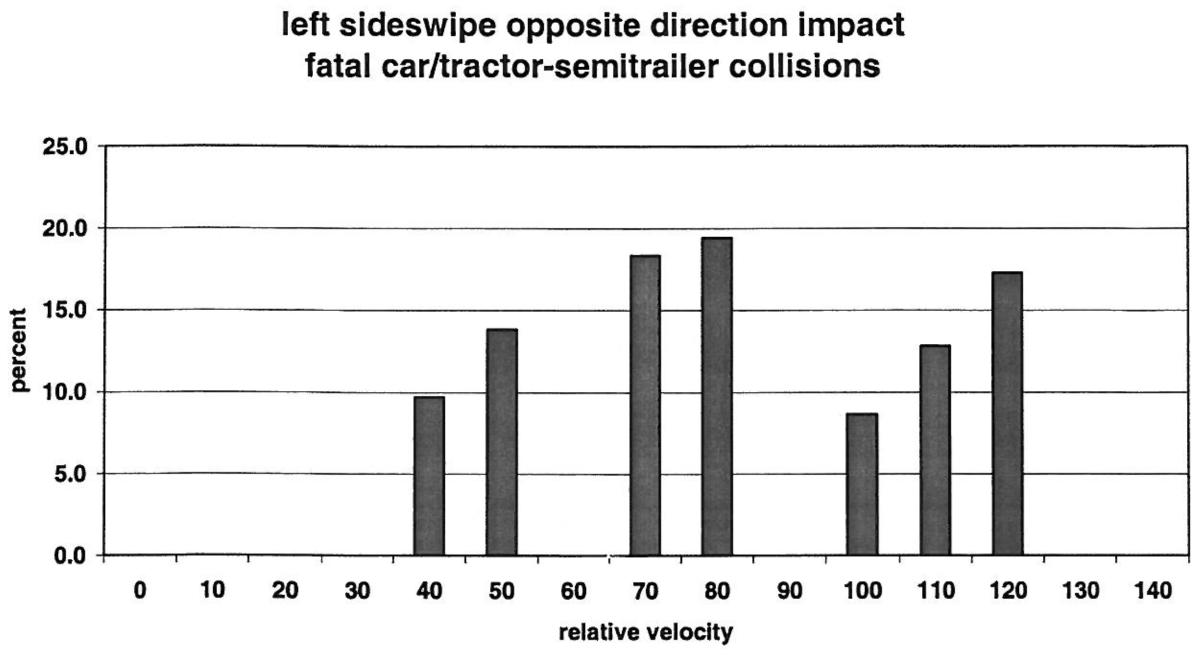
29

Figure C-4. Velocity distribution for rear impact collisions.



