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How to Make a Car Lighter and Safer

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ABSTRACT

About the most firmly established vehicle-safety effect is that the heavier the vehicle, the lower are the risks to its occupants. Empirically data show that the additional mass of a passenger reduces driver fatality risk by 7%. While occupants of heavier vehicles enjoy increased safety, there are two important negatives associated with heavier vehicles. First, they increase risk to occupants of other vehicles into which they crash. Second, they consume more fuel. The size, or length, of a vehicle also affects safety. All other factors, including mass, being equal, a larger vehicle reduces fatality risk to its occupants. But unlike mass, it also reduces risk to occupants in vehicles into which it crashes. A quantitative relationship expressing fatality risk as a function of the mass and size of both cars involved in a two-car crash was derived in *Causal influence of car mass and size on driver fatality risk*, Am J Pub Health. 91:1076-81;2001. This relationship is used to provide quantitative examples of vehicles that are lighter, but at the same time larger by amounts computed so that the net effect is to lower driver fatality risk. The modified car thus provides lower fatality risk to its occupants, lower fatality risk to occupants of vehicles into which it crashes, and uses less fuel. While manufacturing such a vehicle requires increased use of more expensive lightweight materials, doing so produces concurrent benefits in safety, oil independence, and environment.

INTRODUCTION

It has been well established for over three decades that when traffic crashes occur, occupants in heavier/larger vehicles are at lower risk than occupants in lighter/smaller vehicles.[1-5] Since then support and details have been added by many studies through the latest.[6] Policies aimed at reducing fuel use have led to lighter vehicles, which have increased traffic fatalities.[7]

There are clear physical reasons why increased mass in a vehicle protects its occupants in nearly all types of crashes.[8] However, in two-vehicle crashes, an increase in mass of one vehicle exposes the occupants of the other vehicle to increased risk. Increased size of a vehicle also protects its occupants, but without any adverse effect on occupants of vehicles into which it crashes.

A vehicle's mass and size are strongly correlated, which has made it difficult to determine the separate causative roles of mass and size on risk. This paper quantifies how the increased fatality risk of reducing mass can be offset by increases in size leading to a car which provides increased protection to its occupants while at the same time reducing risk to occupants of cars into which it crashes.

The analysis relies on an equation expressing the fatality risk to a driver in a two-car crash as a function of the mass and size of the driver's car and the mass and size of the other involved car.[9] In order to make the present paper self-contained, the equation will be derived below prior to applying it.

WHY FOCUS ON TWO-CAR CRASHES? Data in the Fatality Analysis Reporting System (FARS)[10] show that, of the 25,840 drivers killed in US traffic in 2001, 43% died in two-vehicle crashes compared to 49% in single-vehicle crashes. Because cars constitute less than half of the vehicles on US roads, about one in five of all two-vehicle crashes involved two cars. There were 3288 fatalities in two-car crashes in 2001, 7.8% of all fatalities.

The reason why two-car crashes are studied so intensively is because they provide insight into crash process. For single-vehicle crashes, little information is generally available on damage suffered by struck objects. For a two-vehicle crash, the injury information collected for the other vehicle provides information that depends on crash factors such as impact severity. Curb masses are coded in FARS for cars, but not for other types of vehicles.

The quantitative risk results in this paper all relate exclusively to two-car crashes. However, it is plausible to interpret them as reflecting principles that are transferal to crashes in general.

SUMMARY OF STUDY RELATING RISK TO CAR MASS AND SIZE

While it has been long established that drivers of larger, heavier cars have lower risks in crashes than drivers of smaller, lighter cars, the question of how adding mass to an existing car affects risk proved more difficult to answer. One common way to express this question is

"Am I safer if I put bricks in my trunk?" While kinematic considerations[8,11,12] suggest an answer, there is little empirical information. Data sets rarely contain information on cargo, or on actual mass during crashes. All that is generally coded is a curb mass that is identical for all cars of the same make, model and engine. Information is, however, available on occupants.

One step in quantifying the role of mass without any consequent change in size was to assume that adding a passenger was equivalent to adding mass.[9] Head-on crashes between two cars were examined using 1975-1998 FARS data. One car contained only a driver, while the other contained also a right-front passenger. If all other factors are the same, the masses of the cars differed by the mass of the passenger.

