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Safety of a Downsized Vehicle Fleet: Effects of Mass Distribution, Impact Speed and Inherent Protection in Car-To-Car Crashes

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ABSTRACT

Vehicle fleet downsizing has been discussed in Europe as an aspect to reduce fuel emissions. A recently developed mathematical model was used to study the individual effects of fleet mass distribution, impact speed reductions and inherent vehicle protection on average injury and fatality rates for downsized fleets. A baseline fleet of 700-2000 kg was downsized by a) reducing all vehicle masses by 10% or 20% and b) by removing all cars heavier than 1400 or 1200 kg.

The results showed that the safety can be maintained if the vehicle masses are reduced proportionally to their original mass. A higher safety level can be achieved by removing the heavier vehicles. Traffic safety can be further enhanced by impact speed reductions or by improvements of restraint systems and vehicle compatibility. The safety level would rise more by implementation of radar-activated brakes or controlling city speed limits than by intensified highway patrols, to eliminate crashes with impact speeds over 140 mph or with an average velocity change of 70 mph. However, a maximum impact speed at 100 mph would reduce the number of fatalities more effectively than a small reduction in all impact speeds.

It was concluded that a downsized fleet can result in fewer fatalities, depending on the downsizing strategy. Furthermore, the model can be used to estimate the effects of potential safety strategies.

INTRODUCTION

Because of environmental concerns, Several European countries have discussed vehicle fleet downsizing to as an aspect of fuel emission reductions (Dreyer et al. 1981, Tingvall 1996, Larsson et al 1996, Broughton 1995). Downsizing generally refers to reducing vehicle fleet mass, and can be accomplished in several ways. It would benefit fuel efficiency, air pollution, parking in congested cities, and would reduce societal costs. However, the effect of downsizing on safety remains unclear.

Vehicle mass has a dominant effect on occupant and collision partner fatality risks in car-to-car crashes (Evans 1994a). Some studies have shown that downsizing would improve overall traffic safety (Dreyer et al. 1981; Richter & Zobel 1982; Thomas et al. 1990; Tarriere et al. 1994; Broughton 1996a,b). Broughton (1995, 1996 a,b,c) accounted for the lower impact speed associated with lighter vehicles in his calculations. However, Evans (1987, 1991, 1993, 1994a&b), Evans & Frick (1993) and Korner (1996) showed that a lighter car fleet would increase the total number in crash fatalities. All researchers used real world accident fatalities observed in various vehicle mass classes, relative to fatality numbers expected from crash exposure. They determined fatality effects for changes in the proportions of light and heavy vehicles, but could not assess mass changes of all vehicles. Furthermore, vehicle mass was not isolated from size, stiffness and inherent safety (Evans 1989, Ernst 1991, Wood 1997, Korner 1996).

More recently, Mizuno et al. (1997) and Buzeman et al. (1998) isolated vehicle mass from these factors and estimated the effects on the total number of fatalities in car-to-car collisions. Both found an injury and fatality increase for a uniformly reduced vehicle fleet mass. Buzeman et al. (1998) however showed improved traffic safety for a fleet with smaller mass range, due to a monotonously increasing relationship between the average fatality rate and average fleet mass ratio. Furthermore, their results indicated that a higher fatality rate from a downsized fleet may be compensated for by reduced impact speeds and improved inherent vehicle protection. The combined effects of a downsized fleet and impact speed reductions or improvement, however, have not been fully examined yet. A more thorough study is therefore needed of the safety of various downsized vehicle fleets and the role of various speed reduction strategies and improved inherent protection to optimize the safety of downsized fleets more effectively.

OBJECTIVE

The purpose of this study was to predict the safety of various downsized vehicle fleets, as well as the safety effects influence of various speed reduction strategies and of improved inherent vehicle protection.

METHOD DEVELOPMENT AND INPUT MATERIALS

For this purpose, a mathematical simulation was used to compare the average of occupant and partner driver injury and fatality rates for several safety strategies. The model was previously developed by Buzeman et al. (1998).

