CAR CRUSH, SIZE and SAFETY in FRONTAL COLLISIONS

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ABSTRACT

This study examines the frontal crush behaviour of the car population and shows that the specific energy absorption per unit mass properties of the car population are independent of car size. Examination of the car to car collision equations in this context shows that the mean deceleration experienced by a car is inversely proportional to car length, is related to the square root of collision closing speed and to the inverse of the fourth root of mass ratio and of crush depth. It is hypothesised for any specific car population and given degree of occupant protection within this population that Relative Injury Risk is proportional to the 2.5 power of mean deceleration. The model so derived is compared with published Relative Injury Risk data for collisions between similar cars, dissimilar cars, for overall risk to cars of specific size within the car population and for individual car ratings derived from analysis of accident data and very high correlations obtained.

INTRODUCTION

There has been concern for many years about car size and safety, particularly the relative safety of small cars. Various studies (refs. 1 to 10) have shown that car mass has a profound effect on safety and that injury risk is inversely related to car mass. A study in the U.S. (5) has indicated for frontal collisions, that, when cars of dissimilar mass collide, the fatality risk of drivers in the lighter car is between 7 and 13 times that of drivers in the larger car where the mass ratio between the cars is 2. A further U.S. study (2) has shown, when two light cars (mass 900 kg.) collide head on with each other, the driver's risk of serious or fatal injury is twice the risk of similar injury when two heavy cars (mass 1800 kg.) collide with each other. Recent studies in Germany by BASt. of frontal collisions (9,10) has obtained similar results. The BASt. investigation has also indicated that the mean risk of injury in a small car (mass 700 kg.), regardless of the size of the opposing car, is 2.5 times that of a large car (mass 1400 kg.) while a Swedish study (8) has found that drivers of 800 kg. cars have twice the injury rate of drivers of 1400 kg. cars.

Various possible explanations have been advanced for this phenomenon, the greater deformation space in larger cars, the differences in the aggressivity of the car structures, in the safety enhancing features of larger cars, etc.. This paper examines the frontal crush characteristics of the car population and the influence of the energy absorbing properties of car fronts and car size on relative safety.

FRONTAL CRUSH OF CARS

On impact the initial forces are frequently low. A large force pulse occurs as the engine becomes involved in the crushing process. High crushing forces are generated as the full front structure of the car is engaged. Emori (11) showed that the crush behaviour of car fronts could be represented by a linearly increasing force while Lim (12) showed that the fronts of some cars could be considered as having a constant crushing force. More recent investigations (13, 14, 15, 16) show that the frontal crush of cars can be represented as two constant crushing force regimes, an initial low crushing force followed by a high crushing force with a transition when the engine becomes involved in the crushing process. In more general terms Prasad (17) has shown that the frontal crush of cars can be equally well represented as either being constant force or linearly increasing force crushing.

Of particular interest is the ability of car fronts to absorb energy. Thornton (18) has shown that a key measure is the energy absorption per unit mass, called the Specific Energy Absorption. For structures which crumple with a constant force Thornton (18) and Pugsley (19) show that the

Specific EnergyAbsorption is related to an effective stress/ density parameter and to normalised crush depth.

$$SEA = \frac{E}{M_k} = \frac{\sigma}{\rho} \times \frac{d}{L} \qquad (1)$$

The effective crumpling stress/density parameter is also referred to as the Specific Energy Absorption Capacity (SEAC). For linear and other force representations similar forms of relation can be obtained between specific energy absorption and normalised crush depth. For the linear crushing model the relation between √(2 x Specific Energy Absorption) and normalised crush depth (d/L) is,

$$\left(\frac{2 \times E}{M_k}\right)^{\frac{1}{2}} = b_0 + b_1 \times \frac{d}{L} \qquad (2)$$

Figure 1 shows the value of the b_1 coefficientfor 145 individual cars derivedfrom Prasad's data (17) plotted as a function of overall length. There is no correlation between b_1 and car length. A similar plot of b_1 against curb mass shows that the values of b_1 are independent of mass.

Figure 2 from (20) shows the √(2 x Specific Energy Absorption) from 202 barrier tests involving 67 car types plotted as a function of normalised crush depth (d/L). Both the data in figure 1 and figure 2 show that the Specific Energy Absorption characteristics of the car population can be taken as being independent of car size.

INJURY CRITERION

Occupant injury mechanisms in collisions are complex. The most serious injuries are generally to the neck, head and brain. Gadd (21) derived an empirical injury severity index which was the integral with respect to time of deceleration to the 2.5 power. In car to car frontal collisions the impact durations are broadly similar over the collision range. For these collisions it is hypothesised that injury risk within any car population which has the same degree of occupant protection over the population range is proportional to mean deceleration to the 2.5 power .

RELATIVE INJURY RISK MODEL

The mean deceleration imposed on a car in the course of a collision depends on a large number of factors. Among the most important are the mass ratio of the cars,the aggressivity of the case car, the collision closing speed of the collision partners towards one another, the ratio of the crush depths of the collision partners and the length of the case car. Appendix 1 shows the derivation of the Injury Risk equation,

$$IR \propto \left(\frac{SEAC_c^{\frac{15}{8}}}{L_c^{\frac{5}{2}}}\right) \times \left[\frac{CCS^2}{\left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \qquad (3)$$

When we further assume for a particular car population and for a specific type of collision, urban or rural, thatthe distribution of collision closing speeds is the same for all car sizes and that the degree of seat belt and of other occupant protection is the same for all car sizes the Relative Injury Risk for occupants in the case car of size M_c and L_c in collision with a car of mass M_p becomes,

$$RIR = \left(\frac{SEAC_c}{SEAC_b}\right)^{\frac{15}{8}} \times \left(\frac{L_b}{L_c}\right)^{\frac{5}{2}} \times \left[\frac{4}{\left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \qquad (4)$$

with respect to collisions between two similar cars of length L_b, mass M_b and specific energy absorption $SEAC_b$.

