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Energy Absorbing Structures for the Fronts of Heavy Trucks -- A Theoretical Analysis of the Benefits

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ABSTRACT

Because of the large weight differences that now exist between heavy trucks and cars, car occupants are at risk of serious injury when they collide with large trucks. However, although there is little that can be done to reduce this disparity in weight, it is possible to modify trucks so that the effects of the impact between a heavy truck and a car could be lessened. This paper estimates the effects of modifying the fronts of heavy trucks to incorporate energy absorbing structures with stiffness characteristics similar to the fronts of cars. Equations of motion are developed that show that equipping trucks with energy absorbing structures zones would increase the deceleration distance available to car occupants in car-truck collisions by 40 percent and reduce the average deceleration to restrained occupants by a factor of 1.4. A method is provided that transposes this reduction in acceleration to a reduction in fatality risk using Fatal Accident Reporting System data for 1977-1984. An example is given that shows energy absorbing structures could reduce the likelihood of fatal injury to car occupants by as much as 33 percent.

In 1985 there were nearly 40,000 fatal accidents in the United States and 4,211 or 11 percent of these involved heavy trucks (>26,000 lbs.). While attention has been given to improving the crashworthiness of cars to reduce the risk of serious or fatal injury, virtually nothing has been done to reduce the risk to other road users in collisions with large trucks. Seventy-six percent of all fatal truck accidents involve other vehicles, and 44 percent involve a large truck and a passenger car (Figure 1). Truck-car collisions are the single most common type of fatal truck collision and the deaths are almost always to the car occupants.[1]

Table 1 gives a breakdown of car occupant deaths in car-truck collisions by the impact area to the car and to the truck. Of the 2,187 car occupant deaths in crashes with large trucks 1985, 29 percent occurred in frontal collisions, 32 percent occurred from the truck hitting the side of the car, 9 percent from the car hitting the side of the truck, 12 percent from the car hitting the rear of the truck, and 5 percent from the truck hitting the rear of the car. Engineering design improvements directed toward reducing the aggressiveness of trucks could reduce the severity of many of these crashes. For example, it has been established for some time that truck rear underride guards can reduce fatalities by effectively preventing cars from underriding trucks

when cars strike the rear-ends of trucks. Crash protection devices on the sides of trucks similar to those for rear underride guards could also reduce car occupant fatalities in side impacts. Ways to protect car occupants in collisions where the front of the truck hits the are car are less obvious, but, in theory at least, they can be developed. This paper concentrates on ways of improving crash protection for car occupants in collisions in which the fronts of trucks strike the fronts of the cars.

THEORETICAL DEVELOPMENT

It has been claimed that, because of the large mass difference that now exists between heavy trucks and cars, for a given collision it is difficult to do anything that would reduce the velocity change that the car experiences.[1] Although little can be done to reduce the disparity in mass, it is possible to modify the fronts of trucks so that the injury potential of the impact between a heavy truck and a car could be lessened. The velocity change experienced by the car in a car-truck collision cannot be changed, but the distance and time over which it takes place can be increased by modifying the front of the truck. Increasing the time or distance of the velocity change has the effect of decreasing the deceleration experienced by the car occupants and consequently their risk of injury. This can be accomplished by putting a structure on the front of the truck with energy absorbing characteristics similar to those of a car.

Consider a symmetrical head-on (or central) collision between two vehicles as shown in Figure 2. The following notation is used:

E_1 (E_2) = energy absorbed by vehicle 1 (vehicle 2);

K_1 (K_2) = crush stiffness of vehicle 1 (vehicle 2);

m_1 (m_2) = mass of vehicle 1 (vehicle 2);

d_1 (d_2) = crush distance on vehicle 1 (vehicle 2);

F_1 (F_2) = force on vehicle 1 (vehicle 2); and

a_1 (a_2) = deceleration of vehicle 1 (vehicle 2).

