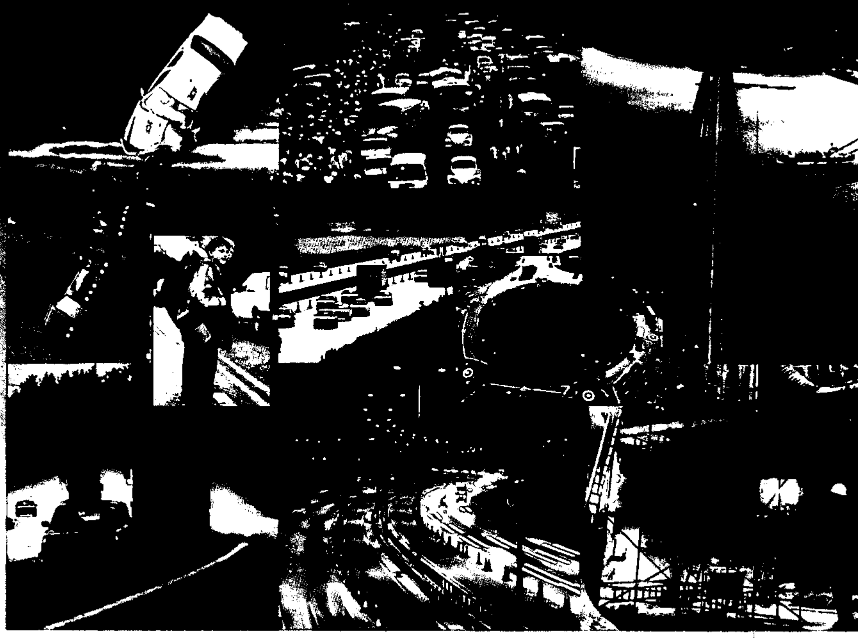

The likely effects of downsizing on driver casualties in two-car accidents

by Dr J Broughton

An executive agency of
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TRL Report 171

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TRL REPORT 171

THE LIKELY EFFECTS OF DOWNSIZING ON DRIVER CASUALTIES IN TWO-CAR ACCIDENTS

by Dr J Broughton

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CONTENTS

EXECUTIVE SUMMARY

This report develops earlier research into statistical methods for comparing the secondary safety of car models (Broughton, 1994). It describes two sets of detailed analyses of data from recent car accidents:

(i) several analyses relating to the likely effects on driver casualties in two-car accidents of downsizing (i.e. a Government-directed move towards lighter cars with the aim of improving fuel efficiency and reducing atmospheric pollution),

(ii) investigations of three issues left unresolved by the earlier report.

The downsizing results relate only to two-car accidents, so the coverage of the casualty effects of downsizing is incomplete. The results apply to accidents which account for about one half of fatalities and three quarters of casualties in cars.

The earlier report showed that the proportion of car drivers injured in two-car accidents declines rather regularly with car mass. This was consistent with previous research, and such results have presumably been the basis for the concerns which have been expressed that downsizing would increase the number of car occupant casualties. The earlier report had also showed, however, that heavier cars tend to be associated with more casualties in the 'other' car. This report combines the two effects and shows that the mean number of casualties per accident does not vary systematically with mass. It then shows that the severity of an accident tends to increase with the combined mass of the two colliding cars. This suggests that downsizing would not increase casualties, and might actually reduce them.

This is studied further by developing a mathematical model to simulate the effects of downsizing. Using two main assumptions, the simulation shows that downsizing is likely to lead to fewer drivers being killed or seriously injured; it also shows that fewer would be injured, although the evidence for this is slightly less certain. A uniform reduction of car mass by 5 per cent is estimated to lead to 3.8 per cent fewer casualties on built-up roads and 2.9 per cent fewer casualties on non built-up roads. The main reservation about these conclusions arises from uncertainty over the reasons underlying the increase of accident severity with combined mass, which the report demonstrates statistically but does not explain. No evidence is found, however, to suggest that downsizing might lead to extra casualties.

The relation between mass and the DOT index of secondary safety studied in the earlier report is then examined in detail, to see how the masses of two colliding cars affect the distribution of the risks of injury between the two cars. It is found that the dominant influence is the difference between the masses of the two cars; as this rises, the probability of the driver of the lighter car being injured rises rapidly, while the probability of the other driver being injured falls. The differences are more marked for fatal and serious casualties.

The earlier report found that current car models of similar mass can provide significantly different levels of protection to their occupants. Hence, there would be fewer casualties if all models were to provide the same level of protection as the most successful designs. The casualty reduction that would be achieved by improved protection is estimated, and naturally depends upon the target level of protection. If the safety of all models were improved to the level achieved or exceeded by the safest tenth of models then the number of drivers injured would fall by 10 per cent and the number killed or seriously injured by 14 per cent. A more demanding target would be the level achieved or exceeded by the safest twentieth of models, and if this could be attained then the number of drivers injured would fall by 12 per cent and the number killed or seriously injured by 22 per cent.

The fact that greater reductions are achievable among the more severe casualties suggests that the level of protection in fatal and serious accidents is more variable than the level in all injury accidents - of which fatal and serious accidents form only a small minority. It had seemed possible that this could be a statistical quirk caused by different sample sizes rather than a genuine result, but this is shown to be a genuine result.

THE LIKELY EFFECTS OF DOWNSIZING ON DRIVER CASUALTIES IN TWO-CAR ACCIDENTS[1]

ABSTRACT

This report develops earlier research into statistical methods for comparing the secondary safety of car models, and investigates:

(i) the likely effects on driver casualties in two-car accidents of downsizing (i.e. a Government-directed move towards lighter cars)

(ii) three issues left unresolved by the earlier report.

It is found that accident severity tends to increase with the combined mass of two colliding cars. A mathematical model of the effects of downsizing is developed from this relationship; results from this model suggest that downsizing would lead to fewer casualties in two-car accidents.

Car models of similar mass can provide significantly different levels of protection to their occupants, so there would be fewer casualties if all models were to provide the same level of protection as the most successful current designs. It is estimated that if the safety of all models were improved to the level achieved or exceeded by the safest twentieth of models then the number of drivers injured would fall by 12 per cent and the number killed or seriously injured by 22 per cent.

1. INTRODUCTION

'Downsizing' is a term which refers to a Government-directed move towards lighter cars with the aim of improving fuel efficiency and reducing atmospheric pollution. Opponents of this policy have argued that it would increase the number of casualties in car accidents. This report examines the evidence provided by the current range of cars for indications that lighter cars are associated overall with more casualties than heavier cars when involved in accidents: in the absence of such evidence, it would be difficult to argue that a policy of downsizing would reduce occupant safety.

This work has arisen from an earlier report (Broughton, 1994) which studied the ways in which the safety of different car models can be compared using data now held in the Stats19 database of police accident reports. It concluded that the lack of sufficiently detailed exposure data means that comparisons of primary safety (e.g. casualties per million kilometres travelled) would not be reliable, and that the best that can be achieved is to compare secondary safety, i.e. the injury consequences of an accident. The most satisfactory index of secondary safety was first used in publications of the Department of Transport (DOT) (e.g. Department of Transport, 1994), so is referred to as the DOT index.

The DOT index is calculated using data from a restricted set of accidents, those which involve exactly two cars and at least one injured driver. The earlier report shows that the index declines rather regularly as car mass increases, reflecting the greater protection offered by a larger car in an accident. This is consistent with previous research showing that it is the driver of the lighter car who is at greater risk when two cars collide: such results are presumably the basis for concerns about the casualty consequences of downsizing.

The report also showed, however, that lighter cars tend to be associated with fewer casualties in the 'other' car, so that the combined risk of injury in the two cars may not fall with mass. If this were true, downsizing would not lead to an overall increase in casualties in these two-car accidents. The question is studied in Section 2 by developing the DOT index to investigate the influence of a model's mass on the mean number of injured drivers per accident in which that model is involved. This number is then related to the combined mass of the cars involved in an accident in order to simulate the effects of downsizing.

The origins of this work account for its focus on two-car accidents. It would be unwise to generalise its conclusions to single-car accidents, for example, although it may prove possible to develop analytical methods for application to these other groups of accidents.

Sections 3 and 4 investigate several issues left unresolved by the earlier report. Section 3 studies the relation between mass and the DOT index in greater detail, to see how the difference between the masses of two colliding cars affects the distribution of the risks of injury between the two cars. Section 4 then estimates the casualty reduction that would be achieved if all car models provided the same level of protection as the most successful current designs. It also considers whether the greater dispersion of the DOT index for fatal and serious accidents, compared with the index for all accidents, is a genuine result or a statistical quirk caused by different sample sizes. Section 5 brings together the conclusions that can be drawn from these analyses.

2. THE CASUALTY EFFECTS OF DOWNSIZING

The effect of downsizing on car occupant casualties in two-car accidents will be studied in two ways. First, Section 2.1 considers the effects for individual models, developing the approach applied in the earlier report (Broughton, 1994). Sections 2.2 - 2.4 then study accident data grouped according to the mass of the cars involved. Section 2.5 discusses the factors which may influence the results and presents the conclusions that may be drawn.

The analyses presented below deal exclusively with two-car accidents. Sound reasons for this restriction were set out in the earlier report, but Table 1 sets the analyses in a broader context by comparing driver casualties in two-car accidents with casualties in other types of accident. The data come from 1992, but the distribution varies very little from one year to the next.

Thus, the commonest type of accident in which car drivers are injured is the two-car accident, which accounts for the majority of casualties but less than one third of fatalities. Results derived for two-car accidents can probably be generalised to accidents which involve three or more vehicles, as these principally involve cars; however, such a generalisation may well not be valid for single vehicle accidents and those involving a car and a heavier vehicle such as a lorry. Thus, while the results presented below should apply to about one half of fatalities and three quarters of casualties, significant gaps will still remain in the analysis of the casualty effects of downsizing.