IMPACTS BETWEEN CARS OF SIMILAR SIZE

When the case car and its partner are the same size the Relative Injury Risk equation reduces to,

$$RIR_{s\ to\ s} = \left(\frac{L_p}{L_c}\right)^{\frac{5}{2}} \qquad (5)$$

for cars of average specific energy absorption capacity.

BASt (9,10) evaluated the proportion of fatally and seriously injured drivers in frontal collisions which involved either serious injury or serious material damage. This study of both urban and rural accidents in Rhine-Westphalia, over the period August 1984 to December 1988 when seat belt usage was is excess of 90%, determined injury risk by mass of the case car and of its collision partner. The car population was divided into 4 mass groups with mean masses of 700, 900, 1100 and 1400 kg.

The actual and calculated Relative Injury Risk for collisions between cars of similar mass, e.g. 700 kg versus 700 kg., 900 kg. versus 900 kg., etc. is compared using the Relative Injury Risk for collisions between cars of mass 1400 kg. as 1.0. The calculated Relative Injury Risk was computed using the car length to mass relationship derived in (20) for saloon cars (sedans),

$$L_m = -0.74 + 0.49 \times [M_k(kg)]^{\frac{1}{3}} \qquad (6)$$

This relation is based on data for 832 cars and has a correlation coefficient, r = 0.932.

Evans (2) published data for the proportion of serious and fatal injuries in collisions between cars of similar mass in New York State in 1971 and 1972 and estimates for North Carolina for the period 1968-1971. The seat belt usage was 41% forthe New York accidents. Linear and Power regression equations of the forms:

$$RIR_a = a + b \times RIR_{Calc}$$

$$RIR_a = c \times RIR_{Calc}^{n}$$

were used to compare the actual and calculated Relative Injury Risk values. This analysis shows:

Data Source	N	Linear Regression			Power Regression		
		a	b	r	c	n	r
BASt	8	0.11	0.91	0.986	1.01	0.941	0.990
New York and North Carolina	11	0.12	0.86	0.901	0.97	0.943	0.910
Combined	19	0.07	0.92	0.960	0.99	0.974	0.957

Figure 3 compares the actual and calculated Relative Injury Risk for the three sets of data. A high degree of agreement between the data and calculated Relative Injury Risk is apparent. While the best fit linear regression does not go through the origin the power regression indicates a virtual 1:1 correspondence between calculated and actual Relative Injury Risk.

CRUSH DEPTH

The Relative Injury Risk for the case car in the general case depends on the ratio of the mean crush depths of the case car and its collision partner. This ratio will depend on the crush characteristics of the two cars, the nature of the collision, the degree of overlap between the two cars and the manner in which the overlap influences the crushing force variation with crush depth. An equation of the general form,

$$\left(\frac{d_p \times L_C}{d_c \times L_p}\right) = \left(\frac{SEAC_c}{SEAC_p}\right)^{\frac{1}{n}} \times \left(\frac{L_p}{L_c}\right)^{\frac{1}{n}} \times \left(\frac{M_c}{M_p}\right)^{\frac{1}{n}} \tag{7}$$

was used to analyse crush data from 36 frontal collisions, 5 full width, 19 with overlap between 40% and 60% with the balance having overlaps in the range 10% to 40%. Power regression yielded the relation,

$$\frac{d_p}{d_c} = \left(\frac{L_p}{L_c}\right)^{2.342} \times \left(\frac{M_c}{M_p}\right)^{1.342} \tag{8}$$

with a correlation coefficient, r = 0.375. This correlation is significant at the 2.5% level. Calculation of the ratio of the Specific Energy Absorption Capacities, $SEAC_c/SEAC_p$, yielded a mean ratio of 0.99 with a coefficient of variation of 0.23. This compares with a coefficient of variation for the Specific Energy Capacity for the car population of 0.19 (22).

IMPACTS BETWEEN CARS OF DISSIMILAR SIZE

When the case car collides with a car of dissimilar mass the Change in Relative Injury Risk of the case car in comparison with a collision with a similar car is,

$$\Delta(RIR) = \left[\frac{4}{\left(1+\frac{M_c}{M_p}\right) \times \left(1 + \left\{\left(\frac{M_c}{M_p}\right)^{1.342} \times \left(\frac{L_p}{L_c}\right)^{2.342}\right\}\right)}\right]^{\frac{5}{8}} \tag{9}$$

for cars of average specific energy absorption capacity.