During the collision the forces on each vehicle are equal and opposite so that $F_1 = F_2$. If it is assumed that the force on the vehicle is proportional to the vehicle crush, then

$$F_1 = K_1 d_1 = F_2 = K_2 d_2. \qquad (1)$$

The energy absorbed in crushing vehicle 1 is given by

$$E_1 = K_1 d_1^2/2.$$

The energy absorbed in crushing vehicle 2 is given by

$$E_2 = K_2 d_2^2/2.$$

Then the total energy (E) absorbed during the collision is given by

$$E = E_1 + E_2$$

$$= K_1 d_1^2/2 + K_2 d_2^2/2.$$

In a truck-car collision, the crush on vehicle 2 (the truck) is zero and the total energy absorbed is given by

$$E = K_1 d_1^2/2.$$

Alternatively, the crush on vehicle 1 is

$$d_1 = \sqrt{2E/K_1}.$$

If the truck is modified so that its stiffness is equal to that of the

car, the truck absorbs a proportion of the energy and the total energy absorbed is given by

$$E = K_1 d'^2_1/2 + K_2 d_2^2/2,$$

where d'_1 is the new crush of vehicle 1. However, Equation (1) shows that if the vehicles have equal stiffness the amount of crush on each vehicle will also be equal such that $d'_1 = d_2$ so that

$$E = K_1 (d'_1)^2. \qquad (2)$$

Rearranging Equation (2), the crush d'_1 is given by

$$d'_1 = \sqrt{E/K_1}.$$

However, the total crush between the two vehicles is $2d'_1 = 2\sqrt{E/K_1}$. Note that the energy E, absorbed in the collision, is the same irrespective of whether the truck is modified. Also the velocity change, ΔV, that the occupants of the car undergo is the same, but when the truck is modified the car occupants are decelerated over a longer distance so that their average deceleration is less. The ratio of the two deceleration distances is $2d'_1/d_1$. Then

$$2d'_1/d_1 = 2\sqrt{E/K_1} \quad \sqrt{2E/K_1} = \sqrt{2}.$$

Thus, if the truck is modified so that its stiffness is equal to that of the car, the occupants of the car derive about 40 percent more ride down, i.e., the distance in which they are decelerated to rest is increased by 40 percent. To determine what effect this increased ride down has on the likelihood of injury for the car occupants, the most straightforward approach is to see how their average deceleration is reduced. Assuming a force is proportional to crush relationship, the

average force $\bar{F}$ on the car during the impact is given by

$$\bar{F} = \int_0^{d_f} Kxdx/d_f,$$

where x is the crush distance at any time during the impact, and d_f is the final crush distance. Then $\bar{F} = Kd_f/2$.

Comparing the average force on the car in the unmodified truck collision ($\bar{F}$) with that in the modified collision ($\bar{F}_m$) we have

$$\bar{F}_m/F = \sqrt{E/K_1}\ \sqrt{2E/K_1} = 1/\sqrt{2} = 0.7 \qquad (3)$$

However, because the mass of the vehicle is unchanged the ratio of modified versus unmodified average force also represents the change in the deceleration that the car occupants will experience providing they are restrained, i.e., modified deceleration = 0.7 (original deceleration).

Thus, equipping the fronts of trucks with a crush zone of stiffness equal to that of cars will reduce the deceleration that restrained car occupants experience by a factor of 1.4. Unrestrained car occupants will derive less benefit from the ride down.

ESTIMATED REDUCTION IN FATALITY RISK FROM MODIFIED TRUCK FRONT-END DESIGN

If the deceleration of the occupant can be reduced by 1.4, injury severity will also be reduced particularly if the occupants are restrained. In effect, the increased crush space gives the occupant more distance in which to decelerate while the velocity change for the car remains the same. Another way to look at this reduction in acceleration is as an increase in the effective mass of the car.

This can be seen by rearranging Equation (3):

$$\bar{F}_m = \bar{F}/\sqrt{2} \text{ so that } \bar{F}_m/m = \bar{F}/m\sqrt{2} \text{ or } a' = F/m\sqrt{2}.$$

Hence, for the purposes of calculating the effect of the crushable zone on reducing the risk of fatal injury, the reduced acceleration is effectively achieved by increasing the mass of the car by a factor of $\sqrt{2}$, i.e., the effective mass $m' = m\sqrt{2}$.