All analyses in this report refer to car driver casualties, whereas about three-fifths as many car passengers are injured each year. This group must be omitted, however, because of irregular variations in the number of passengers per car. These relate more to patterns of ownership and use than to physical capacity: for example, models which are typically owned and driven by young adults tend to carry more passengers than those which are typically company-owned. By contrast, there is precisely one driver per accident-involved car (excluding parked cars). It seems reasonable to expect that the proportional effect of downsizing on passenger casualties will follow the effect for drivers very closely.

2.1 THE DOT INDICES

The DOT index is used to compare the secondary safety rating of different car models. In order to standardise, as far as possible with the data available, the risks faced by drivers who become involved in accidents, it is calculated on the basis of data from those two-car accidents in which at least one driver is injured. Further, the index is calculated using a statistical procedure which minimises the possibility of bias arising from, for example, a particular model being driven more often than the average on high speed roads where accidents tend to be severe. The basic DOT index for model m cars can be expressed as

D(m) = Proportion of drivers of model m cars who are injured when involved in two-car accidents where at least one driver is injured.

$$= \frac{\text{Number of drivers of model m cars who are injured in these accidents}}{\text{Number of drivers of model m cars involved in these accidents}}$$

The index is heavily influenced by driver casualties that are recorded by the police as slight, which are far more numerous than fatal and serious casualties. In order to focus on these more important casualties, a second index is calculated by further restricting the set of accidents to include only those where at least one driver is killed or seriously injured (ksi):

$D_B(m)$= Proportion of drivers of model m cars who are ksi when involved in two-car accidents where at least one driver is ksi.

(D_A refers to an alternative index that was shown to be less satisfactory than D_B).

These indices refer to the protection offered to the driver of the model m car in this standardised set of accidents, and ignore the injuries in the 'other' car. To include these injuries, an Aggressivity index is defined for these accidents:

A(m) = Proportion of drivers of cars which are in collision with model m cars who are injured

TABLE 1

Percentage of car driver casualties by accident type, 1992

Severity of driver casualty	Vehicles involved: 2 cars	1 car 1 car +	1 car + 1 lighter vehicle	1 car + 1 heavier vehicle	1 car + >1 other vehicle	at least 1 car
fatal	28	27	0	22	22	100
fatal or serious	43	25	1	12	19	100
all	54	16	1	10	19	100

and $A_B(m)$ is defined correspondingly. Figures 1 and 2 are taken from the earlier report, and show how increasing the mass of a model tends to be associated with:

(i) reduced risk of injury for the drivers of that model, but

(ii) increased risk of injury for the drivers of the cars with which they collide.

This raises the possibility that these tendencies will cancel out, and that mass has little or no effect on the number of injured drivers per accident. This is studied first in the context of individual models, using the index:

M(m) = mean number of injured drivers per accident which involves at least one model m car,

The Appendix shows that M(m) is approximately equal to A(m)+D(m) but, to avoid any possibility of bias from the approximation, the results presented below have been calculated directly from the accident data.

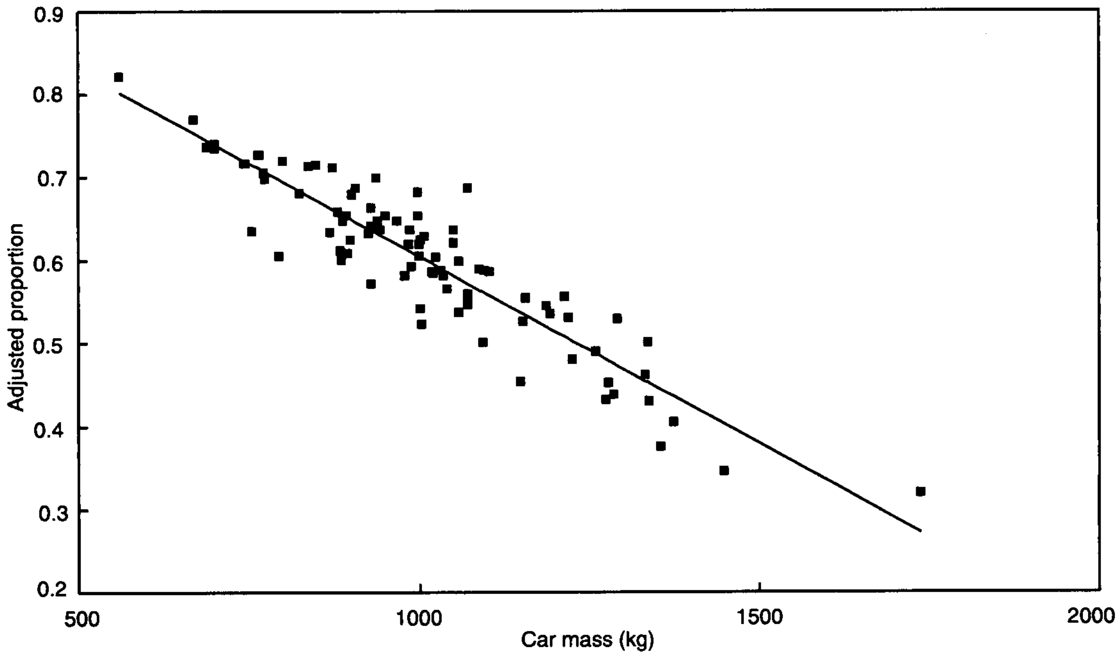

Fig. 1 The relationship between car mass and the DoT index D

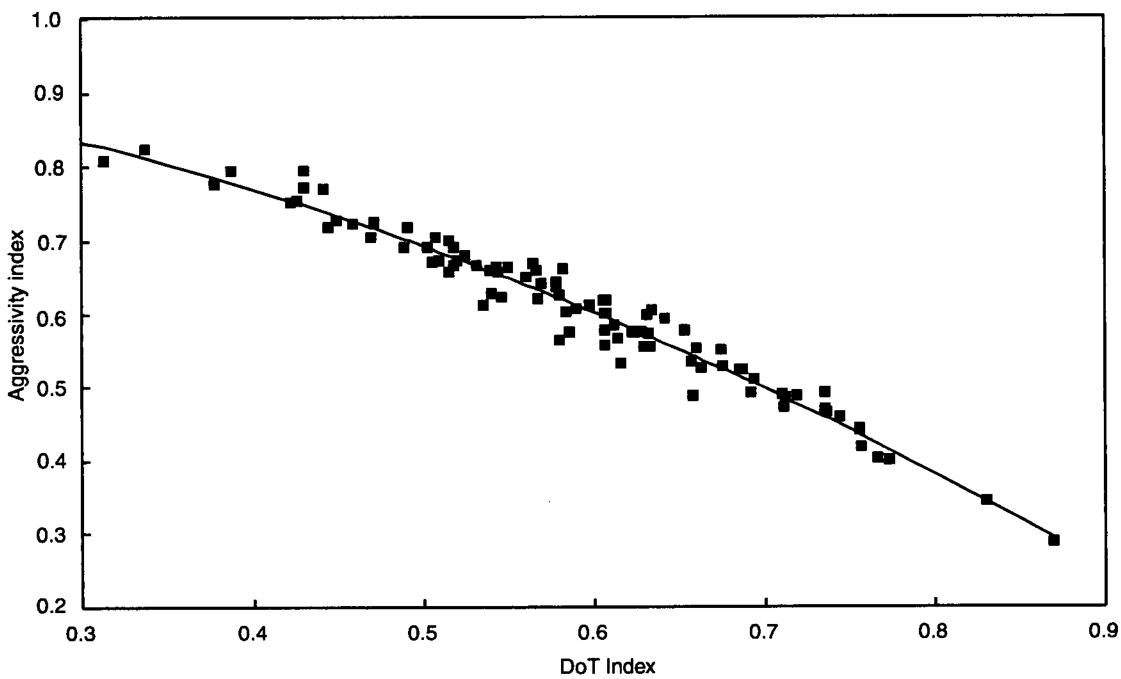

Fig. 2 The relationship between aggressivity and the DoT indices

The results presented throughout this report derive from the data set that was used to prepare the earlier report. It comprises all accidents from the Stats19 files from 1989-92 which involved just two cars, at least one of the drivers being injured. Wherever the Stats19 report contained a car's Vehicle Registration Mark, the files had been supplemented with details obtained from the DVLA database, including the car's make and model. In order to concentrate on the most popular models and to minimise the effects of chance, the only models included in the analyses are those on a list in a recent report (Department of Transport 1993) which includes all models with more than 20,000 vehicles registered in 1992. The mass of 87 of the 91 models was established from a commercial report (Glass's Guide Service 1992); this could only be done approximately because the variants of models such as the Ford Sierra have a range of masses.

The earlier report concluded that the indices D and D_B for a particular model can be biased by factors such as an unusually high mileage on rural roads (leading to greater exposure to risk in high-speed accidents) or a high mean driver age (the elderly being more prone to injury in accidents). It described a statistical method that allows for such effects, adjusting the indices to be free from these biases (within the limits imposed by the available data). The adjusted indices represent the values that would be found if all models had a standard range of drivers and a standard proportion of their mileage was driven on rural roads, these standards being the means calculated for all cars.

This method can also be applied with M, the mean number of driver casualties per accident. Figures 3a-3c show how three sets of means vary with mass of car:

3a - the mean number of dead drivers per fatal accident,

3b - the mean number of drivers KSI per fatal or serious accident,

3c - the mean number of injured drivers per accident.

Adjusted means are presented in 3b and 3c, but the number of fatalities is too small to carry out the adjustment and the means in figure 3a are unadjusted. Also, the mean number of dead drivers per fatal accident is heavily influenced by chance in the case of less common models as these tend to be involved in very few fatal accidents, so models are only included in figure 3a if they had been involved in more than 10 fatal accidents.

There is no clear trend in any of these figures. The heaviest model exerts considerable leverage on the analyses for figures 3b and 3c; when it is excluded, there is no indication of increasing mass being associated with fewer casualties. Thus, vehicle mass has no systematic effect on the mean number of injured drivers per accident, although the mean number does vary markedly between models.