The results contributed to the development of an equation that distinguishes between causal contributions from mass and size. The many relationships reported between fatality risk and car mass and between fatality risk and car size (additional references in Ref. 9) cannot distinguish between such causal contributions because mass and size are so highly correlated [13,]. The equation derived[9] expresses the risk to a driver as a function of the size and mass of both involved cars.

EFFECT OF ADDING MASS OF PASSENGER For every crash between two cars of known masses m_1 and m_2 we can define[14] a mass ratio, μ,

$$\mu = \frac{m_2}{m_1} = \left(\frac{\text{mass of heavier vehicle}}{\text{mass of lighter vehicle}}\right) \quad (1)$$

Consider a set of crashes with the same value of μ, or with values of μ confined to a narrow range. Assume that the total number of drivers killed in the lighter vehicles is N_1 and that N_2 drivers are killed in the heavier vehicles. A driver fatality ratio, R, can be defined as

$$R = \frac{F_1}{F_2} = \frac{N_1}{N_2} \ . \quad (2)$$

Many analyses using FARS data[15-18] have found that R and μ are related according to

$$R = \mu^{\lambda} . \quad (3)$$

For the case of interest here, cars crashing head-on into each other, the value of the parameter is λ=3.58 (Fig. 1). Eqn 3 applies to cars which are not differentiated by any attribute other than mass, so, by definition, R=1 when μ=1. The relationship is thus constrained to pass through the point μ =1, R = 1. Fitting data to Eqn 3 yields only one parameter, λ.

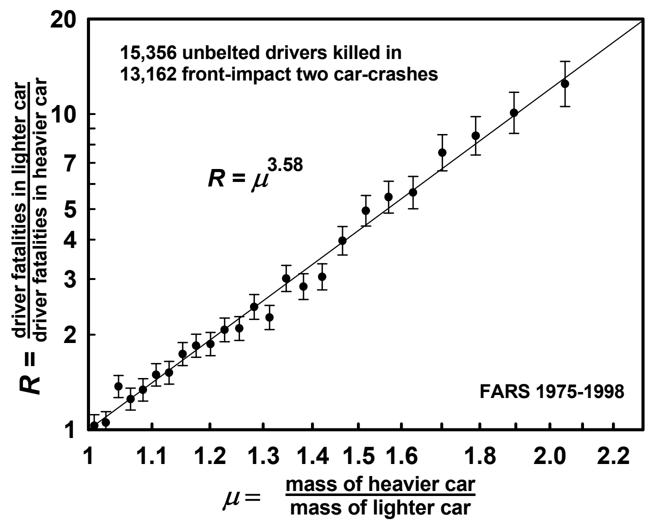

Fig. 1. The ratio, R, of driver fatalities in the lighter compared to in the heavier car versus the ratio, μ, of the mass of the heavier to the mass of the lighter car for frontal crashes (both cars with principal impact point at 11, 12 or 1 o'clock). The relationship is the first of the two "laws" of two-car crashes.[9]

When cars of the same mass crash into each other, Eqn 3 provides no useful information. However, five sets of data[19,20] and a calculated relationship[11] support (Fig. 2) that the relative driver risk, R_{MM}, when two cars of the same mass, M, crash into each other is given by

$$R_{MM} = \frac{k}{M} \quad (4)$$

where k is a constant.

Eqns 3 and 4 and their associated Figs 1 and 2, may be regarded as two "Laws of two-car crashes"; both refer only to relative risk. Later they contribute to an equation to estimate absolute risks to individual drivers.

If the cars are differentiated by some attribute other than mass, say one car is old and the other is new, then the value of R when μ = 1 measures the influence of car age on fatality risk. The earlier study[14] found that the relationship

$$R = \alpha\mu^{\lambda} \ , \quad (5)$$

fitted well such cases; the parameter α estimates the influence of the attribute when the masses are equal. In the present application, the cars differ in the attribute that one contains a passenger and the other does not.