THEORETICAL RELATIONSHIPS – For each car mass, average occupant and partner driver fatality rates were calculated when occupants replaced their car by a heavier or lighter car. A car-to-car crash was considered between cars with mass Mj and Mk at impact speed Vimp. The resulting velocity change in car Mj, ΔVj, is given by:

$$\Delta V_j = \frac{M_k}{M_k + M_j} * V_{imp} \qquad \text{(I)}$$

The velocity change causes a driver injury risk, IR, or fatality risk, FR, which is exponentially related to the ΔV (Evans 1993) by:

$$IR(\Delta V)=(\Delta V/ \Delta V_{0,IR})^{NIR},$$

$$\text{for } \Delta V< \Delta V_{0,IR}; IR=1 \text{ for } \Delta V> \Delta V_{0,IR} \qquad \text{(IIa)}$$

$$FR(\Delta V)=(\Delta V/ \Delta V_{0,FR})^{NFR},$$

$$\text{for } \Delta V< \Delta V_{0,FR}\text{ ; } FR=1 \text{ for } \Delta V> \Delta V_{0,FR} \qquad \text{(IIIa)}$$

The curves (eq. (IIa) and (IIa)) were fit to published data (Evans 1994a), using the least squares method. This yielded (with one standard deviation):

$$NIR=2.57 \pm 0.17,\ \Delta V_{0,IR}=69.2 \pm 0.60 \text{ mph} \qquad \text{(IIb)}$$

$$NFR=4.51 \pm 0.056,\ \Delta V_{0,FR}=70.0 \pm 0.74 \text{ mph} \qquad \text{(IIIb)}$$

The expected number of driver fatalities in the considered crash, FF, was calculated by the fatality risk of both drivers in the crash, FRtotal, multiplied by their collision probability, Pcoll(Mj)* Pcoll(Mk), and by the probability of that crash speed, Pimp(Vimp) (Buzeman et al. 1998). The average driver fatality rate in a frontal car-to-car accident, FFave, was obtained from FF, summed over all possible impact speeds and vehicle masses:

$$FF_{ave}={}_{Mj}\Sigma_{Mk}\Sigma_{Vimp}\Sigma\ FR_{fatal}(V_{imp},M_j,M_k)* P_{imp}(V_{imp})*P_{coll}(M_j)*P_{coll}(M_k) \qquad \text{(IV)}$$

Similarly, the average injury rate was calculated. It was assumed that impact speed distribution and inherent protection were equal for all vehicle masses (Mizuno et al. 1997). In this way, the vehicle mass, impact sped and inherent protection parameters were studied separately. The average fatality rate per crash was multiplied by the factor 4389 to obtain the fatality rate per 100,000 registered vehicles. Equations (I) to (IV) were implemented in the software program MATLAB, which is used for matrix calculations. The implementation procedure was described in Buzeman et al. (1998).

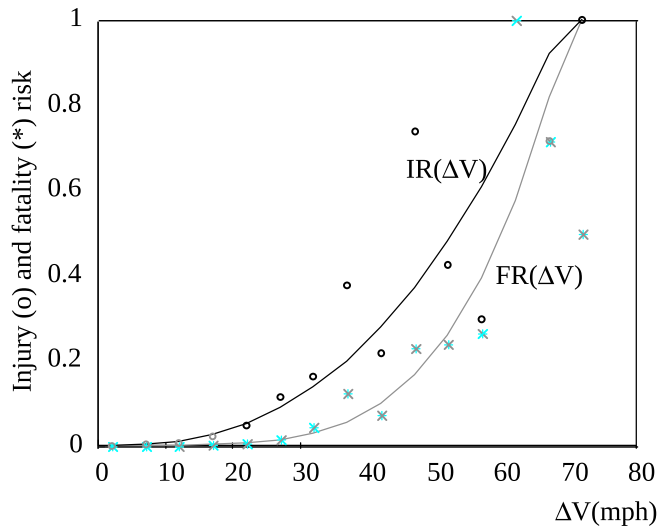

Figure 1. Observed injury (o) and fatality risk (*) with velocity change, and corresponding curve fits (based on Evans 1994a, adjusted similarly to Larsson et al. 1996).