2.2 ACCIDENT SEVERITY

The injury consequences of a particular accident are strongly related to its severity. There is no consensus about how to measure accident severity, although change in velocity during an impact is a reasonable proxy. Different car models are likely to have different distributions of accident severity, but the *ideal* safety index would compare the performance of different models in a *common* range of accidents and hence be free of bias arising from differences between the distributions. This ideal cannot be achieved so, as mentioned above, the safety indices D and A are calculated using a statistical method to standardise the results and compensate for differences in accident severity using information about the age and sex of the car drivers and the proportion of accidents on rural roads. No measure of accident severity is routinely available in accident reports, so this compensation is probably imperfect.

Such standardisation is inappropriate when analysing the effects of downsizing, since the main interest lies in the overall effect on casualties. This is demonstrated by the following simplified example. Suppose that:

(a) there are only serious and slight accidents, and only one casualty class,

(b) the present range of cars is involved in 1000 serious accidents and 1000 slight accidents per year: there are C_{ser} casualties per serious accident and C_{sli} casualties per slight accident, giving a total of $C' = 1000*(C_{ser} + C_{sli})$ casualties,

(c) after downsizing, the new range of cars has the same secondary safety features, i.e. C_{ser} and C_{sli} are unchanged, and there is the same total number of accidents but with a different severity distribution which leads to 1000+N serious accidents and 1000-N slight accidents.

After downsizing, the number of casualties would be

$$(1000+N)*C_{ser} + (1000-N)*C_{sli} = N*(C_{ser}-C_{sli}) + 1000*(C_{ser}+C_{sli})$$

$$= N*(C_{ser}-C_{sli}) + C'$$

Severe accidents lead to more casualties per accident than slight accidents, so $C_{ser} > C_{sli}$ and downsizing would affect the number of casualties (the number would rise if N>0 and fall if N<0). However, a standardised comparison would rely on 'before and after' comparisons for serious and slight accidents separately and would find no effect, as C_{ser} and C_{sli} have been assumed to remain unchanged.

This example is simplified to demonstrate the result clearly, but the result can be shown to be generally true. Hence, standardisation of accident severity is inappropriate when investigating the effects of downsizing, although it is entirely appropriate when comparing secondary safety.

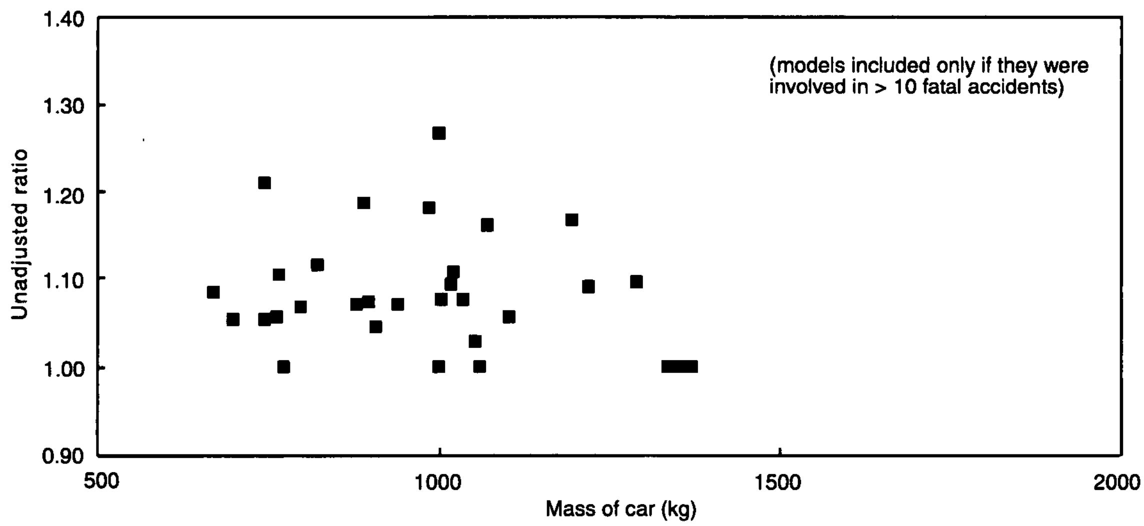

Fig. 3a The number of drivers killed per fatal accident

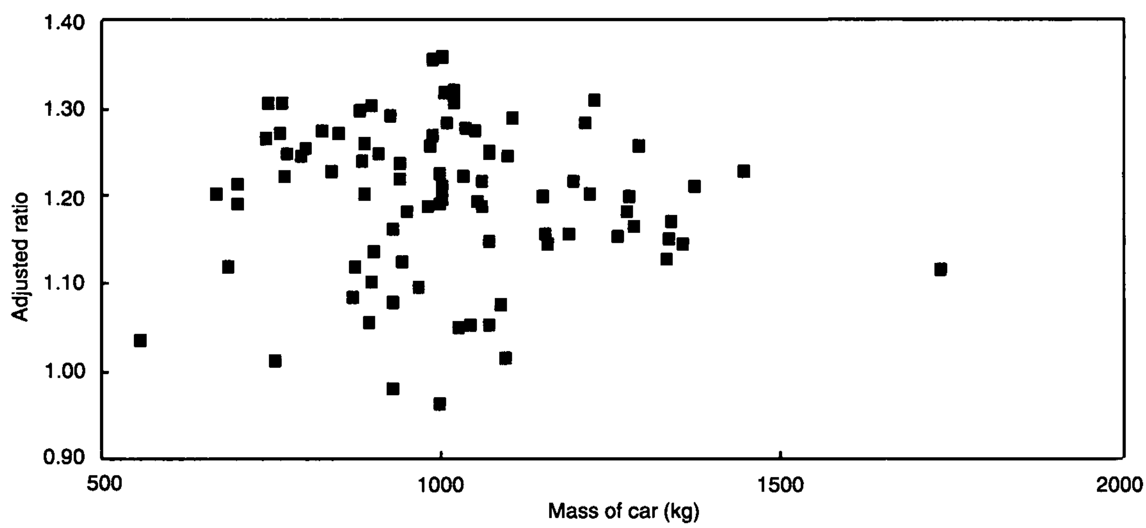

Fig. 3b The number of drivers ksi per fatal or serious accident

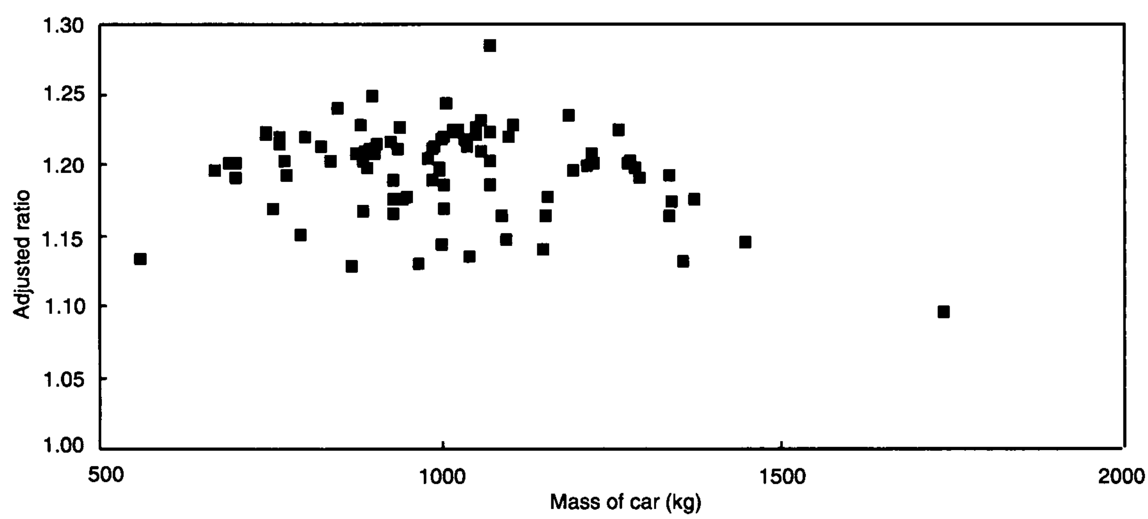

Fig. 3c The number of drivers injured per injury accident

In order to apply this conclusion, figures 3a-3c need to be developed by expanding the denominators (i.e. 'fatal' to 'fatal or serious' or 'all injury' accidents for 3a, 'fatal or serious' to 'all injury' accidents for 3b). Unfortunately, the shortage of data from damage-only accidents prevents 3c from being developed. The results are shown in figures 4a-4c (models involved in 5 or fewer fatal accidents are excluded from figures 4a and 4b). The three figures show:

4a - the mean number of drivers killed per fatal or serious accident,

4b - the mean number of drivers killed per injury accident,

4c - the mean number of drivers killed or seriously injured per injury accident.

All three show a tendency for the number of drivers killed or seriously injured per accident to rise with the mass of the models involved. The line fitted by linear regression is included in each figure, mass being the only independent variable. Each linear model explains only a small part of the variability in the data ($R^2 = 0.09, 0.15, 0.12$ respectively), but each mass coefficient is significant ($t=2.18, 3.46, 3.47$ respectively). Downsizing would lead to a general mass reduction across the range of cars, so these figures imply that downsizing is likely to reduce the proportion of injury accidents which involve fatal or serious driver casualties and so reduce overall accident severity.

2.3 DRIVER CASUALTIES AND COMBINED MASS

One shortcoming of figures 4a-4c as a basis for predicting the consequences of downsizing is that the graphs relate the driver casualties to the mass of one of the cars involved in an accident, whereas the mass of the other car would also influence the number of casualties. The earlier report compared the 'target' ranges of particular models, i.e. the ranges of cars with which each model collides. It found only small differences, which implies that figures 4a-4c are unbiased. Nevertheless, it seems preferable to relate the injury consequences of an accident to the combined mass of the two cars (the difference in masses need not be considered as it has little effect on the number of injured drivers per accident and will be affected far less than the combined mass by downsizing). Results will be prepared separately for built-up (bu) roads, which have speed limits of at most 40 mph, and non built-up (nbu) roads which have higher speed limits, to take account of the greater severity of accidents on nbu roads.