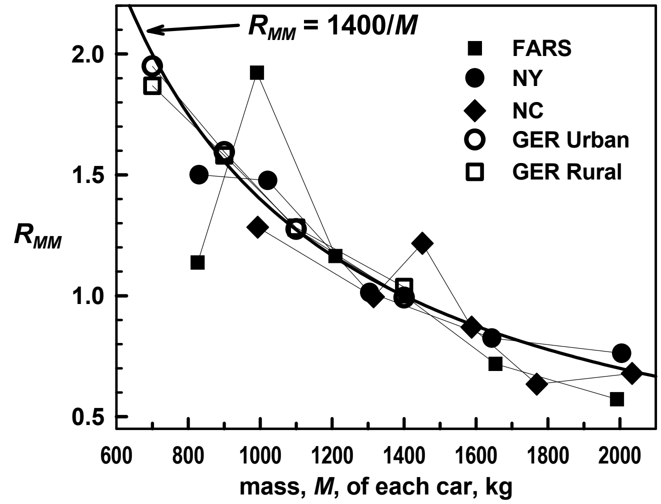

Fig. 2. Relative risk, R_{MM}, of driver injury or fatality when cars of similar mass crash head-on into each other versus M, the mass of each car. In all cases the data are scaled to assign a risk of 1 to M=1400 kg. The relationship is the second of the two "laws"[9]

FARS	Fatalities in US
NC	Injuries in North Carolina]
NY	Injuries in New York State]
GER Rural	Injuries on rural roads in Germany]
GER Urban	Injuries on roads in built-up areas in Germany]
Analytical curve	Computed from structural considerations

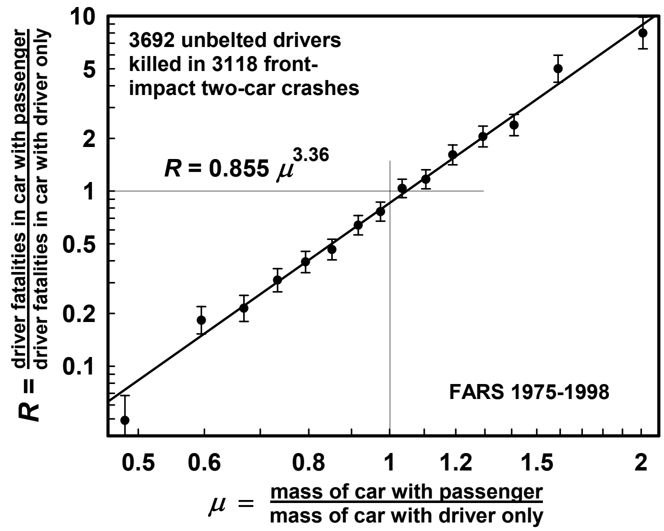

Fig. 3. The effect of adding a passenger.

Data. Two-car crashes satisfying the following criteria were extracted from FARS data[9] for 1975-1998.

- One car has a driver and a right-front passenger, whereas the other has only a driver.
- Frontal crashes only, defined as principal impact point[10] = 11, 12, or 1 o'clock for both cars.
- At least one of the drivers was killed (crashes in which the passenger was the only fatality were excluded).
- All three occupants were coded as unbelted.

This filtering process produced a sample of 3118 crashes. Each of the 15 points plotted in Fig. 3 uses at least 200 crashes.

The line in Fig. 3 is a weighted least squares fit to

$$\mathrm{Ln}(R) = \mathrm{Ln}(\alpha) + \lambda\ \mathrm{Ln}\,(\mu)\,, \tag{6}$$

the natural logarithm transformation of Eqn 5.

The fit gives λ = 3.36 ± 0.10, and, more central to the present study, α = 0.855 ± 0.023. It is convenient to discuss α in terms of $\Delta R = 100*(\alpha - 1)/R$, the percent change from the R = 1 value. The finding from Fig. 3 is that the presence of a passenger gives $\Delta R = -(14.5 \pm 2.3)\%$. This effect arises from an undetermined decrease in the accompanied driver's risk and an undetermined increase in the lone driver's risk. Note that the variable m in the equations so far introduced always refers to an existing car of mass m, so that larger values of m will imply also larger cars; The equations do not apply to adding mass to an existing car.

DERIVATION OF FUNCTION SEPARATING INTRINSIC MASS AND SIZE EFFECTS. When two cars, car_1 and car_2, of curb masses m_1 and m_2, crash into each other, the first of the two "laws" (Eqn 3) gives

$$R = \left(\frac{m_2}{m_1}\right)^{\lambda} \tag{7}$$

where R = the risk in car_1 divided by the risk in car_2.