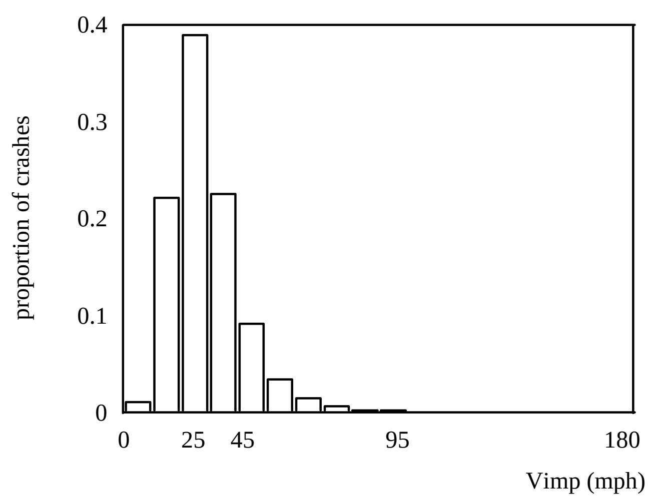

Figure 2. Proportion of crashes per impact speed class (Evans 1994)

PARAMETER CHANGES – A hypothetical baseline vehicle fleet consisted of cars with masses normally distributed between 700 and 2000 kg, in agreement with Buzeman-Jewkes et al. (1998). This fleet is exposed to crashes at 0-180 mph, with the impact speed distribution (Figure 2) based on NASS data from 1982-1991 (Evans

1994a). It was assumed that the vehicle mass distribution was similar in each ΔV category, implying that collision speed distribution and ΔV distribution were equivalent.

The baseline fleet was downsized to a 10 or 20% lower average mass in two ways. The first method reduces all car masses by 10 or 20% respectively, and the second method removes all cars heavier than 1400 kg or 1200 kg, reflecting a 10 or 20% reduction in average fleet mass respectively. The effect of impact speed reduction and improved inherent vehicle protection is examined for the 10% downsized fleets. For this purpose, the impact speed is reduced by either 1-3% or by eliminating all crashes with impact speeds higher than 170, 160, …, 100 mph. An improvement of inherent vehicle protection is reflected by a 1-3% increase in either of the risk curve parameters N_{FR} or $\Delta V_{0,FR}$. An overview of the calculation matrix is shown in Table 1.

RESULTS

The model predicts 235.8 casualties and 34.0 fatalities per 100,000 registered cars for the baseline fleet, which agrees reasonably well with the passenger car involvement in fatal crashes of 24.7 to 30.4 per 100,000 registered vehicles between 1988 and 1994 in the US (FARS 1994, table 3, p.17).

Table 1. Matrix with parameter changes and resulting injury and fatality rates.

Fleet Mass	**Impact Speed**	N_{FR}	$\Delta V_{0,FR}$	**Injury per 10^5 cars**	**Rate, % relative to baseline**	**Fatality per 10^5 cars**	**Rate, % relative to baseline**
Baseline	Baseline	Baseline	Baseline	235.8	100	35.0	100
–10%	-	-	-	235.8	100	35.0	100
-20%	-	-	-	235.8	100	35.0	100
< 1400 kg	-	-	-	233.8	99.1	33.9	96.9
< 1200 kg	-	-	-	232.2	98.5	33.2	94.9
–10%	-1% -2% –3%	-	-	229.7 223.7 217.8	97.4 94.9 92.4	33.4 31.8 30.2	95.4 90.9 86.3
–10%	< 170 mph < 160 mph < 150 mph < 140 mph < 130 mph < 120 mph < 110 mph < 100 mph	-	-	235.8 235.7 235.6 235.1 234.7 233.1 231.5 227.8	100 99.9 99.9 99.7 99.5 98.8 98.2 96.6	34.9 34.8 34.8 34.3 33.9 32.5 31.3 28.9	99.7 99.4 99.4 98.0 96.9 92.9 89.4 82.6
–10%	-	-1% -2% -3%	-	229.1 222.5 216.2	97.2 94.4 91.7	33.8 32.8 31.7	96.6 93.7 90.6
–10%	-	-	-1% -2% -3%	229.9 224.2 218.7	97.5 95.1 92.7	33.5 32.0 30.6	95.7 91.4 87.4
< 1400 kg	-1% -2% –3%	-	-	227.1 221.2 215.3	96.3 93.8 91.3	32.1 30.6 29.1	91.7 87.4 83.1
< 1400 kg	< 170 mph < 160 mph < 150 mph < 140 mph < 130 mph < 120 mph < 110 mph < 100 mph	-	-	233.1 233.0 233.0 232.4 232.0 230.4 228.7 225.0	98.8 98.8 98.8 98.6 98.4 97.7 97.0 95.4	33.6 33.5 33.5 32.9 32.5 31.1 29.8 27.4	96.0 95.7 95.7 94.0 92.9 88.9 85.1 78.3
< 1400 kg	-	-1% -2% -3%	-	226.4 219.9 213.5	96.0 93.3 90.5	32.6 31.5 30.5	93.1 90.0 87.1
< 1400 kg	-	-	-1% -2% -3%	227.3 221.6 216.2	96.4 94.0 91.7	32.2 30.8 29.5	92.0 88.0 84.3