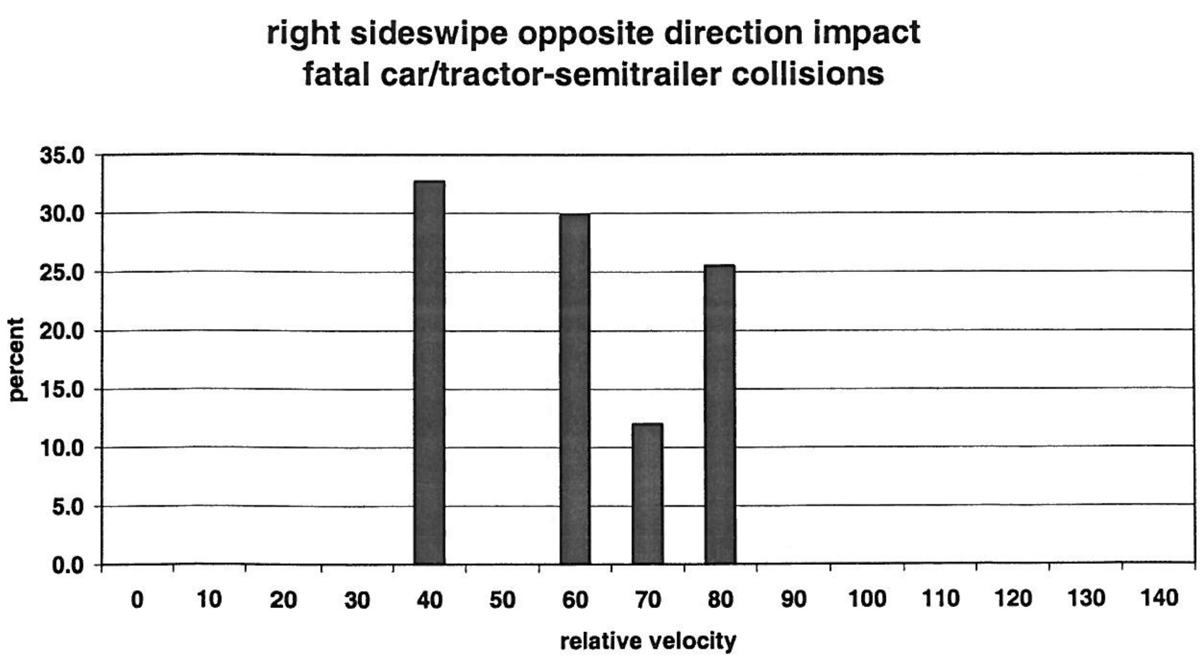
N=9

Figure C-5. Velocity distribution for same direction sideswipes.



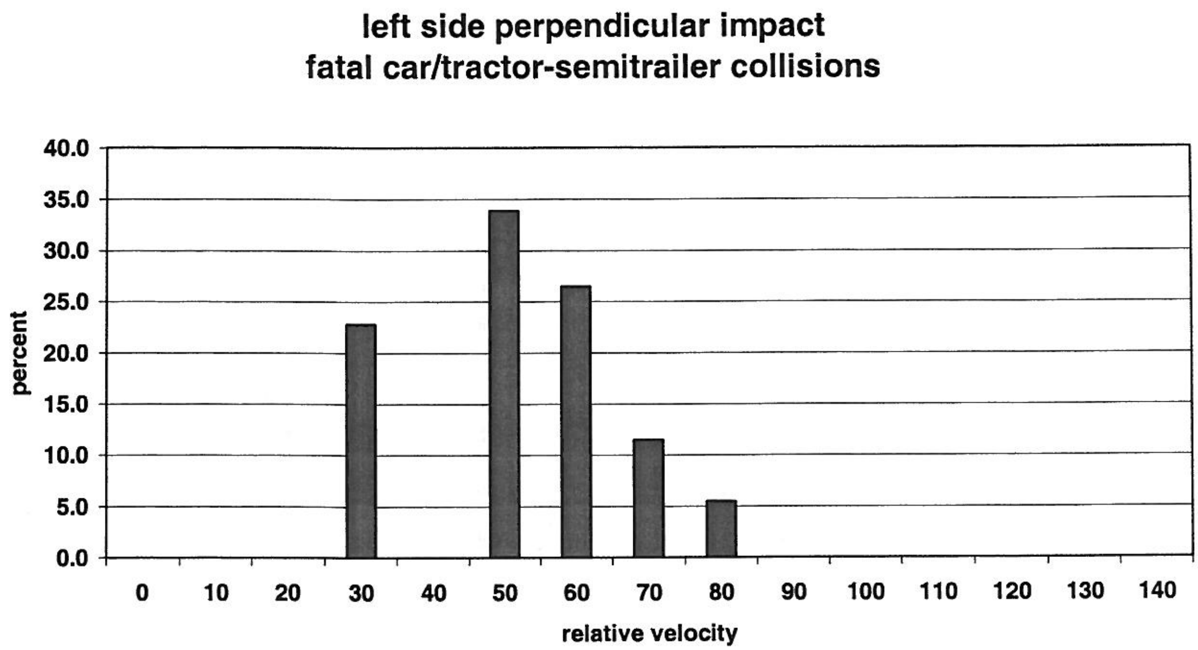
N=10

Figure C-6. Velocity distribution for opposite direction sideswipes.