There is evidence that the risk of fatality in car-truck collisions increases as the mass of the car decreases.[1] If this effect can be quantified, the reduction in fatalities that could be achieved by increasing the effective mass of the car could be assessed.

Using Fatal Accident Reporting System (FARS) for years 1977 to 1985, Table 2 gives the ratio of car occupant to truck occupant fatalities for fatal accidents involving large trucks (>26,000 lbs) analysed by subcategories of vehicle weight in increments of 500 lbs; the mean mass of the cars involved is given for each car weight category. Figure 3 shows the fatality ratio plotted against the mean car mass for each weight category. The increasing fatality risk with decreasing car size is clearly evident, and the strength of the relationship is confirmed by the regression analysis correlation coefficient of -0.8 ($p<.001$). Because of the already large disparity in mass between cars and trucks, the increase in the number of car occupant fatalities cannot be attributed to the increase in the mass ratio. A primary cause for the increase in severity is that as cars are downsized their crush stiffness

is increased[2] and the amount of crush for a given velocity change is reduced. This means that the deceleration that an occupant experiences is increased with a corresponding increase in the risk of injury. Another reason for the increased risk is the higher likelihood that small cars will suffer occupant compartment intrusion. However, given the wide range of severities that occur, there will be a significant number of crashes that occur without compartment intrusion in which increased crush space would be beneficial.

To establish whether frontal crash protection would work, it is necessary to further restrict the analysis to collisions involving the front of the truck and the front of the car. Table 3 gives the ratio of car occupant to truck occupant fatalities as a function of car weight for head-on collisions involving the front of the car and the front of the truck. Figure 4 gives the car occupant to truck occupant fatality ratio plotted against mean car mass for each weight category. The correlation coefficient of -0.8 suggests a strong empirical relationship between the ratio of fatality of car occupants to truck occupants and mass of car.

However, although there is a clear increase in the ratio of car occupant to truck occupant fatalities with decreasing mass, a number of possible confounding effects must be considered. Since the 1970s, there has been a progressive downsizing of cars and a steady annual increase in the ratio of car occupant to truck occupant fatalities.[1] This means there is the possibility of simultaneous effects of car mass and accident year. Also larger cars could produce more severe car-truck crashes, which would increase the likelihood of fatal injury to the truck driver. This would increase the denominator in the fatality ratio and produce an

anomalous effect of increasing fatality ratio with decreasing car mass. One would intuitively expect the effect to be small because, at closing speeds of 60 mph, the increase in velocity change experienced by a 40,000 lb. truck in a frontal collision with a 2,000 lb. car compared to 4,000 lb. car is less than 1 mph.

To examine these effects, multiple logistic regression procedures were used.[4] To fit the regression models the CATMOD procedure from the SAS Institute was used.[5] The dependent variable in each observation was the presence or absence of a fatal injury, and the independent or predictor variables were car mass, year of accident, and the interaction of car mass with year of accident. Car mass was centered about its mean by recoding car mass as the difference between the mean mass and the mass of the accident involved car. Regression equations were used to predict the log odds of occupant fatality for the following situations: death of a car occupant given a fatal head-on car-truck accident; death of a car occupant given a fatal head-on car-truck accident in which the truck driver died; death of a truck occupant given a fatal head-on car-truck accident. The results are given in Tables 4 through 6.

The odds of fatality for car occupants (Table 4) increased significantly with decreasing car mass ($p < 0.002$), they were not dependent on accident year, and the interaction of car mass and accident year was not significant. The odds of fatality for car occupants (Table 5), given a truck occupant death, is dependent neither on car mass nor accident year. This is most likely because accidents in which truck drivers are killed are so severe that their outcome is not dependent on the size of the car. This means that the denominator of the fatality

ratio of car occupant to truck occupant death, in Figures 3 and 4, acts as a surrogate for truck exposure.