Figure 4 compares the data from BASt (9,1 0) with the calculated values. Regression yields the following,

Regression	N	Equation	r
Linear	24	$\Delta(RIR) = -0.01 + 1.05 \times Calc$	0.935
Power	24	$\Delta(RIR) = 1.04 \times Calc^{1.021}$	0.955

The total Relative Injury Risk for the case car whether it collides with similar or dissimilar cars will depend on the masses and lengths of the case car and its partner, their specific energy absorption capacities and on the length of the base car size, equation 4. Figure 5 compares the Relative Injury Risk for cars of average specific energy absorption capacity, calculated using equations 4 and 8, with the BASt data plotted as a function of mass ratio. Regression analysis yields,

Regression	N	Equation	r
Linear	32	$RIR_a = 0.058 + 0.98 \times Calc$	0.981
Power	32	$RIR_a = 1.04 \times Calc^{0.988}$	0.986

OVERALL RELATIVE INJURY RISK AND CAR SIZE

Provided each case car size is equally involved with all other car sizes in the course of frontal collisions then it is hypothesised that the Overall Relative Injury Risk for the case car size would be equivalent to the case car colliding with a collision partner of mass and length equal to the mean mass and length for the car population under consideration. This can be determined from equation 4 by using the mean mass and length of the car population as the collision partner. BASt (9, 1 0) detailed the proportion of serious and fatal driver injuries in rural accidents for 1 0 car mass sizes from 650 kg. in 1 00 kg increments to 1 550 kg. Figure 6 shows the variation in the actual and calculated Overall Relative Injury Risk as a function of car mass. The calculated data uses a mean car mass of 1 050 kg. and mean length of 4.24 m. The Overall Relative Risk is set to 1 .0 for the mean car mass of 1050 kg. Folksam Insurance (6) published data on the Overall Relative Injury Risk of 47 cars. Figure 7 compares the calculated risk with the Folksam rating which is based on actual accident data. Linear regression shows,

Data Source	N	Equation	r
BASt	10	$ORIR = 0.04 + 0.987 \times Calc$	0.994
Folksam	47	$ORIR = 0.10 + 1.020 \times Calc$	0.784

DISCUSSION

Examination of the frontal crush characteristics of the car population indicates that the energy absorption capacity per unit mass of the car population can be regarded as being independent of car size. This implies that the mean deceleration experienced in a collision is, among other factors, inversely proportional to car length. Examination of barrier test data for 67 car types involved in 202 staged tests shows (22) that the specific energy absorption of the car population can be represented by a function of the normalised crush depth to the 4/3 power. This relation is due to the essentially constant force crushing of most cars and to the effectively uniform density distribution of car mass which results in decreasing residual mass with increasing crush depth (22).

Derivation of the mean deceleration experienced by the case car in car to car collisions shows that it is inversely proportional to the car length, is related to the square root of collision closing speed, and to the inverse of the fourth root of both the mass ratio and to the ratio of crush depths. It is hypothesised, based on Gadd, Severity Index, and H.I.C., that general injury risk is proportional to the 2.5 power of mean deceleration. Thus an Injury Risk model is derived.

This injury risk model is tested against actual Relative Injury Risk data for serious and fatal injuries in collisions between cars of similar size viz, 800 kg. versus 800 kg. etc. published by BASt (9,10) and Evans (2) and very high correlation obtained. Specifically, the model predicts that the Relative Injury Risk to drivers when two 700 kg. cars collide is 1.98 times the risk when two 1400 kg cars collide. This compares with the BASt (9,10) results of 1.8 for rural accidents and 1.96 for urban accidents. Evans (2) predicts a Relative Injury Risk of 2.04 for collisions between two 900 kg. cars compared with collisions between two 1800 kg. cars; the model prediction is 1.96.

In order to examine collisions between cars of dissimilar size an empirical equation was derived from 36 collisions for the relationship between the ratio of crush depths and car size. This equation was added to the injury risk model and compared with data from BASt for collisions between dissimilar cars. High correlation was obtained.

It is hypothesised that the Overall Relative Injury Risk of a car mass group within any car population can be determined by representing the car population as a collision partner with the mean mass and length of the car population. Comparison with the Overall Relative Injury Risk data obtained by BASt (9,10) and with individual car injury ratings derived from accident data by Folksam (6) shows high correlations. BASt (9,10) shows that 700 kg cars have an Overall Relative Injury Risk which is 2.5 times that of 1400 kg cars. The model predicts an Overall Relative Injury Risk of 2.67. Nygren (8) found that 800 kg cars have an Overall Relative Injury Rate which is 2.0 times that of 1400 kg cars. The predicted value is 2.22.

This study shows that car mass, length and frontal crush properties are important parameters in determining the Relative Injury Risk of any particular car. The aggregate Specific Energy Absorption properties for the car population are independent of car size: this means that the depth of crush can be considered to be proportional to car length. Consequently the variation in relative injury risk for the overall car population is a function of car mass and length. For individual cars the occupant protection features designed into the particular car will further enhance the safety of the individual car type. However this study shows that the Specific Energy Absorption Capacity of the individual car has a profound effect on the Relative Injury Risk of that car and that safety is improved by having a low Specific Energy Absorption Capacity (i.e. greater crushability). These effects merit further investigation. This study also highlights the need to further examine the car to car interactions obtained in frontal collisions and how these interactions are influenced by the degree of overlap and severity of collision.