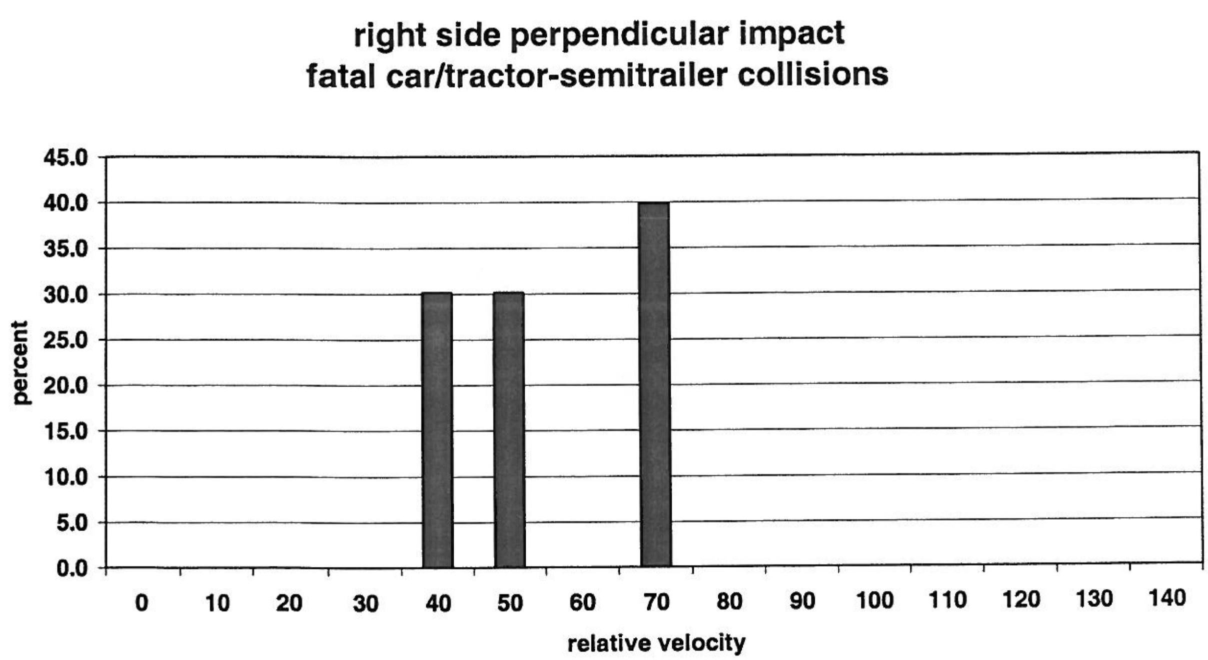
N=7

Figure C-7. Velocity distribution for right sideswipe opposite direction collisions.



N=13

Figure C-8. Velocity distribution for left side perpendicular collisions.



N=3

Figure C-9. Velocity distribution for right side perpendicular collisions.

APPENDIX D

Table D-1. Likelihood of injury at different AIS levels for drivers of any age restrained by three-point belt and airbags in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv (mph)	Likelihood	CI
Driver	3PB + AB	all	MAIS2	30	25.64%	8.17%
Driver	3PB + AB	all	MAIS3	30	4.62%	3.27%
Driver	3PB + AB	all	MAIS4	30	29.00%	0.39%
Driver	3PB + AB	all	fatal	30	0.11%	0.22%
Driver	3PB + AB	all	MAIS2	40	56.09%	9.34%
Driver	3PB + AB	all	MAIS3	40	17.11%	9.63%
Driver	3PB + AB	all	MAIS4	40	1.06%	1.37%
Driver	3PB + AB	all	fatal	40	0.35%	0.71%
Driver	3PB + AB	all	MAIS2	50	82.56%	4.96%
Driver	3PB + AB	all	MAIS3	50	46.80%	14.07%
Driver	3PB + AB	all	MAIS4	50	3.75%	4.55%
Driver	3PB + AB	all	fatal	50	1.16%	2.25%