Now compare driver risks in the following two crashes. The first crash is between two cars each of equal mass m_1. The second is between two cars each of equal mass m_2. The second "law" (Eqn 4) gives

$$\frac{\text{risk when two } m_1 \text{ cars crash into each other}}{\text{risk when two } m_2 \text{ cars crash into each other}} = \frac{m_2}{m_1} \tag{8}$$

When two bodies of the same mass crash into each other, Newtonian Mechanics shows that the value of the mass does not affect their post-crash trajectories. So, although Eqn 8 is expressed in terms of mass, the causal effect is intrinsically size.

The relationships above suggest expressing the risk, $r_{1,2}$, faced by the driver of car_1 in collisions with car_2 as

$$r_{1,2} \quad = \quad \frac{k}{m_1 + m_2} \times \left(\frac{m_2}{m_1}\right)^{t} \tag{9}$$

where k is an arbitrary scaling constant and t is a parameter. Choosing k = 2800 kg leads to the convenience of a driver risk of one for the base case of two 1400 kg cars crashing into each other. The risk, $r_{2,1}$, to the driver of car_2 crashing into car_1 in this same crash is given by Eqn 9 with m_2 and m_1 interchanged.

The risk ratio, $R = r_{1,2}/r_{2,1}$ reproduces the first "law" (Eqns 3 and 7) provided $t = \lambda/2$ (= 1.79). If car_1 and car_2 have the same mass, say m_1, and crash into each other, the risk to each driver is $k/(2\ m_1)$. If the cars have identical mass m_2, then the risk is $k/(2\ m_2)$. The ratio of these reproduces the second "law" (Eqns 4,8).

Based on the above, we decompose Eqn 9 into two components, one reflecting intrinsic size effects, and the other intrinsic mass effects.

$$r_{1,2} \quad = \quad k \quad \times \quad \frac{1}{m_1 + m_2} \quad \times \quad \left(\frac{m_2}{m_1}\right)^t$$

$$\begin{bmatrix}\text{net}\\ \text{effect}\end{bmatrix} \quad = \quad \begin{bmatrix}\text{intrinsic}\\ \text{size}\end{bmatrix} \times \begin{bmatrix}\text{intrinsic}\\ \text{mass}\end{bmatrix} \qquad (10)$$

The intrinsic mass effect is what happens if mass changes (such as by adding cargo), but size does not. The intrinsic size effect is what happens if size changes, but mass does not.

Although presented as a function of mass, the intrinsic size effect should be considered exclusively a function of the sizes of the cars associated with the indicated masses.

If cars of unequal mass crash into each other, the ratio of the risks to the drivers, r_1/r_2 is computed from Eqn 10 as

$$\frac{r_{1,2}}{r_{2,1}} = \frac{m_2 + m_1}{m_1 + m_2} \times \left(\frac{m_2}{m_1}\right)^t \times \left(\frac{m_1}{m_2}\right)^{1/t} = \mu^{2t} = \mu^{\lambda}, \qquad (11)$$

the same relationship in Eqn 3

If the cars are of the same mass M, Eqn 10 computes the risk in each as k/M, the same the relationship in Eqn 4 plotted in Fig. 2.

<u>Application of Eqn 10 to adding passenger</u>. Consider two 1400 kg cars crashing into each other with identical initial driver risks $r_{1,2} = r_{2,1} = 1$. If the mass of the first car is increased to 1475 kg by adding 75 kg cargo, its driver risk is reduced to (1400/1475) = 0. 911 but the risk in the struck car with unaltered mass is increased to (1475/1400) = 1.098. The ratio of these gives a reduction in risk ratio of 17.0%. This is in reasonable agreement, although somewhat larger than the empirically observed 14.5% reduction associated with adding a passenger. The difference may be a reflection of the fact that the passenger was unbelted and accordingly not locked to the vehicle structure, thereby discounting the influence of mass. If the risks to the individual drivers are rescaled so that the risk ratio matches the empirically determined value, we conclude that the addition of a passenger reduces the risk to the accompanied driver by 7.5%, but increases the lone driver's risk by 8.1%.

EQUATION 10 FITS MUCH EMPIRICAL DATA. Eqn 10 was shown to reproduce the two fundamental laws of two-car crashes shown in Figs 1 and 2. It also fits the empirical observations of effects due to changing car mass by the addition of a passenger. As this equation fits the key empirical data for two-car crashes, we use it below to make inferences about the safety effects of independently varying the mass and size of cars.