The odds of fatality for truck occupants (Table 6) also does not appear to depend on the mass of the car, although the parameter estimate for the mass effect does have the appropriate sign, i.e., truck occupant death increases with increasing car size. It is reasonable to conclude that the effect of increasing risk of car occupant death with decreasing car mass is predominantly a car mass effect and is not caused by anomalous effects of truck occupant deaths or accident year. However, considering the mass effects shown in Tables 4 and 6 simultaneously in terms of the ratio of car occupant deaths to truck occupant deaths, the two mass effects are additive. The mass effect in Table 4 shows that the probability of car occupant fatality decreases with increasing car mass, and the mass effect in Table 6 (although not statistically significant) shows an increase in the probability of fatality for truck occupants with increasing car mass. This means that, although the ratio of car to truck occupant fatalities (Table 3) is likely to be controlled predominantly by the car occupant/mass effect of the numerator, there could be some truck occupant/mass effect in the denominator. This would have the effect of reducing the ratio for large cars and increasing it for small cars.

The results in Figure 4 provide a means of estimating the reduction in fatality risk that could be achieved by equipping trucks with crushable zones. The parameter estimates for the regression analysis give the following equation

$$\frac{\text{No. Car Occupant Fatalities}}{\text{No. Truck Occupant Fatalities}} = 110.1 - 0.0163\ (\text{mass of car}).$$

The mean mass of the car population in car-truck fatal accidents in 1985, was 2,921 lbs. Putting a crushable zone on all trucks would effectively increase this mean mass by a factor of $\sqrt{2}$ to 4,131 lbs. Substituting this value in the regression equation from Figure 4 gives a reduced fatality ratio of 42.8 compared to the original value of 62.5. This suggests that crushable zones would reduce the risk of fatality to car occupants in frontal car-truck collisions by 32 percent.

DISCUSSION

The results of this analysis suggest that putting energy absorbing structures on the fronts of trucks could reduce the risk of fatality to car occupants in car-truck collisions by about one-third. Although the concept of energy absorbing structures or front guards has received little attention in the United States, their feasibility has been assessed in Europe. A United Kingdom study estimated that about 25 percent of car occupants killed in car-truck collisions would have survived with a suitably constructed front energy absorbing guard.[6] A prototype guard was constructed with a crushable distance or stroke of 40 cm (15.7 in.). This was based on the fact that 50 to 60 cm is the maximum crush distance available in the smallest mini-cars before serious intrusion starts to occur. The characteristics of the prototype bumper allowed it to start to stroke at a load of 146 kN (approximately 10 tons). However, crash tests of a 1,000 kg car into a 5,100 kg truck at 50 km/h (angled offset) and 64 km/h (perpedicular offset) showed that the bumper did not stroke fully, although it proved effective in preventing

underun and passenger compartment intrusion. A central perpendicular test of a 1,550 kg car into the truck at 56 km/h also failed to stroke the bumper fully. To optimize the energy absorption the load required to stroke the bumper was reduced to 68 kN. The modified bumper stroked fully, in a central impact with a 1,000 kg car at 65 km/h (40 mph). This study clearly demonstrated that protection for car occupants at closing speeds of 65 km/h was possible providing occupant restraints are used. If seat belts are not worn or air bags are not provided, protection cannot be provided for occupants at relative speeds much above 40 km/h (25 mph).

A German study that looked at the possibilities of reducing the consequences of car-truck accidents found that more than half of car-truck fatalities occur to car occupants involved in frontal collisions with trucks.[7] The study concluded that, although the relative speeds in frontal collisions were high, reducing the agressitivity of the front end of the truck would also reduce the risks in truck collisions. In fact, if the results of the United Kingdom study (i.e., fatal collisions below 65 km/h are survivable with front energy absorbing guards) are applied to the German accident data, more than 40 percent of the fatal frontal collisions between cars and trucks would be affected.

The results of all three studies lead to the conclusion that energy absorbing bumpers on the fronts of trucks could provide a substantial saving of life. Over 2,000 accidents in the United States each year involve a car-truck collision in which there is fatal injury to the car occupant. Table 1 shows that in 1985, 624 of these collisions are

frontal impacts so that 32 percent or about 200 fatal accidents per year could be ameliorated by energy absorbing bumpers.

CONCLUSIONS

1. If trucks were constructed with front energy absorbing guards so that their energy absorbtion characteristics were similar to that of cars, the severity of injuries to car occupants involved in car/truck accidents could be substantially reduced.
2. Energy absorbing zones on the fronts of trucks could increase the ride down distance available to car occupants by 40 percent and reduce their average deceleration by a factor of 1.4.
3. Energy absorbing zones on the fronts of trucks could reduce the risk of fatal injury in car-truck collisions by as much as 33 percent.