The mass of each car involved in a two-car accident must be known to calculate the combined mass. Hence, only a subset of the original accidents can be used; accidents which involved a car of unknown model or a car of known model but unknown mass are excluded.

Figures 5a and 5b are comparable with figures 3b and 3c, but show a trend for the number of driver casualties to decrease as the combined mass increases. These figures conceal the tendency for drivers to be more seriously injured when accidents involve heavier cars, as shown by figure 5c (comparable with figure 4c). Figure 6 confirms that accident severity does increase with the combined mass of the cars involved.

The relations shown in figures 5a-5c and 6 are sufficiently regular to allow the effects of downsizing to be simulated. They have been simplified by fitting the linear models shown in the figures, and these models are used in the next section.

2.4 THE SIMULATED EFFECTS OF DOWNSIZING

This section will simulate the effect of downsizing on driver casualties. It should be emphasised once more that these results relate only to two-car accidents; strictly, they relate only to two-car accidents where at least one driver was injured (because of the origin of this research in the earlier study of secondary safety ratings), but there is no reason to think that the conclusions cannot be safely extended to all two-car accidents.

The simulation will be carried out by taking the driver casualties in the set of accidents studied previously, and comparing them with the casualties that would have been expected if all cars had been lightened by a certain percentage. The simulation thus assesses the effect of downsizing if it could be carried out instantaneously. In practice, downsizing would occur over a number of years and new safety features would presumably be introduced concurrently, but no attempt is made to represent this.

2.4.1 The number of drivers injured

Figures 5 and 6 suggest that downsizing would have two contrary effects:

(i) accidents would become less severe, but

(ii) at any level of severity, more drivers would be injured relative to the number of accidents.

Some mathematics are needed to show whether the net effect will be to increase or reduce the number of driver casualties. Two scenarios are compared: A is the *status quo* as represented by the existing set of two-car accidents where at least one driver was injured, B includes the same set of accidents but with each car downsized, its mass having been reduced by a factor $[1-\theta]$. Consider the accidents in scenario A which involve pairs of cars with combined masses in the range r, and let:

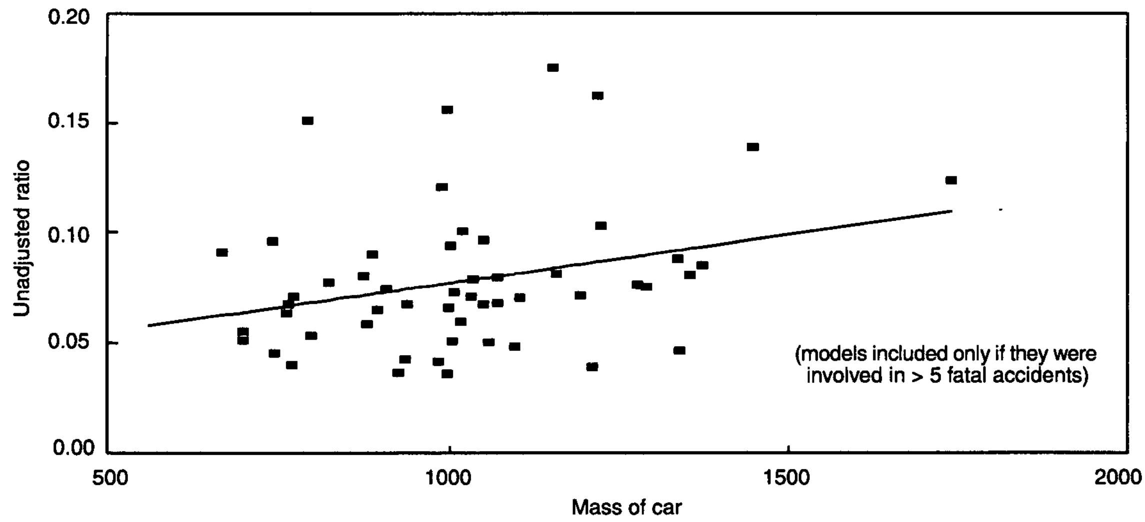

Fig. 4a The number of drivers killed per fatal or serious accident

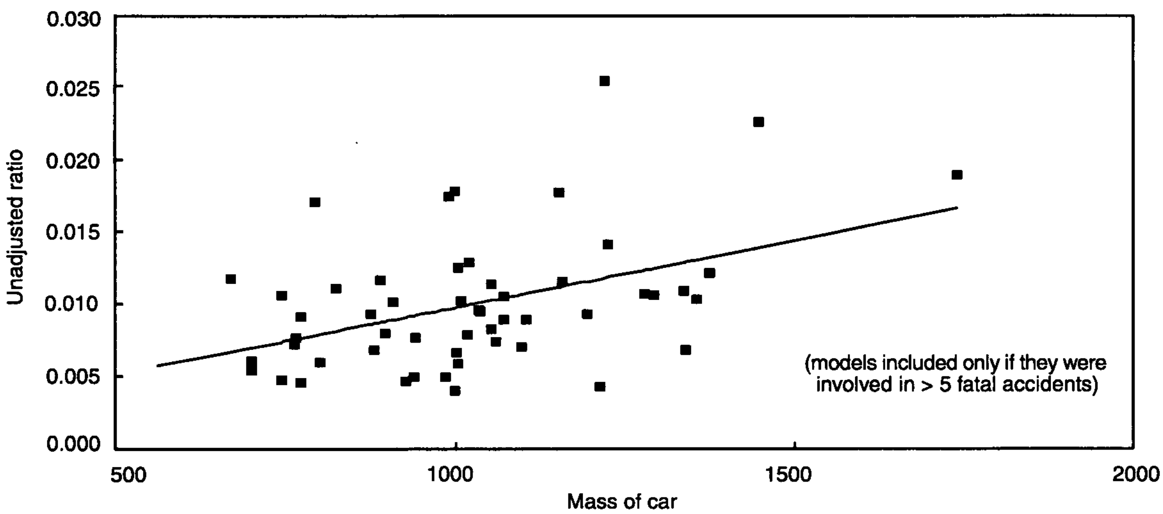

Fig. 4b The number of drivers killed per injury accident

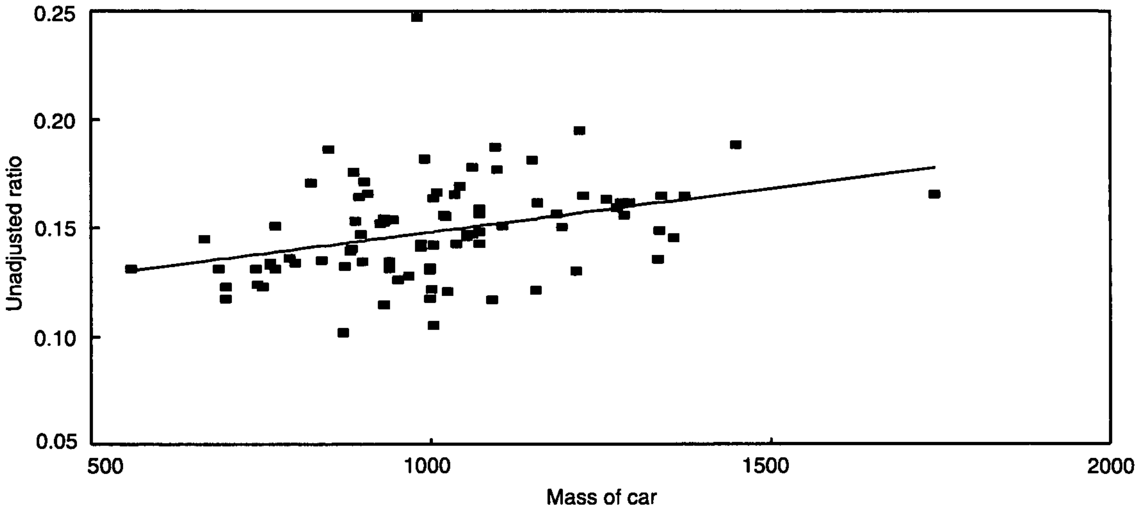

Fig. 4c The number of drivers ksi per injury accident

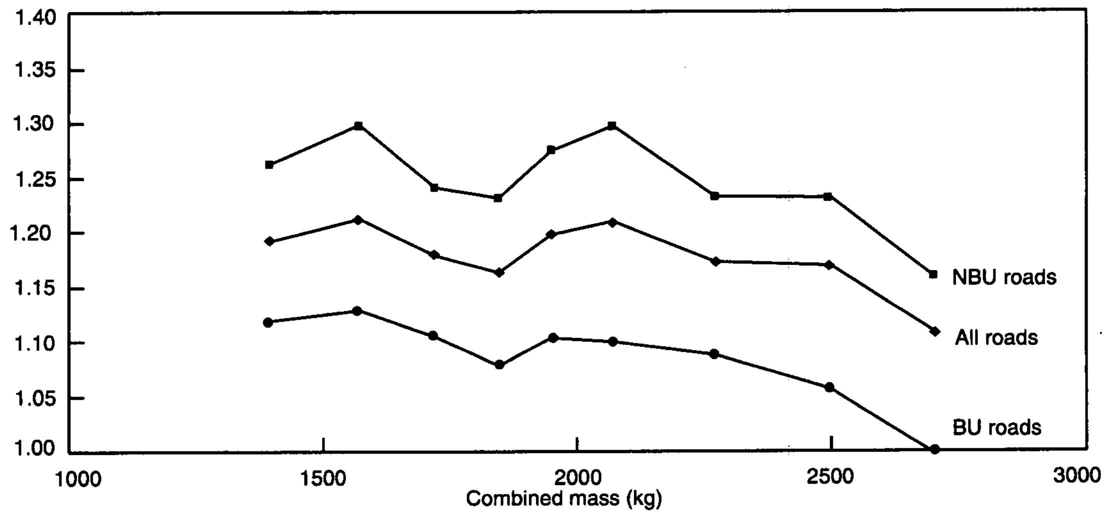

Fig. 5a The number of drivers ksi per fatal or serious accident

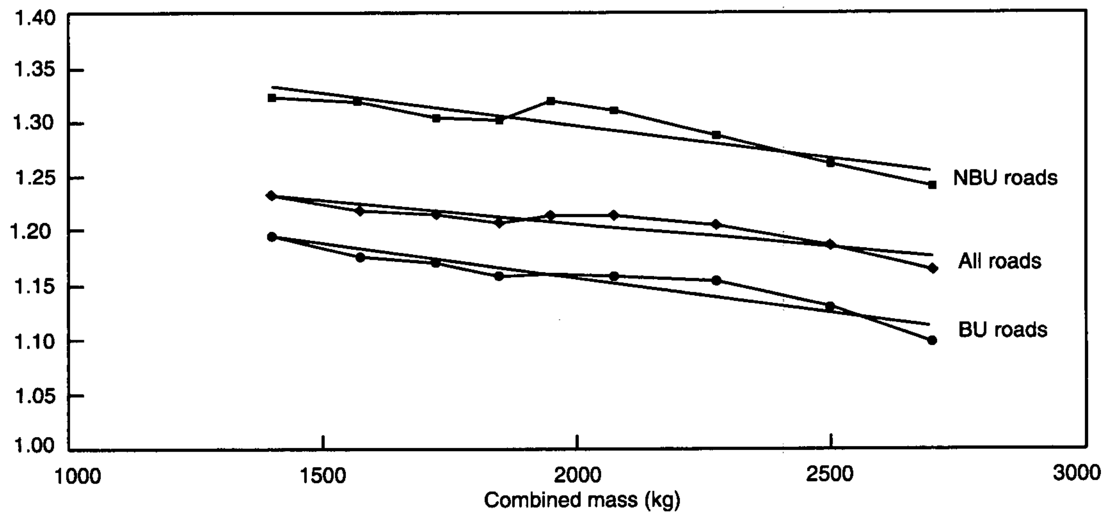

Fig. 5b The number of drivers injured per injury accident

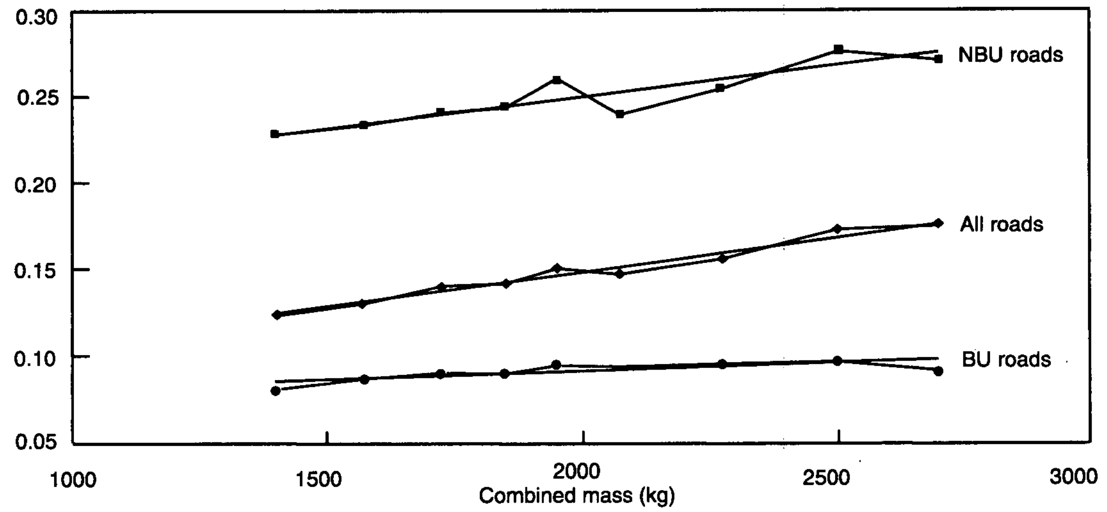

Fig. 5c The number of drivers ksi per injury accident

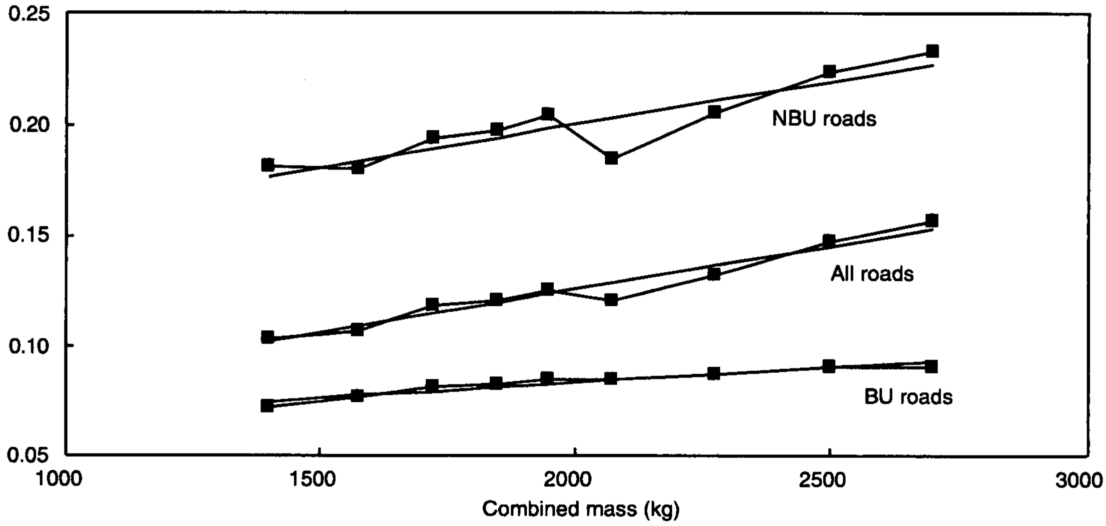

Fig. 6 The proportion of injury accidents which are fatal or serious

$I(A,r)$ = number of injury accidents in scenario A (known from Stats19 data)

$p(r)$ = proportion of all two-car accidents (i.e. including damage-only accidents) which involve at least one injured driver

$\rho(r)$ = number of drivers injured per injury accident

The total number of accidents in scenario A is simply $N(r) = I(a,r)/p(r)$. By assumption, the same number will occur in scenario B. The number of injured drivers is, by definition,

$$C(A,r) = N(r).p(r).\rho(r) \qquad \text{in scenario A and}$$

$$C(B,r) = N(r).p(r[1-\theta]).\rho(r[1-\theta]) \qquad \text{in scenario B}$$

since in scenario B the combined masses in range r are reduced to $r[1-\theta]$. Hence, the increase in driver casualties is

$$\Delta(r) = C(B,r) - C(A,r) = N(r).\{p(r[1-\theta]).\rho(r[1-\theta]) - p(r).\rho(r)\}$$

$$= I(A,r).\{p(r[1-\theta]).\rho(r[1-\theta]) - p(r).\rho(r)\}/p(r)$$

This is true irrespective of the form of p and ρ, but p and ρ must now be specified in order to evaluate $\Delta(r)$. Figure 5b shows that ρ is linearly related to r, and can be represented by the linear model $r(r)=a+\beta r$ with $\beta<0$. The shortage of data from damage-only accidents means that the form of p is less certain, but the evidence of figure 6 suggests that it can be represented by the linear model $p(r)=a+br$ with $b>0$. Substituting these equations gives

$$\Delta(r) = \frac{I(A,r)\{(a + br[1-\theta])(\alpha+\beta r[1-\theta]) - (a + br)(\alpha+br)\}}{(a + br)}$$

$$= I(A,r)r\theta\{-a\beta - b\alpha - b\beta r(2-\theta)\}/(a + br)$$

$$= -I(A,r)r\theta b\beta\{(a/b) + (\alpha/b) + r(2-\theta)\}/(a + br) \qquad (1)$$

so the number of driver casualties in range r will increase only if

$$-b\beta\{(a/b) + (\alpha/b) + r(2-\theta)\} > 0.$$

As information about damage-only accidents is not collected systematically in Great Britain, the value of p(r) is only known approximately. It has been reported (Department of Transport, 1991) that about 1 in 8 of the car accidents known from insurance claims would have been recorded as Stats19 injury accidents, which suggests an overall value of 0.12 - very similar to the proportion of injury accidents which are fatal or serious. For illustrative purposes, the equation used for p(r) will be the one shown in figure 6. The ratio of the constant to the gradient for the three road types are:

	bu roads	nbu roads	all roads
Equation for ρ(r): (α/β)	-20700	-23500	-29900
Equation for p(r): (a/b)	3950	3060	1170

$b > 0$ and $\beta<0$ so $-b\beta > 0$. $\quad r(2-\theta)<6000$ since $r < 3000$ kg.

Hence, for each road type and mass range r:

$(a/b) + (\alpha/b) + r(2-\theta) < 0$, so

$-b\beta\{(a/b) + (\alpha/\beta) + r(2-\theta)\} < 0$ and $\Delta(r) < 0$.

Thus, these ratios indicate that the number of driver casualties will fall as a result of downsizing.

The values used for (a/b) are proxies for the unknown values which represent the relation between damage-only and injury accidents, so it is important to consider the sensitivity of this favourable conclusion to these values. The actual values would have to be at least 4 (bu roads) and 6 (nbu roads) times higher for $\Delta(r)$ to be positive for range

r. Thus, the conclusion is relatively robust: the conclusion would only be false if accident severity rises far less rapidly with mass than is shown in figure 6.