Table D-2. Likelihood of injury at different AIS levels for right-front passengers of any age restrained by three-point belt and airbags in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv (mph)	Likelihood	CI
Passenger	3PB + AB	all	MAIS2	30	37.12%	15.49%
Passenger	3PB + AB	all	MAIS3	30	15.33%	5.17%
Passenger	3PB + AB	all	MAIS4	30	55.00%	0.56%
Passenger	3PB + AB	all	fatal	30	0.15%	0.20%
Passenger	3PB + AB	all	MAIS2	40	65.09%	12.72%
Passenger	3PB + AB	all	MAIS3	40	45.29%	8.81%
Passenger	3PB + AB	all	MAIS4	40	2.55%	2.51%
Passenger	3PB + AB	all	fatal	40	0.99%	1.29%
Passenger	3PB + AB	all	MAIS2	50	85.48%	6.23%
Passenger	3PB + AB	all	MAIS3	50	79.10%	5.25%
Passenger	3PB + AB	all	MAIS4	50	11.06%	9.16%
Passenger	3PB + AB	all	fatal	50	6.13%	7.12%

Table D-3. Likelihood of injury at different AIS levels for drivers of any age restrained by airbags only in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv (mph)	Likelihood	CI
Driver	airbag	all	MAIS2	30	33.92%	8.21%
Driver	airbag	all	MAIS3	30	17.54%	6.76%
Driver	airbag	all	MAIS4	30	4.39%	1.45%
Driver	airbag	all	fatal	30	2.14%	0.95%
Driver	airbag	all	MAIS2	40	33.92%	8.21%
Driver	airbag	all	MAIS3	40	17.54%	6.76%
Driver	airbag	all	MAIS4	40	4.39%	1.45%
Driver	airbag	all	fatal	40	2.14%	0.95%
Driver	airbag	all	MAIS2	50	76.01%	5.79%
Driver	airbag	all	MAIS3	50	71.34%	7.64%
Driver	airbag	all	MAIS4	50	47.00%	7.51%
Driver	airbag	all	fatal	50	28.97%	8.31%

Table D-4. Likelihood of injury at different AIS levels for right-front passengers of any age restrained by airbags only in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv (mph)	Likelihood	CI
Passenger	airbag	all	MAIS2	30	17.93%	11.06%
Passenger	airbag	all	MAIS3	30	6.15%	8.60%
Passenger	airbag	all	MAIS4	30	1.54%	2.56%
Passenger	airbag	all	fatal	30	0.34%	1.18%
Passenger	airbag	all	MAIS2	40	30.13%	14.49%
Passenger	airbag	all	MAIS3	40	13.41%	15.61%
Passenger	airbag	all	MAIS4	40	6.95%	9.96%
Passenger	airbag	all	fatal	40	1.82%	5.91%
Passenger	airbag	all	MAIS2	50	45.98%	15.41%
Passenger	airbag	all	MAIS3	50	26.80%	22.34%
Passenger	airbag	all	MAIS4	50	26.21%	22.99%
Passenger	airbag	all	fatal	50	9.15%	22.08%

Table D-5. Likelihood of injury at different AIS levels for drivers and right-front passengers aged 20, 40, 60, or 80 years restrained by three-point belts plus airbags in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Driver	3PB + AB	20	MAIS2	30	17.58%
Driver	3PB + AB	20	MAIS3	30	2.53%
Driver	3PB + AB	20	MAIS4	30	0.17%
Driver	3PB + AB	20	fatal	30	0.15%
Driver	3PB + AB	20	MAIS2	40	44.15%
Driver	3PB + AB	20	MAIS3	40	9.77%
Driver	3PB + AB	20	MAIS4	40	0.58%
Driver	3PB + AB	20	fatal	40	0.47%
Driver	3PB + AB	20	MAIS2	50	74.55%
Driver	3PB + AB	20	MAIS3	50	31.15%
Driver	3PB + AB	20	MAIS4	50	2.02%
Driver	3PB + AB	20	fatal	50	1.51%
Driver	3PB + AB	40	MAIS2	30	24.14%
Driver	3PB + AB	40	MAIS3	30	4.51%
Driver	3PB + AB	40	MAIS4	30	0.42%
Driver	3PB + AB	40	fatal	30	0.44%
Driver	3PB + AB	40	MAIS2	40	54.12%
Driver	3PB + AB	40	MAIS3	40	16.48%
Driver	3PB + AB	40	MAIS4	40	1.47%
Driver	3PB + AB	40	fatal	40	1.41%
Driver	3PB + AB	40	MAIS2	50	81.38%
Driver	3PB + AB	40	MAIS3	50	45.19%
Driver	3PB + AB	40	MAIS4	50	5.01%
Driver	3PB + AB	40	fatal	50	4.41%
Driver	3PB + AB	60	MAIS2	30	32.19%
Driver	3PB + AB	60	MAIS3	30	7.92%
Driver	3PB + AB	60	MAIS4	30	1.08%
Driver	3PB + AB	60	fatal	30	1.32%
Driver	3PB + AB	60	MAIS2	40	63.76%
Driver	3PB + AB	60	MAIS3	40	26.44%
Driver	3PB + AB	60	MAIS4	40	3.69%