REDUCING MASS WHILE INCREASING SAFETY

In Eqn 10 the intrinsic size term is expressed in terms of mass in order to keep the equation as simple as possible. However, the intrinsic size term, m_1 means a car the size of a car of mass m_1. In what follows it will be more appropriate to express the intrinsic size term explicitly in terms of a vehicle's linear dimensions.

To do this we use the data shown in Fig. 4, which shows mass versus wheelbase for each of the 4081 unique pairs of wheelbase and mass combinations for cars of all model years coded in 2001 FARS. Cars associated with more than one mass (say because they are sold with different engine choices) contribute more than one data point. However, the number of unique wheelbase-mass pairs reflects mainly the enormous variety of cars on the roads.

The function fitted to the data is

$$m = (7.10w)^{2.45} \quad . \qquad (12)$$

where m is the curb mass in kg and w is the wheelbase in meters. Substituting this into Eqn 10, and assuming that the overall length, L, of a car is proportional to its wheelbase leads to

$$r_{1,2} \quad = \quad c \quad \times \quad \frac{1}{L_1^{2.45} + L_2^{2.45}} \quad \times \quad \left(\frac{m_2}{m_1}\right)^t$$

$$\begin{bmatrix}\text{net}\\ \text{effect}\end{bmatrix} \quad = \quad \begin{bmatrix}\text{intrinsic}\\ \text{size}\end{bmatrix} \quad \times \in \begin{bmatrix}\text{intrinsic}\\ \text{mass}\end{bmatrix} \qquad (13)$$

where L_1 and L_2 are the total lengths of the cars of masses m_1 and m_2, and t = 1.79. The value of the constant c is chosen so that the risk to a driver in a "typical" 1400 kilogram car of length 4.8 meters crashing into an identical car is equal to one. That is, $c = 2 \times (4.8^{2.45})$. Eqn 13 gives the absolute risks (to within this fixed scaling constant) as the masses and lengths of the cars change. Absolute risks will thus be

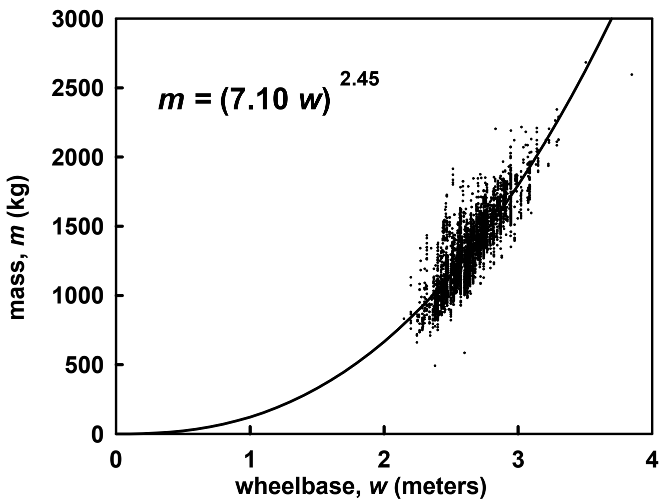

Fig. 4. Mass versus wheelbase for vehicles coded in 2001 FARS data

expressed in units in which the value one refers to one typical car crashing into another typical car.

MAKING A CAR LIGHTER AND SAVER

Let us characterize car$_1$ by the parameters m_1 and L_1. Using Eqn 13 we can estimate the risk, $r_{1,2}$, faced by the driver of the first car when it crashes into a second car of mass m_2 and length L_2. Similarly, Eqn 13 gives the risk, $r_{2,1}$, of the driver of the second car in this same crash. The total risk (societal risk, or risk to society), r_T, is

$$r_T = r_{1,2} + r_{2,1} \tag{14}$$

Because there are four independent variables in each of the two terms in Eqn 14 it is difficult to visualize how each affects total risk. However it is straightforward to estimate for specific cases using spreadsheet software such as Excel. A number of examples are presented below using three cars for illustrative purposes: -

- Small car mass = 1000 kg, length = 4.2 m
- Typical car mass = 1400 kg, length = 4.8 m
- Large car mass = 1800 kg, length = 5.3 m

TYPICAL CAR CRASHING INTO A TYPICAL CAR. In the results presented in Table 1 the simplest case of two typical cars crashing into each other is identified as case 1. The risks to each driver are identical, and because of our choice of the constant *c* in Eqn 13, are equal to one.