2.4.2 The number of drivers killed or seriously injured

This approach can be extended to estimate the change in the number of drivers killed or seriously injured by setting $\rho(r)$ = number of drivers ksi per injury accident. Using the relations fitted in figure 5c, $\beta>0$ and the values of (α/b) for the three road types are 8840, 5170 and 1740 respectively. Hence,

$$-b\beta < 0,\ (a/b) + (\alpha/\beta) + r(2-\theta) > 0 \text{ and}$$
$$\Delta(r) = -b\beta\{(a/b) + (\alpha/\beta) + r(2-\theta)\} < 0$$

This indicates that the number of drivers ksi will also fall after downsizing. This conclusion is robust since $(\alpha/\beta)>0$ in each of these cases, so (a/b) would have to be negative for $\Delta(r)$ to be positive, i.e. accident severity would have to fall with mass. There has been no indication of this in the data studied. Hence, the evidence supporting the conclusion that downsizing would lead to fewer driver casualties is clearer in the case of fatal or serious injuries than in the earlier case of all injuries.

2.5 DISCUSSION

Equation (1) has been evaluated to illustrate the effects numerically in the case of a 5 per cent downsizing (i.e. $\theta = 0.05$), using the coefficients listed above. The forecast casualty reductions are:

	Built-up roads	Non built-up roads
Drivers killed or seriously injured	3.8%	2.9%
Drivers injured	1.2%	1.8%

The conclusion that downsizing will reduce the number of driver casualties depends on three assumptions. The first has been mentioned several times, namely that p(r) - the proportion of two-car accidents (including damage-only) which involve at least one injured driver increases linearly with the combined mass r, i.e. b>0. The evidence from injury accidents supports this strongly, and the conclusion is robust in the case of fatal and serious driver casualties - although the level of reduction will depend on the exact value of a/b. Only in the case of all casualties is there any doubt, and the numerical results show that a/b would have to be at least four times greater than the value used in the simulation for downsizing to have no effect. As a is known approximately, this would require b to be only one quarter of the value used. This cannot be ruled out in the absence of firmer evidence about the relation between damage-only and injury accidents, but the value seems unlikely to be so low.

The second assumption is that drivers will be neither more nor less likely to collide with other drivers when their cars are smaller, so the number of accidents (i.e. including damage-only) will remain constant and downsizing will affect the number of casualties only by changing accident severity. This seems plausible, but cannot be proved.

The final, and probably most critical, assumption is that the current accident characteristics of cars in range r will prove representative of the characteristics of *downsized* cars in range r in the new car fleet. Information about the reasons for the increase of accident severity with mass is needed to judge the validity of this assumption. If it is a consequence of physical laws (e.g. lighter cars → less energy released in accident → less risk of injury) then the assumption is probably valid, whereas if it is a consequence of driver behaviour (e.g. drivers of lighter cars are more cautious → they tend to be less involved in serious accidents) then it may not be.

There is inevitably a limit to what can be learnt about likely future developments from any statistical analysis of current data. Studies could undoubtedly be devised to shed more light on the validity of these assumptions. To test the first, detailed data would be collected for a sample of accidents which included a representative number of damage-only accidents. Testing the third would require observations of driving behaviour for cars of different sizes, together with details of their accident involvement. In the absence of such studies, the statistical analysis reported above leads to the following conclusions:

(i) downsizing will reduce the number of drivers killed or seriously injured in two-car accidents,

(ii) downsizing is likely reduce the number of drivers injured in two-car accidents.

Perhaps more importantly:

(iii) no evidence has been found to suggest that downsizing would increase the number of drivers injured in two-car accidents.

3. THE DISTRIBUTION OF RISK BETWEEN THE LIGHTER AND HEAVIER CAR

Section 2.1 mentioned that the DOT index D tends to fall and the Aggressivity index A tends to rise with increasing mass. There is, in effect, a transfer of injury risk from the heavier to the lighter car, and this will now be explored.

The two-car accidents that have been studied can have three possible outcomes:

1. only the driver of the lighter car is injured,
2. both drivers are injured,
3. only the driver of the heavier car is injured.

The case of accidents involving two cars of similar mass is slightly ambiguous. Some models have variants covering a range of masses, but the data set used for these analyses has only a mean mass for each model. Thus, it is unclear which car is the heavier in these accidents, so accidents involving cars in the same mass range with only one injured driver are divided equally between categories 1 and 3 irrespective of which model is nominally heavier.

Table 2 shows how the division of accidents between these three categories varies with the mass of the two vehicles: it presents the proportion of accidents for each combination of mass-ranges which fall into categories 1, 2 and 3. Because of the small numbers of accidents in some cells, certain proportions have relatively large standard errors - up to .03 for accidents involving two cars of at least 1200 kg. Nonetheless, it is clear that the proportions on each diagonal are very similar so, for example, when a 951-1050 kg car collides with a 1051-1200 kg car then the distribution of risk between the two cars is essentially the same as when a 751-850 kg car collides with a 851-950 kg car. The proportion of type 2 accidents is almost constant, the proportion of type 1 accidents rises and the proportion of type 3 accidents falls as the disparity between the masses grows. One minor exception to this pattern occurs at the extreme, where the heaviest cars collide with the lightest (up to 850 kg); here, slightly fewer accidents are of type 2.

These results suggest that the dominant factor which influences the distribution of driver casualties between two cars in a collision is their relative mass (note that the mean number of drivers injured per accident=1 + P_2 and varies

TABLE 2

Distribution of accidents, by mass of colliding cars

			Mass of one car involved (kg)					
			≤ 750	751-850	851-950	951-1050	1051-1200	>1200
Mass of other car involved (kg)	≤750	P_1	.38	.42	.56	.58	.62	.72
		P_2	.23	.23	.19	.21	.19	.13
		P_3	.38	.35	.25	.21	.18	.15
	751-850	P_1		.38	.51	.55	.58	.69
		P_2		.24	.22	.21	.20	.17
		P_3		.38	.27	.24	.22	.15
	851- 950	P_1			.38	.45	.46	.55
		P_2			.23	.21	.23	.21
		P_3			.38	.34	.32	.24
	951-1050	P_1				.39	.40	.51
		P_2				.21	.23	.20
		P_3				.39	.37	.29
	1051-1200	P_1					.39	.50
		P_2					21	.19
		P_3					.39	.30
	>1200	P_1						.39
		P_2						.22
		P_3						39

Note: P_1 = proportion of accidents where only the driver of the lighter car is injured,
P_2 = proportion of accidents where both drivers are injured,
P_3 = proportion of accidents where only the driver of the heavier car is injured.

very little with relative mass, except for the most extreme case). The casualty data have been analysed by relative mass, using 50kg ranges; accidents in the 0-50 kg range were allocated equally between categories 1 and 3 because of the imprecision of the mass data, and results for the 51-100 kg range were omitted for the same reason. Two sets of results are presented in figure 7, for drivers ksi in fatal or serious accidents and for drivers injured. The presentation emphasises the trichotomy in the possible outcomes from any accident:

the lower graph represents P_1, i.e. accidents where only the driver of the lighter car is injured,

the upper graph represents P_1+P_2, so the gap between the two graphs represents P_2, i.e. accidents where both drivers are injured,

the gap between the upper graph and the line P=1 represents P_3, i.e. accidents where only the driver of the heavier car is injured.

The graphs are approximately linear, both for drivers injured and for drivers ksi. As the difference between the masses increases, the proportion of accidents in which both drivers are injured diminishes, as does the proportion in which the driver of the heavier car is injured. Table 3 summarises these trends, using linear models fitted to the data shown in the figure (the standard errors of the estimates are shown in brackets). It shows that the drivers of lighter cars are at a greater disadvantage in fatal or serious accidents than in other accidents, since at any particular relative mass P_1 is greater and P_2 and P_3 are less in fatal or serious accidents than in all accidents.

4. THE CASUALTY BENEFITS FROM IMPROVED SECONDARY SAFETY

Figure 1 showed the variation with mass of the DOT index D for 87 models of car in 1989-92. Where the index of a