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Driver	3PB + AB	60	fatal	40	4.12%
Driver	3PB + AB	60	MAIS2	50	86.70%
Driver	3PB + AB	60	MAIS3	50	60.04%
Driver	3PB + AB	60	MAIS4	50	11.90%
Driver	3PB + AB	60	fatal	50	12.16%
Driver	3PB + AB	80	MAIS2	30	41.46%
Driver	3PB + AB	80	MAIS3	30	13.55%
Driver	3PB + AB	80	MAIS4	30	2.71%
Driver	3PB + AB	80	fatal	30	3.85%
Driver	3PB + AB	80	MAIS2	40	72.41%
Driver	3PB + AB	80	MAIS3	40	39.58%
Driver	3PB + AB	80	MAIS4	40	8.93%
Driver	3PB + AB	80	fatal	40	11.44%
Driver	3PB + AB	80	MAIS2	50	90.68%
Driver	3PB + AB	80	MAIS3	50	73.24%
Driver	3PB + AB	80	MAIS4	50	25.69%
Driver	3PB + AB	80	fatal	50	29.38%
Passenger	3PB + AB	20	MAIS2	30	18.01%
Passenger	3PB + AB	20	MAIS3	30	6.98%
Passenger	3PB + AB	20	MAIS4	30	0.46%
Passenger	3PB + AB	20	fatal	30	0.16%
Passenger	3PB + AB	20	MAIS2	40	41.92%
Passenger	3PB + AB	20	MAIS3	40	25.75%
Passenger	3PB + AB	20	MAIS4	40	2.16%
Passenger	3PB + AB	20	fatal	40	1.08%
Passenger	3PB + AB	20	MAIS2	50	70.35%
Passenger	3PB + AB	20	MAIS3	50	61.56%
Passenger	3PB + AB	20	MAIS4	50	9.58%
Passenger	3PB + AB	20	fatal	50	6.96%
Passenger	3PB + AB	40	MAIS2	30	24.68%
Passenger	3PB + AB	40	MAIS3	30	11.02%
Passenger	3PB + AB	40	MAIS4	30	1.12%
Passenger	3PB + AB	40	fatal	30	0.57%
Passenger	3PB + AB	40	MAIS2	40	51.85%
Passenger	3PB + AB	40	MAIS3	40	36.38%

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Passenger	3PB + AB	40	MAIS4	40	5.14%
Passenger	3PB + AB	40	fatal	40	3.79%
Passenger	3PB + AB	40	MAIS2	50	77.97%
Passenger	3PB + AB	40	MAIS3	50	72.53%
Passenger	3PB + AB	40	MAIS4	50	20.67%
Passenger	3PB + AB	40	fatal	50	21.20%
Passenger	3PB + AB	60	MAIS2	30	32.83%
Passenger	3PB + AB	60	MAIS3	30	16.95%
Passenger	3PB + AB	60	MAIS4	30	2.70%
Passenger	3PB + AB	60	fatal	30	2.04%
Passenger	3PB + AB	60	MAIS2	40	61.63%
Passenger	3PB + AB	60	MAIS3	40	48.53%
Passenger	3PB + AB	60	MAIS4	40	11.76%
Passenger	3PB + AB	60	fatal	40	12.42%
Passenger	3PB + AB	60	MAIS2	50	84.08%
Passenger	3PB + AB	60	MAIS3	50	81.32%
Passenger	3PB + AB	60	MAIS4	50	39.06%
Passenger	3PB + AB	60	fatal	50	49.18%
Passenger	3PB + AB	80	MAIS2	30	42.17%
Passenger	3PB + AB	80	MAIS3	30	25.18%
Passenger	3PB + AB	80	MAIS4	30	6.39%
Passenger	3PB + AB	80	fatal	30	6.96%
Passenger	3PB + AB	80	MAIS2	40	70.56%
Passenger	3PB + AB	80	MAIS3	40	60.85%
Passenger	3PB + AB	80	MAIS4	40	24.69%
Passenger	3PB + AB	80	fatal	40	33.78%
Passenger	3PB + AB	80	MAIS2	50	88.74%
Passenger	3PB + AB	80	MAIS3	50	87.77%
Passenger	3PB + AB	80	MAIS4	50	61.18%
Passenger	3PB + AB	80	fatal	50	77.68%