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APPENDIX 1

DERIVATION OF INJURY RISK EQUATIONS

NOTATION

$\bar{a}$	=	Mean Deceleration
CCS	=	Collision Closing Speed
d	=	Mean Crush Depth
Δ(RIR)	=	Change in Relative Injury Risk (when case car involved in a collision with a collision partner of different size)
F	=	Crushing Force
IR	=	Injury Risk
L	=	Overall Length of car
M	=	Mass
$\bar{M}_e$	=	Mean Decelerated Mass
M_{equiv}	=	Equivalent mass of two colliding cars
M_k	=	Kerb Mass of car
ORIR	=	Overall Relative Injury Risk of car against specified car population
RIR	=	Relative Injury Risk
SEAC	=	Specific Energy Absorption Capacity

Subscripts:

b	=	baseline car collision
c	=	case car in collision between case car and partner
p	=	partner car in collision between case car and partner
pop	=	mean values of car population
s to s	=	case car and partner of equal size and aggressivity

For structures which have a uniform density distribution and which collapse under the action of an applied force it can be shown that the mean mass which is decelerated is:

$$\bar{M}_e = \frac{\frac{d}{L}}{\ln\left[1\Big/\left(1-\frac{d}{L}\right)\right]} \times M_k \qquad (1)$$

For structures which crumple under the action of a constant crumpling force the relation between crumpling force and length and mass of the structure is:

$$F = \frac{SEAC \times M_k}{L} \qquad (2)$$

The mean deceleration of the structure is thus:

$$\bar{a} = \frac{F}{\bar{M}_e} = \frac{SEAC}{L} \times \frac{\ln\left[1\Big/\left(1-\frac{d}{L}\right)\right]}{\frac{d}{L}} \qquad (3)$$

For the frontal structures of cars there is some crumpling before the structure is fully engaged and the full crumpling force develops. It has been shown (22) that $\ln(1/(1-d/L))$ can be approximated by $(d/L)^{4/3}$. Therefore:

$$\bar{a} = \frac{SEAC}{L} \times \left(\frac{d}{L}\right)^{\frac{1}{3}} \tag{4}$$

for the crushing regime of interest in injury accidents, and the energy absorbed by the front structure of each car is:

$$E = M_k \times SEAC \times \left(\frac{d}{L}\right)^{\frac{4}{3}} \tag{5}$$

In car to car collisions the relationship between energy absorbed in the impact and the Collision Closing Speed of the cars is:

$$E_c \times \left(1 + \frac{d_p}{d_c}\right) = \frac{1}{2} \times M_{equiv} \times CCS^2 \tag{6}$$

where subscript c refers to the case car and subscript p to its collision partner. Substituting 5 in 6 gives:

$$\left(\frac{d_c}{L_c}\right)^{\frac{1}{3}} = \left[\frac{1}{2} \times \frac{M_{equiv}}{M_{k_c}} \times \frac{CCS^2}{SEAC_c \times \left(1 + \frac{d_p}{d_c}\right)}\right]^{\frac{1}{4}} \tag{7}$$

and therefore mean deceleration of the case car is:

$$\bar{a}_c = (SEAC_c)^{\frac{3}{4}} \times \frac{1}{L_c} \times \left[\frac{CCS^2}{2 \times \left(1 + \frac{M_c}{M_p}\right) \times \left(1 + \frac{d_p}{d_c}\right)}\right]^{\frac{1}{4}} \tag{8}$$

Where

$$M_{equiv} = \frac{M_{k_c} \times M_{k_p}}{(M_{k_c} + M_{k_p})}$$

$$M_c = M_{k_c}$$

$$M_p = M_{k_p}$$

Taking Injury Risk $\propto \bar{a}^{2.5}$ gives the Injury Risk Equation:

$$IR \propto (SEAC_c)^{\frac{15}{8}} \times \frac{1}{L_c^{2.5}} \times \left[\frac{CCS^2}{2 \times \left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \tag{9}$$

The Relative Injury Risk for an occupant in the case car M_c involved in a collision with its partner M_p, compared with a collision between two other cars of masses M_{b_1} and M_{b_2} at the same Collision Closing Speed is:

$$RIR = \left(\frac{SEAC_c}{SEAC_{b_1}}\right)^{\frac{15}{8}} \times \left(\frac{L_{b_1}}{L_c}\right)^{2.5} \times \left[\frac{\left(1+\frac{M_{b_1}}{M_{b_2}}\right) \times \left(1+\frac{d_{b_2}}{d_{b_1}}\right)}{\left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \tag{10}$$

Where the baseline collision is between two cars of equal size L_b, equal crush and equal aggressivity $SEAC_b$ then:

$$RIR = \left(\frac{SEAC_c}{SEAC_b}\right)^{\frac{15}{8}} \times \left(\frac{L_b}{L_c}\right)^{2.5} \times \left[\frac{4}{\left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \tag{11}$$

When the case car and its partner are of equal size and aggressivity then:

$$RIR_{s\ to\ s} = \left(\frac{SEAC_c}{SEAC_b}\right)^{\frac{15}{8}} \times \left(\frac{L_b}{L_c}\right)^{2.5} \tag{12}$$

When the overall car population is being considered $SEAC_c = SEAC_b$:

$$RIR_{s\ to\ s} = \left(\frac{L_b}{L_c}\right)^{2.5} \tag{13}$$

When the case car collides with a partner of different size the Change in Relative Injury Risk for the case car compared with an impact involving a collision partner of equal size is:

$$\Delta(RIR) = \left[\frac{4}{\left(1+\frac{M_c}{M_p}\right) \times \left(1+\frac{d_p}{d_c}\right)}\right]^{\frac{5}{8}} \tag{14}$$