Suppose that the driver of the first car seeks additional crash protection by adding 75 kg of cargo. That is, mass changes but size remains the same. This additional mass reduces the first driver's risk by 8.9% (case #2 in Table 1) but increases the risk to the other driver by 9.8%. The net effect is an increase in total risk of 0.4%. This case is presented because it relates to the effects

Table 1. Results for two-car crashes derived from Eqn 13. The first car characteristics are varied, starting, in case #1, with those of a "typical" car with m_1 = 1400 kilograms and L_1 = 4.8 meters. In all cases the second car is a typical car with m_2 = 1400 kg and L_2 = 4.8 m.

case#	*first-car characteristics*		*driver fatality risks and % change from case #1*		
	L_1, m	m_1, kg	$r_{1,2}$	$r_{2,1}$	r_T
1	4.8	1400	1 –	1 –	2 –
2	4.8	1475	0.911 -8.9%	1.098 +9.8%	2.009 +0.4%
3	5.0	1400	0.950 -5.0%	0.950 -5.0%	1.900 -5.0%
4	4.8	1362	1.050 +5.0%	0.952 -4.8%	2.002 +0.1
5	5.0	1362	0.998 -0.2%	0.904 -9.6%	1.902 -4.9%

previously found empirically[9] for adding a passenger to an existing car.

Increasing the length of the first car from 4.8m to 5.0 m (keeping everything else the same) decreases the first driver's risk by 5.0% (case #3). In accord with Eqn 13, this same risk reduction applies also to the driver of the other car, leading to a total reduction of 5.0%.

The identical risk reduction to both drivers is expected on physical grounds. A car being larger provides more crushable material in front, so that another vehicle crashing into it is provided a longer distance over which to reduce speed. Increased car length might be thought of as equivalent to carrying a mattress in front of the car. In a crash between two cars, this mattress is interspersed between the cars, reducing crash forces on each. Regardless of which car transports the mattress to the location between the cars at the crash scene, each car benefits equally.

Suppose that a vehicle manufacturer in an effort to increase the fuel economy of a typical car reduces its mass from 1400 kg to 1362 kg. This will increase the risk to its driver by 5.0% (case #4). This lighter car reduces the other driver's risk by 4.8%, leading to a 0.1% increase in societal risk. Now suppose that the redesign also incorporates an increase in length from 4.8 m to 5.0 m. The result (case #5) is that the redesigned car now reduces the first driver's risk by 0.2% and the other driver's risk by 9.6%, for a net risk reduction of 4.9%.

The redesigned car thus reduces risk to its occupants, reduces risk to the occupants of vehicles into which it crashes, and, being lighter, consumes less fuel.

TYPICAL CAR CRASHING INTO SMALL OR LARGE CARS. When a typical car crashes into a small car, the typical-car driver's risk is 0.636 and the small-car driver's risk is 2.122, for a total societal risk of 2.759 (the first case #1 in Table 2). Thus the total risk is 38% greater than when two typical cars crash into each other.

Table 2. Varying characteristics of typical car crashing with a small car (top 3 rows) and a large car (bottom 3 rows). For the top 3 rows $m_2 = 1000$ kg and $L_2 = 4.2$ m and for the bottom 3 rows $m_2 = 1800$ kg and $L_2 = 5.3$ m.

case #	*first-car characteristics*		*driver fatality risks and % change from case #1*		
	L_1, m	m_1, kg	$r_{1,2}$	$r_{2,1}$	r_T
1	4.8	1400	0.636 –	2.122 –	2.759 –
2	4.8	1362	0.668 +5.0%	2.020 -4.8%	2.689 -2.5%
3	5.0	1362	0.630 -1.0%	1.904 -10.3 %	2.534 -8.1%
1	4.8	1400	1.379 –	0.561 –	1.939 –
2	4.8	1362	1.448 +5.0%	0.534 -4.8%	1.982 +2.2%
3	5.0	1362	1.384 +0.4%	0.510 -9.0%	1.894 -2.3%

If the typical car is now made 38 kg lighter, it's driver's risk increases by 5.0% and the other driver's risk declines by 4.8%. (These are the same values as before because it is apparent from Eqn 13 that if m_2 is fixed, the same change in m_1 produces the same fractional change in $r_{1,2}$). However as the risk in the small car is much larger than in the typical car, the 4.8% decline is a larger absolute amount, so the net effect is a decrease in total risk of 2.5%. If the typical car is redesigned to increase in length to 5.0 m as well as reducing in mass, its driver has 1.0% reduction in risk, the other driver a 10.3% reduction in risk, for a total risk reduction of 8.1%. So making the typical car 38 kg lighter and 0.2 m longer reduces risk to all in crashes with light cars, and with a greater societal benefit than was so for crashes between two typical cars.