Table D-6. Likelihood of driver and passenger injury at different AIS levels Δv for different Δv s in T-type near-side impacts.

Occupant	Injury level	Δv (mph)	Likelihood	CI
driver	MAIS 2	20	22.88%	6.54%
driver	MAIS 3	20	5.20%	3.90%
driver	MAIS 4	20	1.73%	0.47%
driver	fatal	20	0.79%	0.37%
driver	MAIS 2	20	65.36%	7.25%
driver	MAIS 3	20	27.09%	13.50%
driver	MAIS 4	20	14.16%	3.25%
driver	fatal	20	5.18%	2.28%
driver	MAIS 2	30	92.31%	2.09%
driver	MAIS 3	30	71.91%	10.57%
driver	MAIS 4	30	60.78%	5.67%
driver	fatal	30	27.33%	8.36%
passenger	MAIS 2	30	23.98%	7.89%
passenger	MAIS 3	30	5.57%	2.28%
passenger	MAIS 4	30	2.64%	1.21%
passenger	fatal	30	1.01%	0.79%
passenger	MAIS 2	40	68.27%	7.87%
passenger	MAIS 3	40	31.22%	8.36%
passenger	MAIS 4	40	16.95%	6.20%
passenger	fatal	40	7.26%	5.05%
passenger	MAIS 2	40	93.62%	1.99%
passenger	MAIS 3	40	77.73%	5.71%
passenger	MAIS 4	40	60.61%	8.82%
passenger	fatal	40	37.57%	14.35%

Table D-7. Likelihood of driver and passenger injury at different AIS levels Δv for drivers and passengers aged 20, 40, 60, or 80 years restrained by 3-point belt and airbag different Δv s in frontal impacts.

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Driver	3PB + AB	20	MAIS2	30	17.58%
Driver	3PB + AB	20	MAIS3	30	2.53%
Driver	3PB + AB	20	MAIS4	30	0.17%
Driver	3PB + AB	20	fatal	30	0.15%
Driver	3PB + AB	20	MAIS2	40	44.15%
Driver	3PB + AB	20	MAIS3	40	9.77%
Driver	3PB + AB	20	MAIS4	40	0.58%
Driver	3PB + AB	20	fatal	40	0.47%
Driver	3PB + AB	20	MAIS2	50	74.55%
Driver	3PB + AB	20	MAIS3	50	31.15%
Driver	3PB + AB	20	MAIS4	50	2.02%
Driver	3PB + AB	20	fatal	50	1.51%
Driver	3PB + AB	40	MAIS2	30	24.14%
Driver	3PB + AB	40	MAIS3	30	4.51%
Driver	3PB + AB	40	MAIS4	30	0.42%
Driver	3PB + AB	40	fatal	30	0.44%
Driver	3PB + AB	40	MAIS2	40	54.12%
Driver	3PB + AB	40	MAIS3	40	16.48%
Driver	3PB + AB	40	MAIS4	40	1.47%
Driver	3PB + AB	40	fatal	40	1.41%
Driver	3PB + AB	40	MAIS2	50	81.38%
Driver	3PB + AB	40	MAIS3	50	45.19%
Driver	3PB + AB	40	MAIS4	50	5.01%
Driver	3PB + AB	40	fatal	50	4.41%
Driver	3PB + AB	60	MAIS2	30	32.19%
Driver	3PB + AB	60	MAIS3	30	7.92%
Driver	3PB + AB	60	MAIS4	30	1.08%
Driver	3PB + AB	60	fatal	30	1.32%
Driver	3PB + AB	60	MAIS2	40	63.76%
Driver	3PB + AB	60	MAIS3	40	26.44%
Driver	3PB + AB	60	MAIS4	40	3.69%