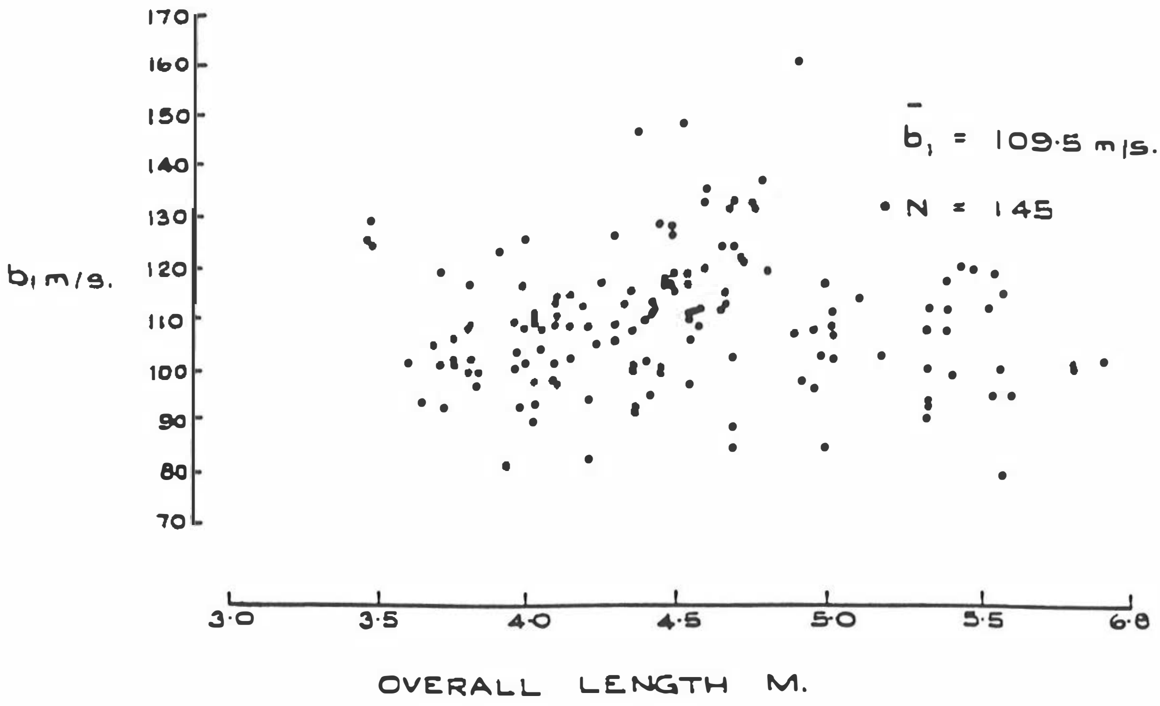
The Overall Relative Injury Risk for the case car M_c with specific energy absorption $SEAC_c$ which is part of a car population of mean mass M_{pop} and mean length L_{pop} is:

$$ORIR = \left(\frac{SEAC_c}{SEAC_{pop}}\right)^{\frac{15}{8}} \times \left(\frac{L_{pop}}{L_c}\right)^{2.5} \times \left[\frac{4}{\left(1+\frac{M_c}{M_{pop}}\right) \times \left(1+\frac{d_{pop}}{d_c}\right)}\right]^{\frac{5}{8}} \qquad (15)$$

for individual cars. For different car sizes within a population:

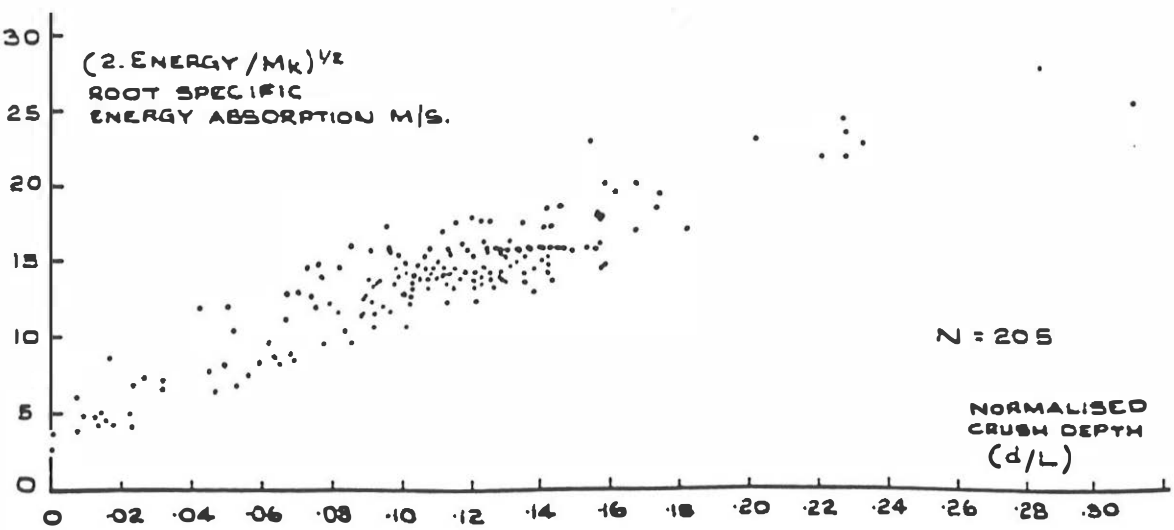
$$ORIR = \left(\frac{L_{pop}}{L_c}\right)^{2.5} \times \left[\frac{4}{\left(1+\frac{M_c}{M_{pop}}\right) \times \left(1+\frac{d_{pop}}{d_c}\right)}\right]^{\frac{5}{8}} \qquad (16)$$

The relationship for d_p/d_c has been determined empirically in the main paper. The above derivation used kerb mass throughout. It can be shown that equations 10 to 16 will be identical when car loads and impact offsets are included subject to the car loads being the same proportion of kerb mass and the impacts under consideration having similar offsets.