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Table 1

Characteristics of Car Occupant Deaths in Car-Truck Crashes--1985 FARS Data

Impact Point		Car-truck Crashes with Car Occupant Fatality	
Truck	Car	N	Percent
Front	Front	624	29
Front	Side	690	32
Side	Front	192	9
Rear	Front	263	12
Front	Rear	118	5
Other		280	13
Total		2,167	100

Table 2

Number of Car Occupant and Truck Occupant Fatalities in Fatal Truck Crashes by Size of Car Involved--
FARS Data 1977-1985

Car Mass-lbs.	Truck Occupant Fatalities (N)	Car Occupant Fatalities (N)	Ratio Car/Truck Fatalities	Mean Car Mass-lbs.
1,500-1,999	17	595	35.0	1,851
2,000-2,499	35	912	26.1	2,275
2,500-2,999	34	1,022	30.1	2,723
3,000-3,499	49	1,601	32.7	3,240
3,500-3,999	52	1,273	24.5	3,741
4,000-4,499	29	756	26.1	4,211
4,500-4,999	14	245	17.5	4,750

Regression analysis results: fatality ratio = -0.0043 (mass) + 41.42; $r = -0.8$.

Table 3

Number of Car Occupant and Truck Occupant Fatalities in Fatal Frontal Car-truck Crashes by Size and Car Involved -- FARS Data 1977-1985

Car Mass-lbs.	Truck Occupant Fatalities (N)	Car Occupant Fatalities (N)	Ratio Car/Truck Fatalities	Mean Car Mass-lbs.
1,500-1,999	3	188	62.7	1,854
2,000-2,499	4	328	82.0	2,267
2,500-2,999	4	322	80.5	2,707
3,000-3,499	7	441	63.0	3,233
3,500-3,999	7	329	47.0	3,736
4,000-4,499	6	169	28.2	4,204
4,500-4,999	2	75	37.5	4,731

Regression analysis results: fatality ratio = -0.0163 (mass) + 110.1; r = -0.824.

Table 4

Regression Equation for Fatal Injury Odds for Car Occupants in Fatal Head-On Car-Truck Crashes

Independent Variable	Beta*	Std. Error	Chi-square	p value
Intercept	-4.810	0.187	664.0	0.0001
Car mass	6.8×10^{-4}	$2. \times 10^{-2}$	9.8	0.002
Accident year	0.079	0.070	1.3	0.26
Mass x year	-9×10^{-7}	8.2×10^{-5}	1.4	0.24

*$\log_e (1-p/p) = B_0 + B_1/ m + B_2 y + B_3 m/y$;
p = probability of fatal injury.

Table 5

Regression Equation for Fatal Injury Odds for Car Occupants Given a Truck Occupant Death in Head-on Car-Truck Crashes