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Driver	3PB + AB	60	fatal	40	4.12%
Driver	3PB + AB	60	MAIS2	50	86.70%
Driver	3PB + AB	60	MAIS3	50	60.04%
Driver	3PB + AB	60	MAIS4	50	11.90%
Driver	3PB + AB	60	fatal	50	12.16%
Driver	3PB + AB	80	MAIS2	30	41.46%
Driver	3PB + AB	80	MAIS3	30	13.55%
Driver	3PB + AB	80	MAIS4	30	2.71%
Driver	3PB + AB	80	fatal	30	3.85%
Driver	3PB + AB	80	MAIS2	40	72.41%
Driver	3PB + AB	80	MAIS3	40	39.58%
Driver	3PB + AB	80	MAIS4	40	8.93%
Driver	3PB + AB	80	fatal	40	11.44%
Driver	3PB + AB	80	MAIS2	50	90.68%
Driver	3PB + AB	80	MAIS3	50	73.24%
Driver	3PB + AB	80	MAIS4	50	25.69%
Driver	3PB + AB	80	fatal	50	29.38%
Passenger	3PB + AB	20	MAIS2	30	18.01%
Passenger	3PB + AB	20	MAIS3	30	6.98%
Passenger	3PB + AB	20	MAIS4	30	0.46%
Passenger	3PB + AB	20	fatal	30	0.16%
Passenger	3PB + AB	20	MAIS2	40	41.92%
Passenger	3PB + AB	20	MAIS3	40	25.75%
Passenger	3PB + AB	20	MAIS4	40	2.16%
Passenger	3PB + AB	20	fatal	40	1.08%
Passenger	3PB + AB	20	MAIS2	50	70.35%
Passenger	3PB + AB	20	MAIS3	50	61.56%
Passenger	3PB + AB	20	MAIS4	50	9.58%
Passenger	3PB + AB	20	fatal	50	6.96%
Passenger	3PB + AB	40	MAIS2	30	24.68%
Passenger	3PB + AB	40	MAIS3	30	11.02%
Passenger	3PB + AB	40	MAIS4	30	1.12%
Passenger	3PB + AB	40	fatal	30	0.57%
Passenger	3PB + AB	40	MAIS2	40	51.85%
Passenger	3PB + AB	40	MAIS3	40	36.38%

Occupant	Restraint	Age	Injury level	Δv	Likelihood
Passenger	3PB + AB	40	MAIS4	40	5.14%
Passenger	3PB + AB	40	fatal	40	3.79%
Passenger	3PB + AB	40	MAIS2	50	77.97%
Passenger	3PB + AB	40	MAIS3	50	72.53%
Passenger	3PB + AB	40	MAIS4	50	20.67%
Passenger	3PB + AB	40	fatal	50	21.20%
Passenger	3PB + AB	60	MAIS2	30	32.83%
Passenger	3PB + AB	60	MAIS3	30	16.95%
Passenger	3PB + AB	60	MAIS4	30	2.70%
Passenger	3PB + AB	60	fatal	30	2.04%
Passenger	3PB + AB	60	MAIS2	40	61.63%
Passenger	3PB + AB	60	MAIS3	40	48.53%
Passenger	3PB + AB	60	MAIS4	40	11.76%
Passenger	3PB + AB	60	fatal	40	12.42%
Passenger	3PB + AB	60	MAIS2	50	84.08%
Passenger	3PB + AB	60	MAIS3	50	81.32%
Passenger	3PB + AB	60	MAIS4	50	39.06%
Passenger	3PB + AB	60	fatal	50	49.18%
Passenger	3PB + AB	80	MAIS2	30	42.17%
Passenger	3PB + AB	80	MAIS3	30	25.18%
Passenger	3PB + AB	80	MAIS4	30	6.39%
Passenger	3PB + AB	80	fatal	30	6.96%
Passenger	3PB + AB	80	MAIS2	40	70.56%
Passenger	3PB + AB	80	MAIS3	40	60.85%
Passenger	3PB + AB	80	MAIS4	40	24.69%
Passenger	3PB + AB	80	fatal	40	33.78%
Passenger	3PB + AB	80	MAIS2	50	88.74%
Passenger	3PB + AB	80	MAIS3	50	87.77%
Passenger	3PB + AB	80	MAIS4	50	61.18%
Passenger	3PB + AB	80	fatal	50	77.68%