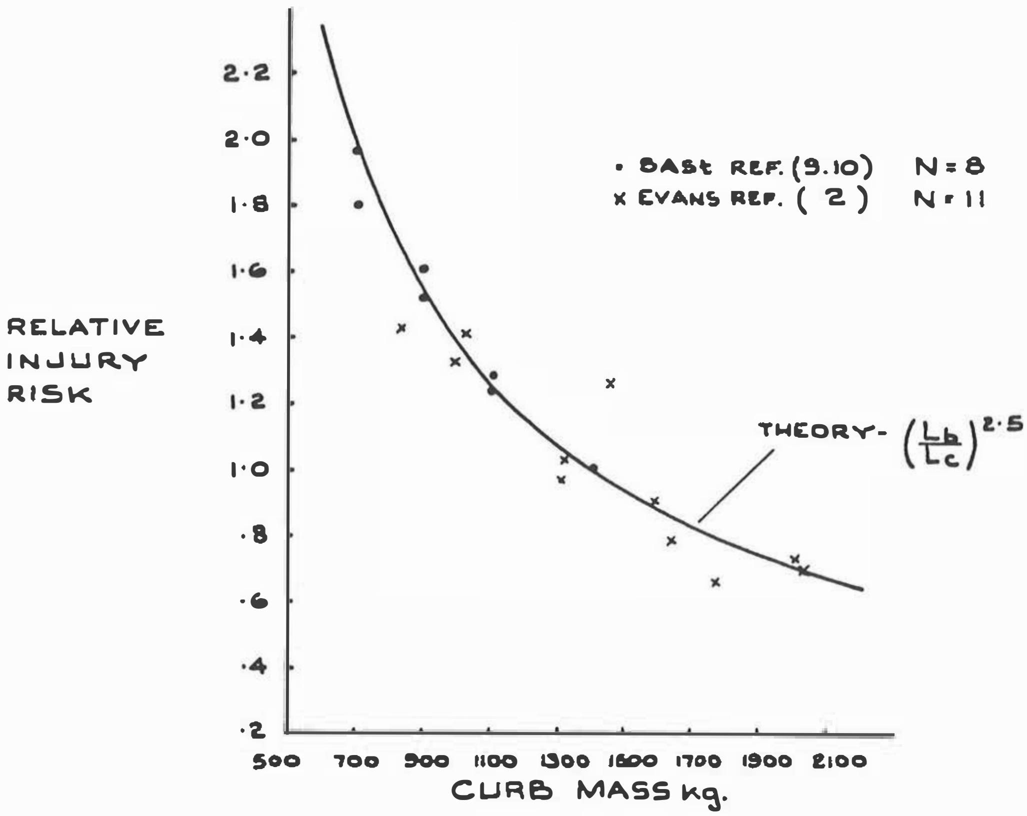
NON DIMENSIONAL b_1 COEFFICIENTS DERIVED FROM (17) PLOTTED AGAINST OVERALL LENGTH OF CAR.

FIGURE.1.

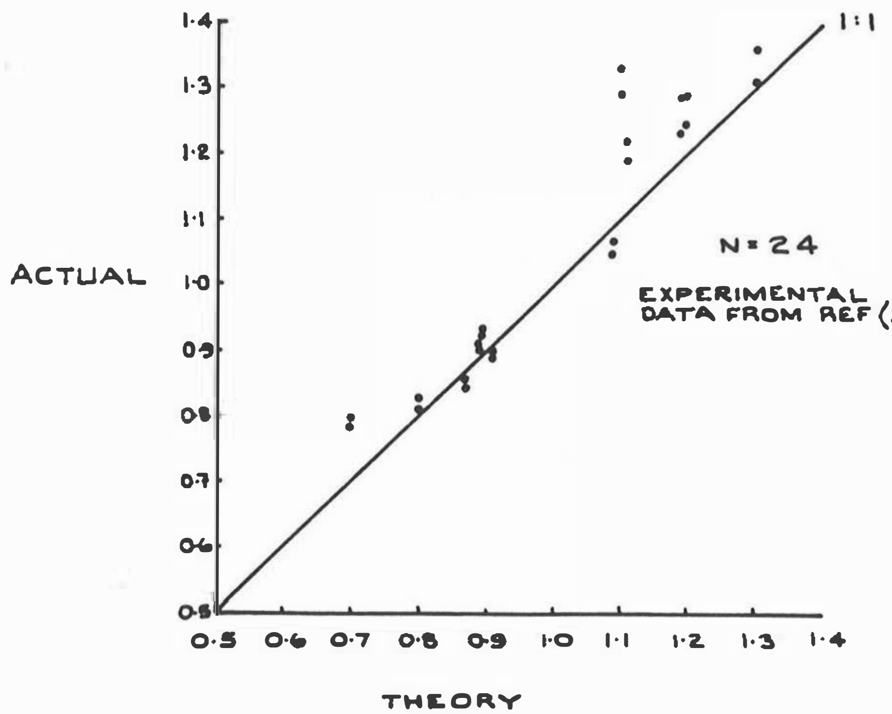


ROOT SPECIFIC ENERGY ABSORPTION VERSUS NORMALISED CRUSH DEPTH (d/L)

FIGURE.2.