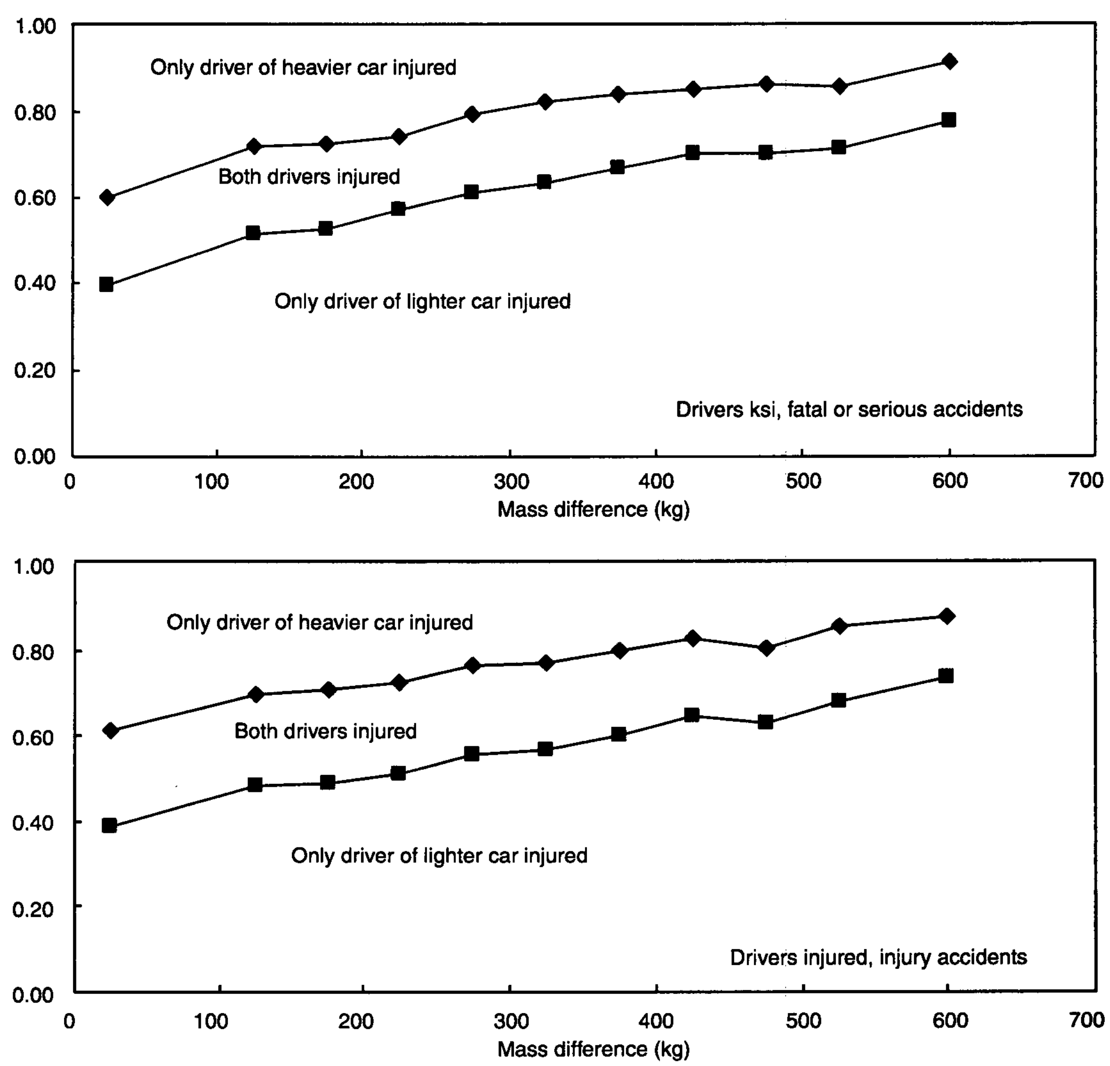

Fig. 7 The distribution of driver casualties between the lighter and heavier car

TABLE 3

The estimated distribution of driver casualties between lighter and heavier cars

		Mass difference (kg)					
		100		300		500	
Fatal or	P_1	.48	(.025)	.61	(.023)	.75	(.024)
serious accidents	P_2	.20	(.011)	.18	(.011)	.15	(.011)
	P_3	.32	(.029)	.21	(.027)	.10	(.028)
All accidents	P_1	.45	(.018)	.56	(.017)	.68	(.017)
	P_2	.22	(.010)	.20	(.009)	.18	(.010)
	P_3	.33	(.018)	.24	(.017)	.15	(.018)

Note: P_1 = proportion of accidents where only the driver of the lighter car is injured,
P_2 = proportion of accidents where both drivers are injured,
P_3 = proportion of accidents where only the driver of the heavier car is injured.

particular model m is greater than that of another model m_1 of similar mass, fewer drivers of model m cars would have been injured if its index had been equal to $D(m_1)$, the lower index of the safer car, instead of its actual value. The expected reduction in the number of casualties in two-car accidents if the safety of m were improved to the level achieved by m_1 is

Number of model m cars involved in accidents . $\{D(m) - D(m_1)\}$ (2)

The straight line in the figure represents the general relation between D and mass, with models which lie below the line being safer than the typical model of that mass. Since the position of a model relative to the fitted line measures its safety relative to that expected from models of the same mass, the earlier report defined the Mass-adjusted Safety Index (MSI) as D minus the expected value. The models which currently achieve the best levels of secondary safety for their mass lie farthest below the line, and so have the most negative values of MSI.

This brings out an unfortunate consequence of the index as originally defined: the *greater* the value of MSI of a car model, the *lower* its secondary safety. It does share this feature with the DOT index D, so the original definition will be retained in this report, but it may be sensible in future to redefine both indices so that a higher value is associated with improved secondary safety.

It is possible to estimate the casualty benefits that would be expected if all models were improved to match the standards of these best models, i.e. if their MSI's were reduced to a value v representative of the best current models. The benefit for model m is, from (2),

Number of model m cars involved in accidents . $\{D(m) - \nu\}$ (3)

The key question is then to choose an appropriate value of ν to evaluate. The models with the lowest values are involved in relatively few accidents, so the confidence intervals for their indices are relatively wide. In view of this, ν will be taken as the n-th lowest MSI, rather than the lowest MSI, to avoid setting an unrealistically optimistic target.

Figure 8 shows the variation with mass of the index D_B, so that it corresponds to figure 1 but excludes slight casualties and accidents. The points in figure 1 lie within a fairly narrow pencil about the fitted line, but the points in figure 8 are more widely dispersed: this is summarised by the cumulative frequency distributions in figure 9. It is straightforward to calculate the casualty reduction for any value of ν, evaluating (3) for each model in turn. When $\nu=\nu_B$, the number of drivers killed or seriously injured falls by a similar percentage to the number injured; however, the greater dispersion of D_B suggests that ν_B should be greater than ν and that consequently there is greater scope (proportionately) for reducing the number of drivers who are killed or seriously injured than the number who are injured.

For any value of n, ν_B is approximately $1^2/_3\nu$ because of the greater dispersion of D_B. Figure 10 shows how the percentage reduction varies with n, for n between 5 and 11 (out of a total of 87 models). The graphs show that if the safety of all models were improved to the level achieved or exceeded by the safest tenth of models (i.e. n=9), the number of drivers injured in two-car accidents would fall by 10 per cent ($\nu = .058$) and the number ksi by 14 per cent ($\nu_B = .083$). The 90% confidence interval for both estimates is $\pm 1^1/_2$ per cent.

A more demanding target would be the level achieved or exceeded by the safest twentieth of models (n=5), and if this could be attained then the number of drivers injured would fall by 12 per cent ($\nu = .069$) and the number ksi by 22 per