When typical car and large cars crash, the risks to the drivers are 1.379 and 0.561 (case #1 in column 4 of Table 2). The total risk, 1.939, is 3% less than when two typical cars crash into each other. If the typical car is redesigned to be 38 kg lighter and 0.2 m longer, its driver has a small increase in risk of 0.4% in a crash with a large car. The driver of the large car has a 9.0% reduction in risk, for a total risk reduction of 2.3%.

In the above results, adjustments in mass and length were made only to the typical car. Below we change the mass and length of small and large cars. However, in all cases the mass reduction is the same 38 kg. To a rough approximation the fuel used per unit mass of vehicle is independent of vehicle mass, so removing the same 38 kg from any vehicle will (other things being equal) reduce national fuel use by a similar amount. It is of course possible to contemplate much larger mass reductions (and size increases) in larger cars. For all illustrations we use the same 0.2 m increase in length. We will refer to an original car reduced in mass by 38 kg and increased in length by 0.2 m as a "redesigned car".

SMALL CARS CRASHING INTO OTHER CARS. The results for making the same changes as above to small cars are shown in Table 3. The initial case of an unaltered small car crashing into a typical car is shown as case #1 in column 1. In crashes with typical cars, the lighter longer small car still exposes its driver to a risk increase of 2.0%, but still much less than the 7.2% increase that would result from the mass increase alone. The net effect of reducing the mass while increasing the length of the small car is a total risk reduction of 1%.

Table 3. Varying characteristics of small car crashing with a typical car (top 3 rows) and a large car (bottom 3 rows). For the top 3 rows $m_2 = 1400$ kg and $L_2 = 4.8$ m and for the bottom 3 rows $m_2 = 1800$ kg and $L_2 = 5.3$ m.

case #	*first-car characteristics*		*driver fatality risks and % change from case #1*		
	L_1, m	m_1, kg	$r_{1,2}$	$r_{2,1}$	r_T
1	4.2	1000	2.122 –	0.636 –	2.759 –
2	4.2	962	2.275 +7.2%	0.594 -6.7%	2.868 +4.0%
3	4.4	962	2.165 +2.0%	0.565 -11.2%	2.730 -1.0%
1	4.2	1000	2.870 –	0.350 –	3.220 –
2	4.2	962	3.076 +7.2%	0.326 -6.7%	3.402 +5.7%
3	4.4	962	2.947 +2.7%	0.313 -10.6%	3.260 +1.3%

In crashes with large cars (the last three columns in Table 3), removing 38 kg while increasing the length of a small car by 0.2 m exposes its driver to a risk increase of 2.7% and in this case leads to a total risk increase of 1.3% (compared to 5.7% if the car had not been increased in length).

LARGE CARS CRASHING INTO OTHER CARS. When crashing into a typical car, the driver of the redesigned large car enjoys a 1.4% reduction in risk, the other driver an 8.6% reduction for an overall societal benefit of 6.5% (Table 4). When crashing into a small car, benefits are even larger. The driver of the redesigned large car enjoys a 2.1% risk reduction, the driver of the other car a 9.3% reduction, for an overall societal reduction of 8.5%.