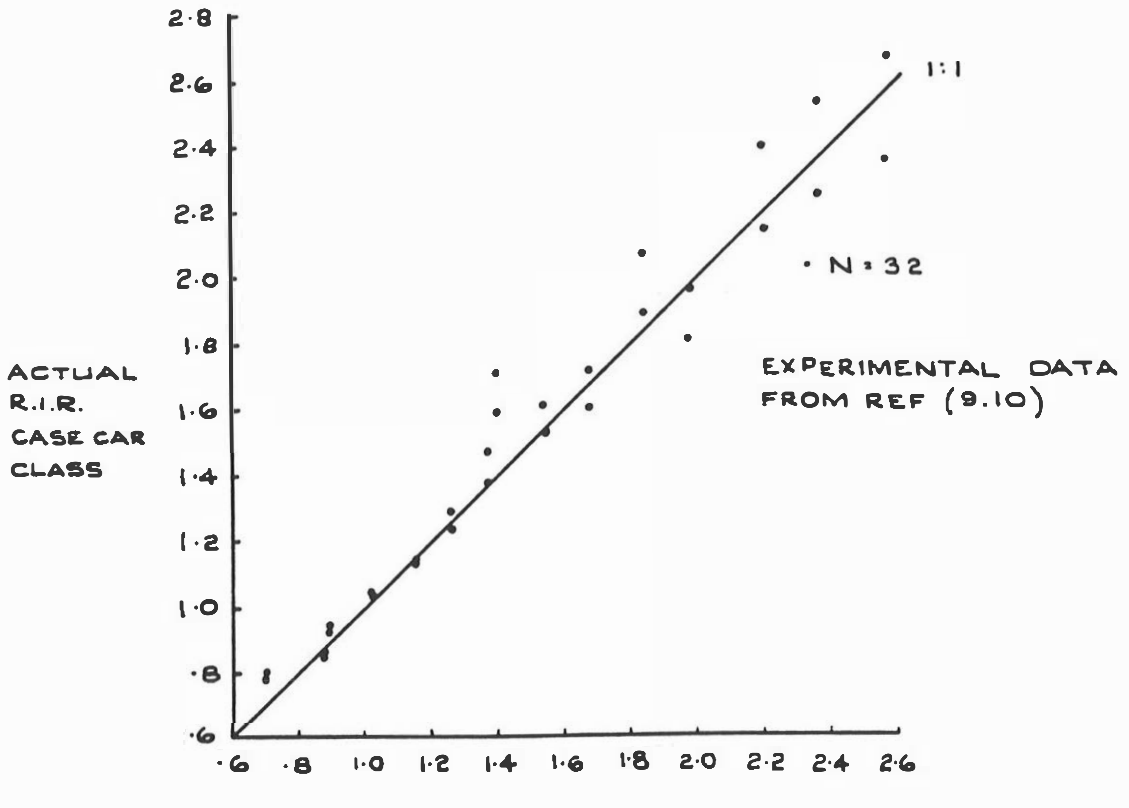


COLLISIONS OF SIMILAR CARS TO SIMILAR CARS FIGURE.3.