Table D-8. Likelihood of different injury levels at different Δv and occupant positions in near-side impacts.

Occupant	Injury level	Δv (mph)	Likelihood	CI
driver	MAIS 2	20	12.35%	3.64%
driver	MAIS 3	20	2.05%	1.43%
driver	MAIS 4	20	1.29%	0.30%
driver	fatal	20	0.62%	0.28%
passenger	MAIS 2	20	6.60%	2.75%
passenger	MAIS 3	20	0.59%	0.23%
passenger	MAIS 4	20	0.64%	0.27%
passenger	fatal	20	1.20%	0.10%
driver	MAIS 2	30	48.00%	7.50%
driver	MAIS 3	30	11.66%	6.87%
driver	MAIS 4	30	9.89%	2.07%
driver	fatal	30	4.24%	1.80%
passenger	MAIS 2	30	34.52%	8.97%
passenger	MAIS 3	30	4.40%	1.64%
passenger	MAIS 4	30	4.70%	1.87%
passenger	fatal	30	0.99%	0.78%
driver	MAIS 2	40	85.81%	3.29%
driver	MAIS 3	40	45.39%	13.49%
driver	MAIS 4	40	48.00%	5.33%
driver	fatal	40	23.92%	7.42%
passenger	MAIS 2	40	79.74%	5.44%
passenger	MAIS 3	40	26.33%	6.95%
passenger	MAIS 4	40	27.31%	7.56%
passenger	fatal	40	7.40%	5.19%

Table D-9. Probability of fatality for given Δv in frontal collisions (with belt & airbag).

Occupant	Restraint	Age	Δv (mph)	Fatality Probability
Driver	3PB + AB	all	0 - 10	0.00
Driver	3PB + AB	all	10 – 20	0.00
Driver	3PB + AB	all	20 – 30	0.00
Driver	3PB + AB	all	30 - 40	0.01
Driver	3PB + AB	all	40 – 50	0.04
Driver	3PB + AB	all	50 – 60	0.08
Driver	3PB + AB	all	60 – 70	0.13
Driver	3PB + AB	all	70 – 80	0.21
Driver	3PB + AB	all	80 – 90	0.29
Driver	3PB + AB	all	90 – 100	0.38
Driver	3PB + AB	all	100 – 110	0.49
Driver	3PB + AB	all	110 - 120	0.61
Driver	3PB + AB	all	120 - 130	0.74
Driver	3PB + AB	all	130 - 140	0.88
Driver	3PB + AB	all	130 - 140	1.00

Table D-10. Probability of fatality for given Δv in frontal collisions (with airbag only).

Occupant	Restraint	Age	Δv (mph)	Fatality Probability
Driver	AB only	all	0 - 10	0.00
Driver	AB only	all	10 – 20	0.00
Driver	AB only	all	20 – 30	0.00
Driver	AB only	all	30 - 40	0.08
Driver	AB only	all	40 – 50	0.18
Driver	AB only	all	50 – 60	0.29
Driver	AB only	all	60 – 70	0.40
Driver	AB only	all	70 – 80	0.48
Driver	AB only	all	80 – 90	0.57
Driver	AB only	all	90 – 100	0.64
Driver	AB only	all	100 – 110	0.70
Driver	AB only	all	110 - 120	0.74
Driver	AB only	all	120 - 130	0.79
Driver	AB only	all	130 - 140	0.82
Driver	AB only	all	130 - 140	1.00