Table 4. Varying characteristics of large car crashing with a typical car (top 3 rows) and a small car (bottom 3 rows). For the top 3 rows $m_2 = 1400$ kg and $L_2 = 4.8$ m and for the bottom 3 rows $m_2 = 1000$ kg and $L_2 = 4.2$ m.

case #	*first-car characteristics*		*driver fatality risks and % change from case #1*		
	L_1, m	m_1, kg	$r_{1,2}$	$r_{2,1}$	r_T
1	5.3	1800	0.561 –	1.379 –	1.939 –
2	5.3	1762	0.583 +3.9%	1.327 -3.7%	1.910 -1.5%
3	5.5	1762	0.553 -1.4%	1.260 -8.6%	1.813 -6.5%
1	5.3	1800	0.350 –	2.870 –	3.220 –
2	5.3	1762	0.364 +3.9%	2.762 -3.7%	3.126 -2.9%
3	5.5	1762	0.343 -2.1%	2.604 -9.3%	2.947 -8.5

These results show that removing the same mass from a larger car generates a lower increase in risk (compare two cases labeled 2 in Table 3 to those in Table 4). If a redesign involves a mass reduction accompanied by a length increase, the safety benefits are greater if the redesign is applied to large cars than to small cars (compare two cases labeled 3 in Table 3 to those in Table 4).

Eqns 10 and 13 are well suited to examine how different distributions of cars by mass and size affect risk in a complete fleet of vehicles, and how different strategies to modify vehicles would affect fleet risk.

DISCUSSION

It has been long recognized that: -

- If a car is heavier, it reduces risk to its driver, but increases risk of other drivers.
- If a car is larger (without also being heavier), it reduces risk to its driver and also reduces risks to other drivers.

While these factors have been recognized qualitatively, quantification has proved elusive. In this paper a quantitative relationship showing how fatality risk depends causally on vehicle mass and length was applied to explore what length increases were required to offset the risk increases from reducing vehicle mass. Examples are given of design changes required to reduce risks to the occupants of vehicles and to the occupants of other vehicles into which they crash.

The analysis is based on results derived from frontal two-car crashes. However, car mass/size effects for crashes in all directions are similar to those for frontals, and similar for belted and unbelted drivers, and similar for different occupants.[14] As increasing the length of car will likely involve increases in other dimensions, increased protection is likely to be available for crashes in all directions. Thus the results are likely to be reasonably transferable to all occupants in all two-vehicle crashes.

Fatality-risk changes due to mass and size arise from changes crash-produced deceleration forces. Hence changes in the risk of non-fatal injuries risk are expected to be in the same direction, but possibly of lower magnitude, as this was the case for mass.[11] That is, a vehicle change that reduces (increase) fatality risk will reduce (increase) injury risk in general.

Increased dimensions in a car provide increased occupant room and comfort, increased trunk space, easier engine maintenance and repair, etc. – all customer benefits. Reducing mass reduces fuel and emissions if the engine remains unaltered. However, the acceleration performance increases as vehicle mass decreases, which is another customer benefit. If lower mass indicates a smaller displacement engine, the fuel savings could, in principle, be compounded with the vehicle performance unaltered.

Unlike the risk ratios (such as in Eqn 5) that are so prevalent in two-vehicle crash research, Eqns 10 and 13 express absolute risks (in arbitrary units). The results therefore apply to crashing into other objects with properties like those of a car. Hence the results have some approximate transferal to certain single-vehicle crashes.

This study does not address such important design considerations as structural stiffness or geometric details. It is generic and does not offer specific design methods to increase vehicle length while reducing mass. Such changes are likely to require increased use of lightweight materials, which tend to cost more than steel. The amount of lightweight material required would be more than that required to reduce the mass of the original vehicle by 38 kg (in our example) because the redesigned vehicle must be 0.2 m longer while at the same time lighter than the former smaller vehicle. Material substitution sufficient to make a longer vehicle lighter than the original vehicle would be required.

The safety benefits from the types of redesigned vehicles explored are substantial. The last example in Table 4 shows that removing 38 kilograms mass and adding 0.2 meters length to a large car generates an 8.5% reduction in net fatality risk in crashes between large and small cars. This reduction applies to all occupants in all seats in both vehicles. Compare this to the 8-12% reduction in fatality risk airbags provide to drivers or right-front occupants[21,22], with a possible increase for other injury levels[23-25]. Airbags add about $500 to the cost of a vehicle; airbags on the roads of the United States in 2003 have cost their owners over 50 billion dollars[26].

CONCLUSIONS

Increasing the amount of light-weight materials in a vehicle can lead to lighter, larger vehicles possessing all of the following concurrent characteristics: -

- Reduced risk to its occupants in two-vehicle crashes
- Reduced risk to occupants in other vehicles into which it crashes
- Reduced risk to its occupants in single-vehicle crashes
- Reduced fuel consumption
- Reduced emissions of carbon dioxide, etc

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