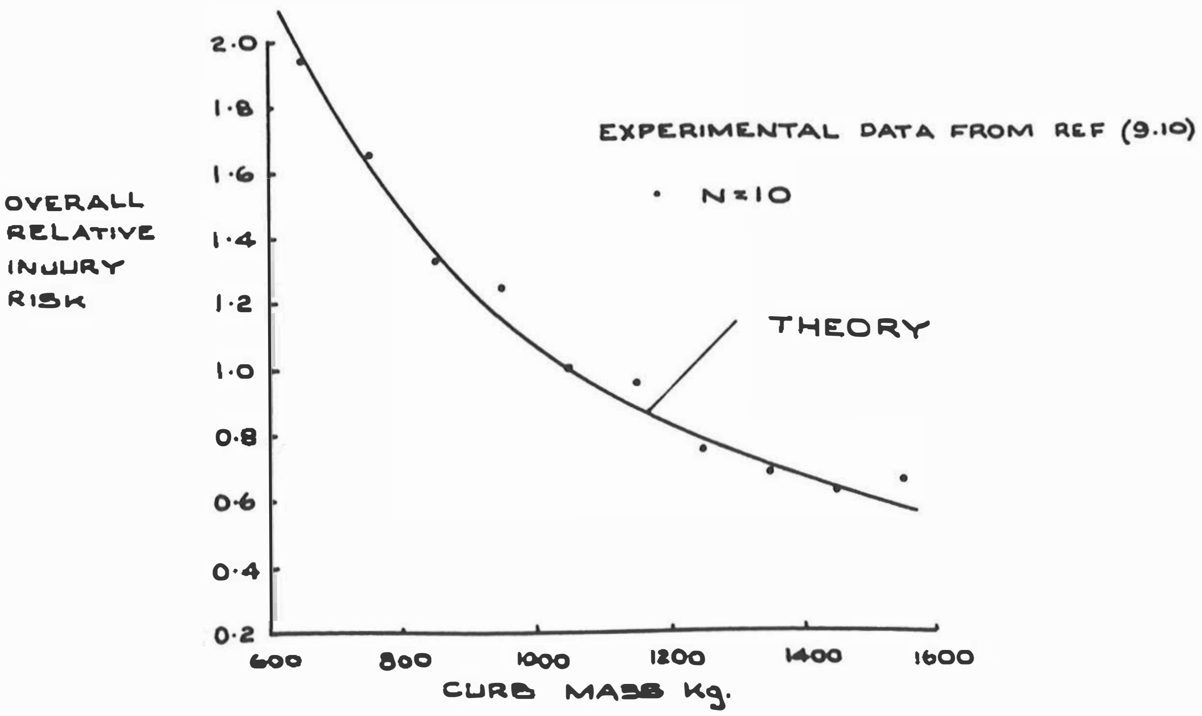
CHANGE IN RELATIVE INJURY RISK FOR COLLISION WITH DISSIMILAR CAR

FIGURE 4.



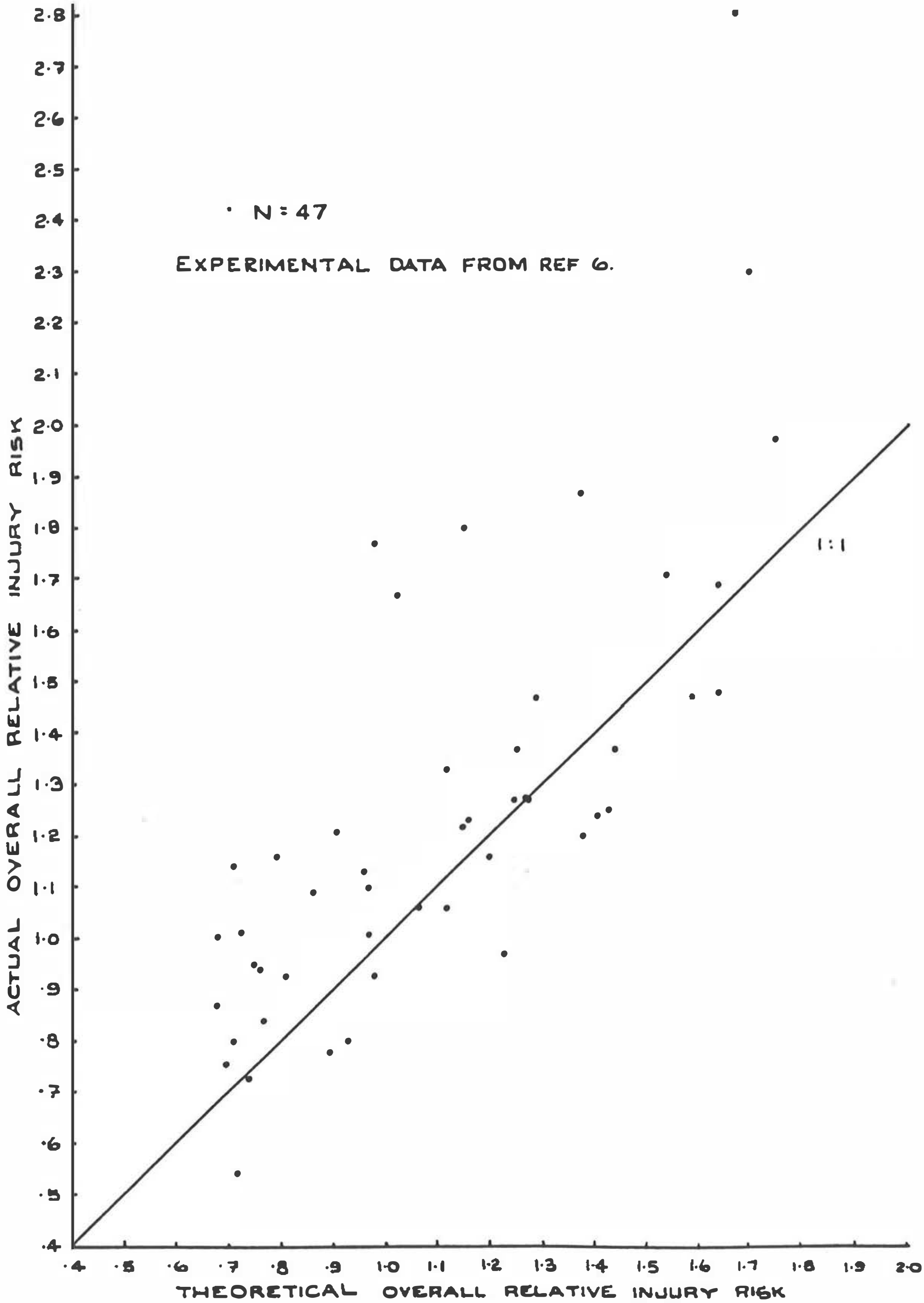
COMPARISON OF ACTUAL AND THEORETICAL RELATIVE INJURY RISK

FIGURE 5



COMPARISON OF OVERALL RELATIVE INJURY RISK FOR DIFFERENT CAR SIZES WITH IN POPULATION

FIGURE 6



COMPARISON OF THEORETICAL OVERALL RELATIVE INJURY RISK OF 47 INDIVIDUAL CAR TYPES WITH ACTUAL RISK DERIVED BY FOLKSAM FROM ACCIDENT DATA.

FIGURE 7.