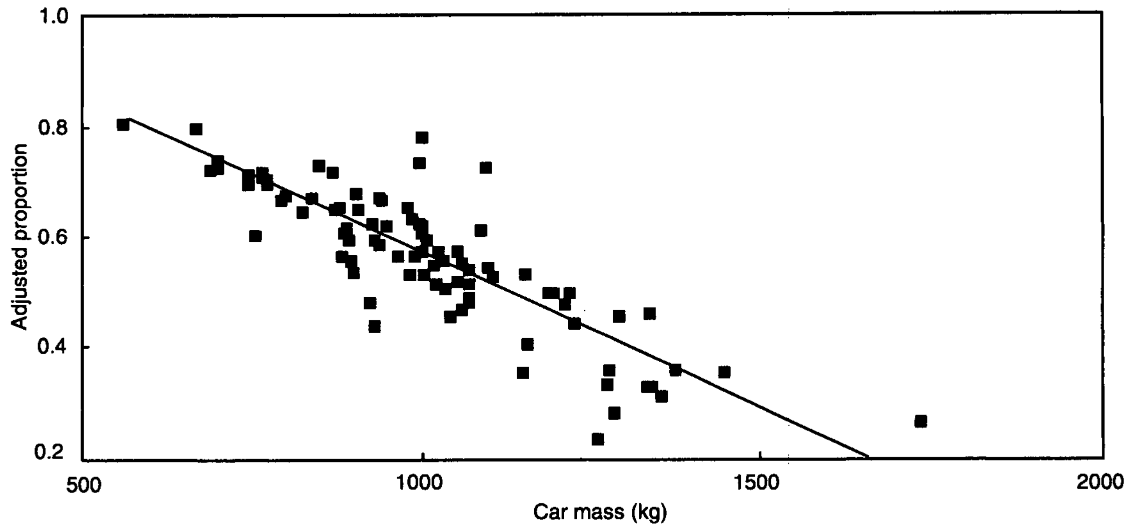

Fig. 8 The relationship between the DoT index D_B and car mass

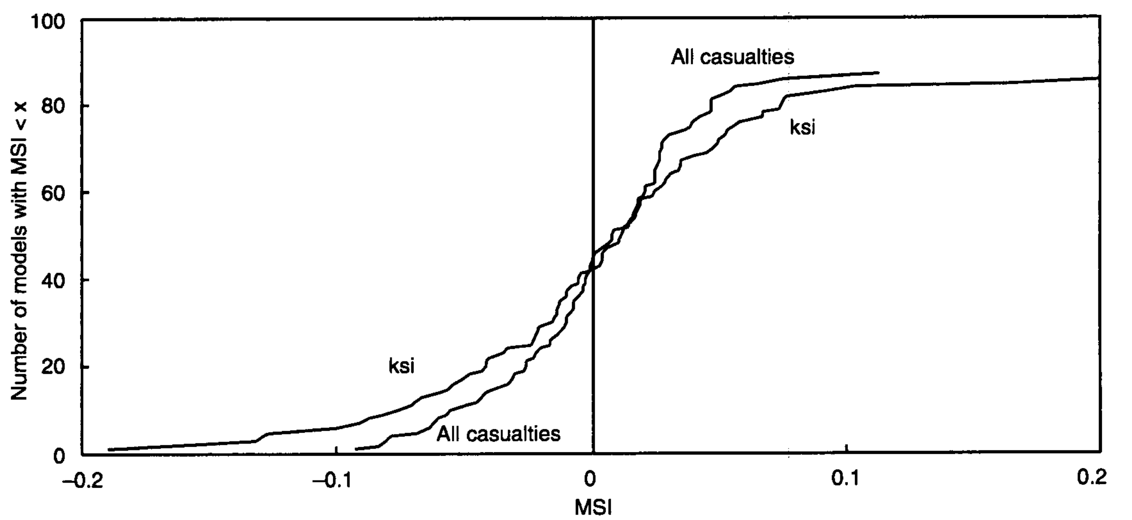

Fig. 9 Cumulative MSI distributions

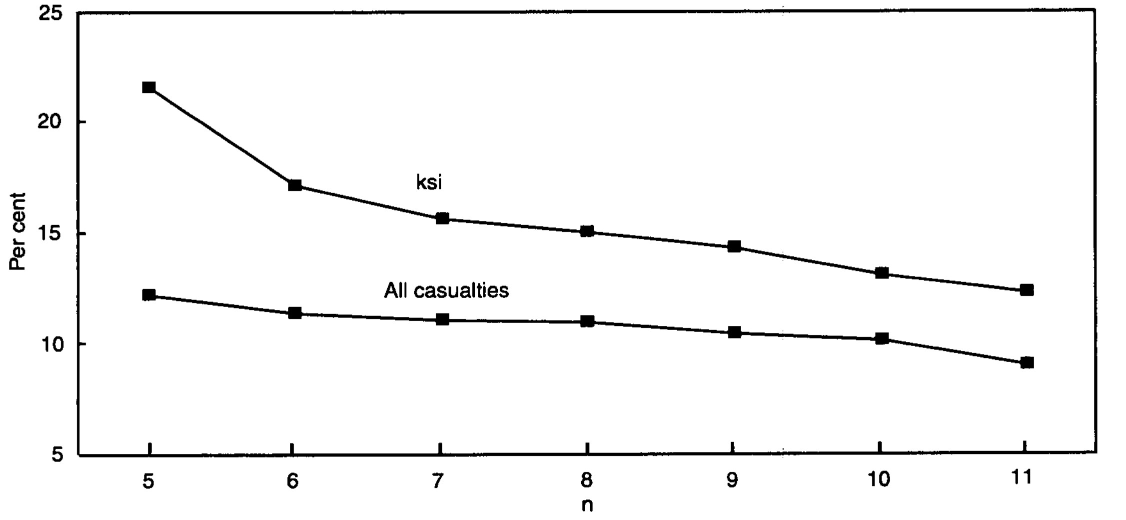

Fig. 10 Casualty reduction if secondary safety of all models improved to the level of the n-th safest model

cent (v_B=.127). The 90% confidence interval is ±2 per cent for the former estimate and ±3 per cent for the latter.

4.1 THE DISTRIBUTION OF THE DOT INDICES

Figure 9 showed the cumulative frequency distributions for the MSI values calculated from D and D_B. Both distributions are effectively normal, with zero mean (because of the definition of MSI) and standard deviations of σ=0.038 and σ_B=0.067 respectively. Only about 16 per cent of two-car injury accidents are fatal or serious accidents, so the calculation of D_B is based on far fewer vehicles than the calculation of D and the estimated values are less precise. This section considers whether the greater dispersion of D_B could be the result of the lower precision and greater scope for random variation.

This possibility is examined by calculating the standard deviations of the values of σ and σ_B, the standard deviations of the two MSI distributions. The standard error of the estimated index for each model is known from the estimation process, and an alternative set of indices can be simulated using this information together with a procedure for generating random normal deviates. This set of indices will differ slightly from the original, the difference being controlled by the standard errors, so a new line must be fitted to represent the slightly different relation between mass and the simulated indices. The MSI's are re-calculated for the simulated data, and the standard deviation of the simulated MSI distribution is computed. The variation of the simulated standard deviation is investigated by repeating the process many times, using different sets of normal deviates.

The upper limit of the range of σ found in the simulation lies well below the lower limit of the range of σ_B, so that v_B is undoubtedly more widely dispersed than v. The standard deviations of σ and σ_B are fairly small, 0.0021 and 0.0024, and the difference between σ and σ_B would have to be as little as 0.0063 (i.e. less than one quarter of the actual value) for there to be a 1-in-20 chance that D_B actually had the same dispersion as D.

This implies that the protection provided in fatal and serious accidents *does* vary more widely between models than the protection provided in slight accidents. The conclusion appears plausible. There are various methods that a car designer can adopt to protect the driver in a severe accident and 'convert' a serious injury into a slight one, whereas it appears more difficult to protect the driver in a slight accident and prevent a slight injury from occurring. Hence, the level of safety is likely to vary more widely between models when measured for fatal or serious accidents than when measured for all injury accidents.

5. CONCLUSIONS

This report has developed earlier research that has already been reported into methods for comparing the secondary safety of car models (Broughton, 1994). The new research has consisted of detailed analyses of data from recent car accidents, and falls into two parts:

(i) analyses relating to the likely effects of downsizing on driver casualties in two-car accidents,

(ii) investigations of three issues left unresolved by the earlier report.

The downsizing results relate only to two-car accidents; they may be generalised to most accidents involving three or more vehicles, but probably not to single-car accidents nor to accidents involving a car and a heavier vehicle such as a lorry. Thus, they apply to accidents which account for about one half of fatalities and three quarters of casualties in cars, and significant gaps still remain in the analysis of the casualty effects of downsizing.

The earlier report showed that the proportion of car drivers injured in two-car accidents declines rather regularly with car mass. This was consistent with previous research, and such results have presumably been the basis for concerns which have been expressed that downsizing would increase the number of car occupant casualties. The earlier report had also shown, however, that heavier cars tend to be associated with more casualties in the 'other' car. This report has combined the two effects and shown that the mean number of casualties per accident (i.e. in both cars) does not vary systematically with mass. It then showed that accident severity tends to increase with the combined mass of the two colliding cars: as the combined mass of the two cars increases, so does the probability of one or more of the drivers being killed or seriously injured. This tends to suggest that downsizing would not increase casualties, and might actually reduce them.

This was studied further by developing a mathematical model to simulate the effects of downsizing, estimating the change in casualties that would be expected if the accident-involved cars had been somewhat lighter but otherwise unchanged. Using two main assumptions, the simulation showed that downsizing is likely to lead to fewer drivers being killed or seriously injured; it is also likely that the number injured will fall, although the evidence for this is slightly less certain. A uniform downsizing of 5 per cent was estimated to lead to 3.8 per cent fewer casualties on built-up roads and 2.9 per cent fewer casualties on non built-up roads.

The main reservation about these conclusions arises from uncertainty about the reasons underlying the increase of accident severity with combined mass, which has been demonstrated statistically but not explained. If the increase has a physical cause, the relation between size and severity should not be affected by downsizing and the model's results will be reliable. If, however, the increase derives from a relationship between driving behaviour and car size, the model's results may be less reliable. No evidence has been found, however, which suggests that downsizing might lead to extra casualties.

The relation between mass and the DOT index of secondary safety studied in the earlier report was then examined in detail, to see how the masses of two colliding cars affects the distribution of the risks of injury between the two cars. It was found that the dominant influence is the difference between the masses of the two cars; as this rises, the probability of the driver of the lighter car being injured rises rapidly, while the probability of the other driver being injured falls. On average, for a difference in mass of 100 kg the probability of the driver of the lighter car being injured is 0.67, and 0.55 for the driver of the heavier car; for a difference of 500 kg, the former rises to 0.86 while the latter falls to 0.33. The differences are more marked for fatal and serious casualties.

The earlier report had found that current car models of similar mass can provide significantly different levels of protection to their occupants. Hence, if all models were to provide the same level of protection as the most successful designs, there would be fewer casualties. The casualty reduction that would be achieved by improved protection was estimated, and naturally depends upon the target level of protection. If the safety of all models were improved to the level achieved or exceeded by the safest tenth of models then the number of drivers injured in two-car accidents would fall by 10 per cent and the number killed or seriously injured by 14 per cent. A more demanding target would be the level achieved or exceeded by the safest twentieth of models, and if this could be attained then the number of drivers injured would fall by 12 per cent and the number killed or seriously injured by 22 per cent.

The fact that greater reductions are achievable among the more severe casualties suggests that the level of protection in fatal and serious accidents is more variable than the level in all injury accidents - of which fatal and serious accidents form only a small minority. It had seemed possible that this was a statistical quirk caused by different sample sizes rather than a genuine result, but it is now clear that this is a genuine result.

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7. ACKNOWLEDGEMENTS

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8. APPENDIX: THE RELATION BETWEEN D, A AND M

Section 2.1 defined three model-specific indices, calculated with data from those two-car accidents where at least one driver is injured:

D(m) = Proportion of drivers of model m cars who are injured when involved in these accidents (the DOT index),

A(m) = Proportion of drivers in collision with model m cars in these accidents who are injured (the Aggressivity index), and

M(m) = mean number of injured drivers in one of these accidents involving at least one model m car.

It was claimed that M(m) is approximately equal to A(m)+D(m), and this will now be demonstrated. Let

x_1 = number of drivers of model m cars involved in two-car accidents,

x_2 = number of drivers of model m cars who are injured,

x_3 = number of drivers in collision with model m cars who are injured,

so $D(m) = x_2/x_1$ and $A(m) = x_3/x_1$. If model m cars never collide with each other then:

number of accidents involving model m cars $= x_1$

number of injured drivers $= x_2 + x_3$

and $M(m) = (x_2 + x_3)/x_1 = x_2/x_1 + x_3/x_1 = D(m) + A(m)$.

However, a minority of accidents does involve two model m cars, so that some drivers of model m cars contribute to both x_2 and x_3. To allow for this, let

y = number of accidents involving two model m cars,

z = number of these accidents where both drivers are injured,

so

number of accidents involving model m cars $= x_1 - y$

number of drivers injured in these accidents $= x_2 + x_3 - z$

Hence, the mean number of injured drivers per accident involving a model m car is

$$M(m) = \frac{x_2 + x_3 - z}{x_1 - y} = \frac{x_2 + x_3}{x_1} + \frac{y(x_2 + x_3) - zx_1}{x_1(x_1 - y)}$$

$$= D(m)+A(m) + \frac{y(D(m)+A(m)) - z}{(x_1 - y)}$$

Thus, calculating M(m) as the sum D(m) + A(m) will lead to a slight underestimation. Section 3 showed that $z \approx y/5$, so $D(m)+A(m) \approx 1.2$ and the error is approximately $y/(x_1 - y)$. The error will be greatest for the most common model of car, the Ford Escort, which accounts for 10 per cent of the car fleet, so $y/x_1 \approx 0.05$ and the greatest error will be approximately 5 per cent. Only 4 other models account for more than 5 per cent of the car fleet, so for the great majority of models the error introduced by the approximation will be less than 2½ per cent. Hence, the mean number of drivers injured per accident is effectively equal to the sum of the DOT and the Aggressivity indices.