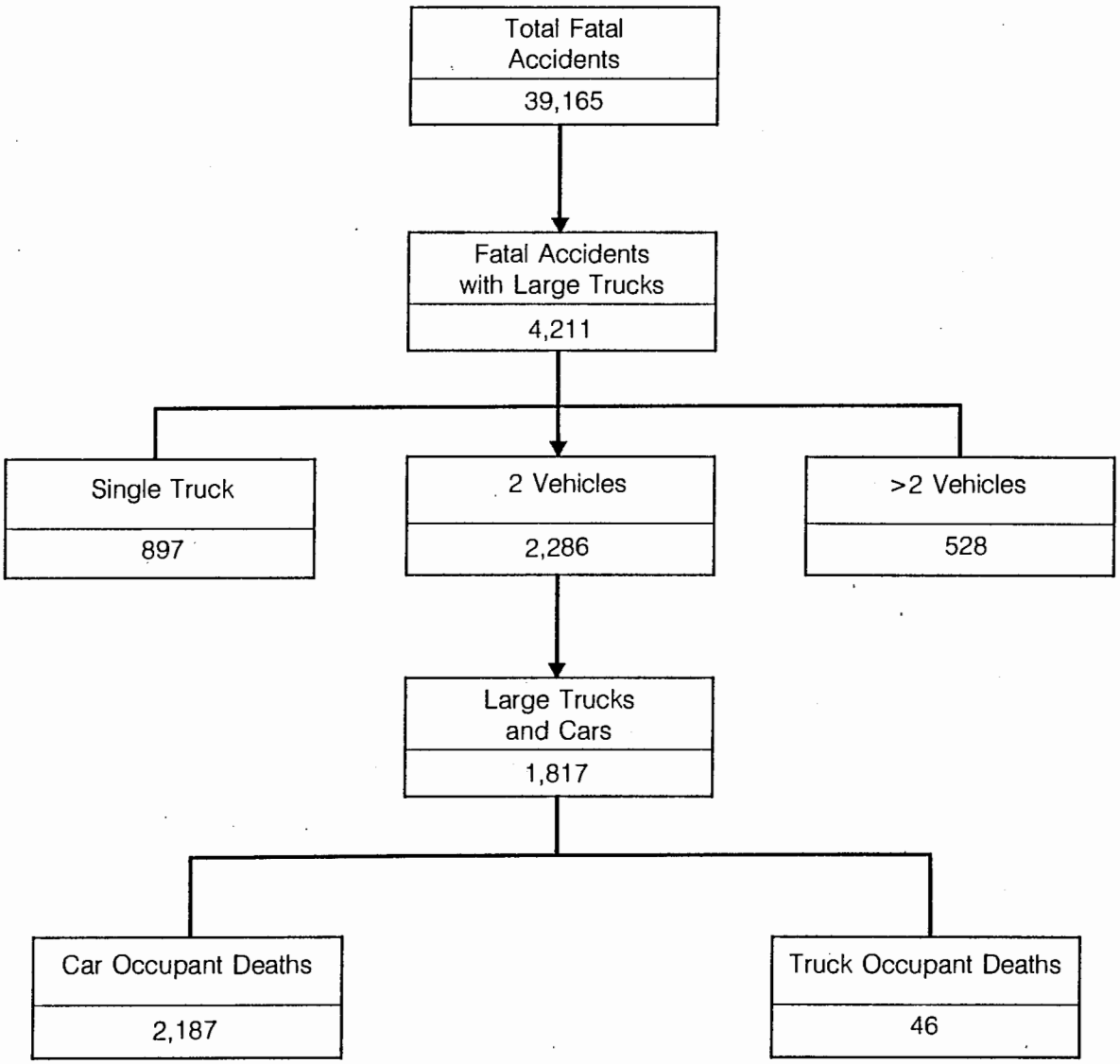
Independent Variable	Beta	Std. Error	Chi-square	p value
Intercept	-0.082	0.235	0.12	0.73
Car mass	4.1×10^{-4}	3.0×10^{-3}	1.51	0.22
Accident year	0.086	0.086	0.59	0.32
Mass x year	-8.0×10^{-5}	0.01	0.49	0.48

Table 6

Regression Equation for Fatal Injury Odds for Truck Occupants Given a Car Occupant Death in a Head-on Car-Truck Crashes

Independent Variable	Beta	Std. Error	Chi-square	p value
Intercept	4.645	0.165	793.4	0.0001
Car mass	-3.0×10^{-9}	0.02	3.6	0.06
Accident year	-0.01	0.063	0.0	0.87
Mass x year	5.0×10^{-5}	8.1×10^{-5}	0.4	0.53

Figure 1 - Distribution of Fatal Truck* Crashes by Number of Vehicles Involved — 1985 FARS Data



*Large trucks ≥ 26,000 lbs GVW.

Figure 2 - Central Collision Between Two Vehicles.

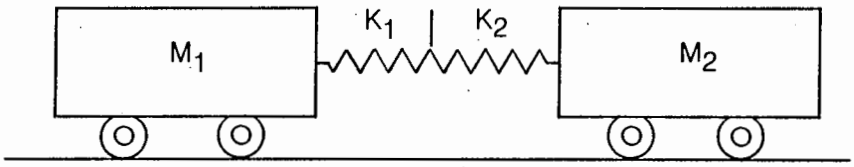


Figure 3 - Ratio of Car Occupant to Truck Occupant Deaths Versus Car Mass — All Crashes

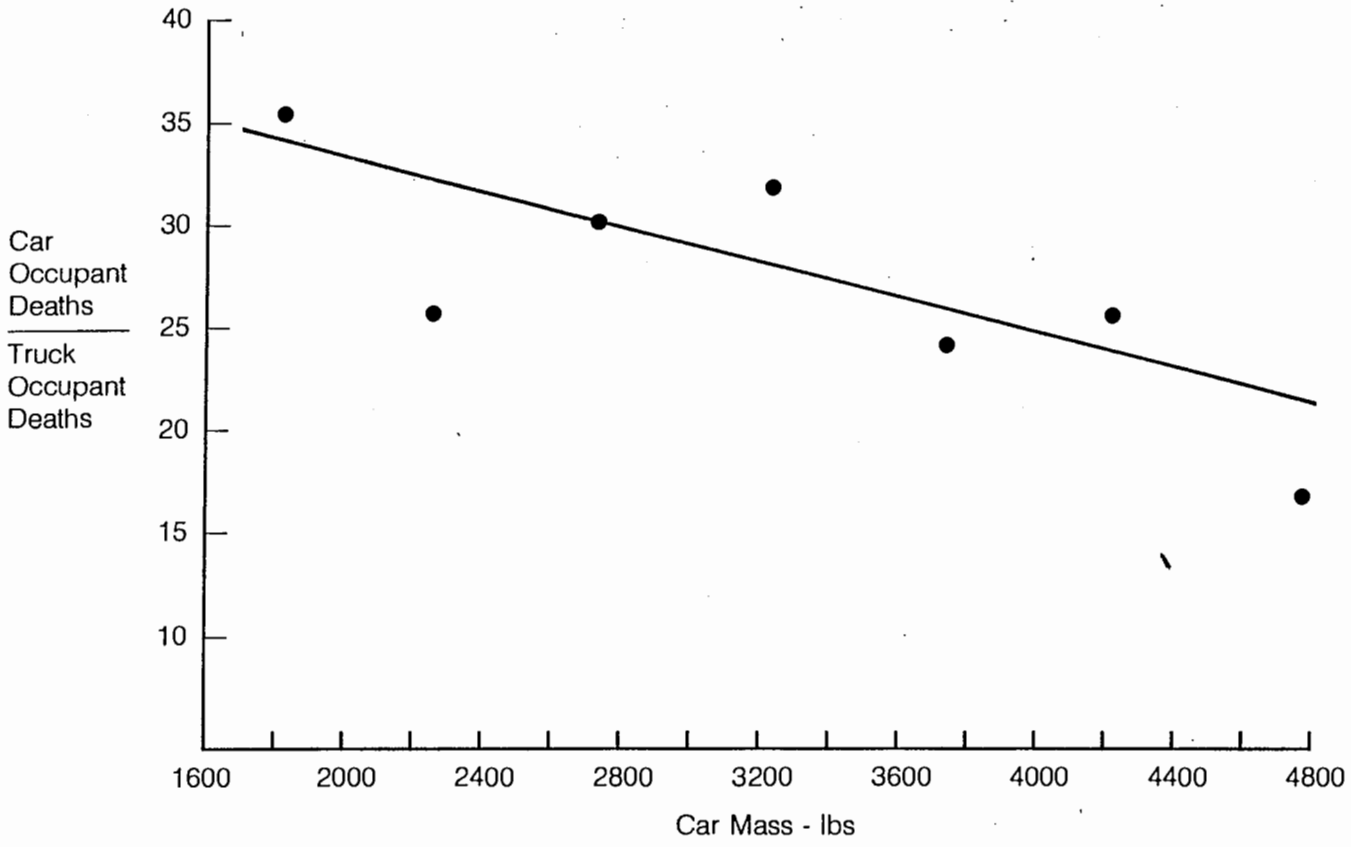


Figure 4 - Ratio of Car Occupant to Truck Occupant Deaths Versus Car Mass — Frontal Crashes