MASS EFFECTS – The injury and fatality rates were not affected by a 10 or 20% mass reduction of all vehicles, since the average fleet-mass ratios were equal to that of the baseline fleet, resulting in equal delta-V distributions. A 3.1 to 5.1% reduction of the fatality rate was obtained by the removal of vehicles heavier than 1,400 kg and 1,200 kg, respectively (Figure 3). The same downsizing strategy led to 1-1.5% fewer casualties.

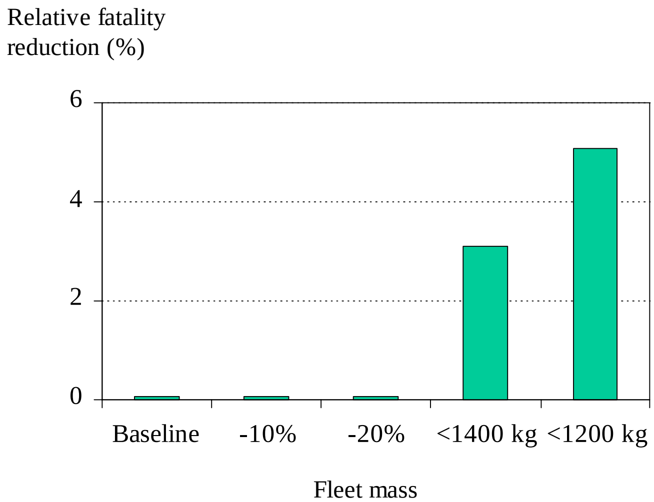

Figure 3. Fatality effects of vehicle downsizing by reducing all car masses by 10 or 20% (10%, 20% in graph), or by removing all vehicles heavier than 1400 kg or 1200 kg (< 1400 kg or < 1200 kg, respectively).

EFFECTS OF IMPACT SPEED AND INHERENT VEHICLE PROTECTION – Figures 4a and 4b show that reducing the impact speed of all crashes had a similar influence on the injury and fatality rates as increasing the inherent vehicle protection parameters. These effects were relatively large compared to those of mass. A 1-3% overall impact speed reduction resulted in 4.6-13.7% fewer fatalities for the baseline and 10% lighter fleet (Figure 4a), while the same speed reductions led to a 8.3% to 16.9% lower fatality rate for the fleet with cars < 1400 kg (Figure 4b). Increasing the inherent protection parameters N_{FR} and $\Delta V_{0,FR}$ by 1-3% decreased the number of killed by 3.4-12.6% for the 10% lighter fleet and by 6.9-15.7% in case of the <1400 kg fleet. The impact speed and protection parameters had similar effects on casualties, although less pronounced than for fatalities (Table 1). The results showed that mass and speed effects could be superimposed within 10% variations.

Eliminating collisions with impact speeds over 140 mph hardly improved traffic safety (Figure 4a-b). The reduced maximum impact speed resulted in less than 1% fewer casualties and 2% fewer fatalities compared to the safety of crashes with a maximum impact speed of 180 mph, which are negligible safety effects compared to those of the 1-3% uniform speed reduction. These results are not surprising, since these speed ranges involve less than 0.01% of all car crashes (figure 2). The same strategy led to a fatality reduction of 4 to 6% for the fleet with maximum vehicle mass of 1400 kg. However, greater reductions of the maximum speed exponentially improved the traffic safety level, leading to 17.4-21.7% fewer fatalities for a 100 mph maximum impact speed. The 100 mph to 180 mph speed range comprises approximately 0.1% of all car crashes.

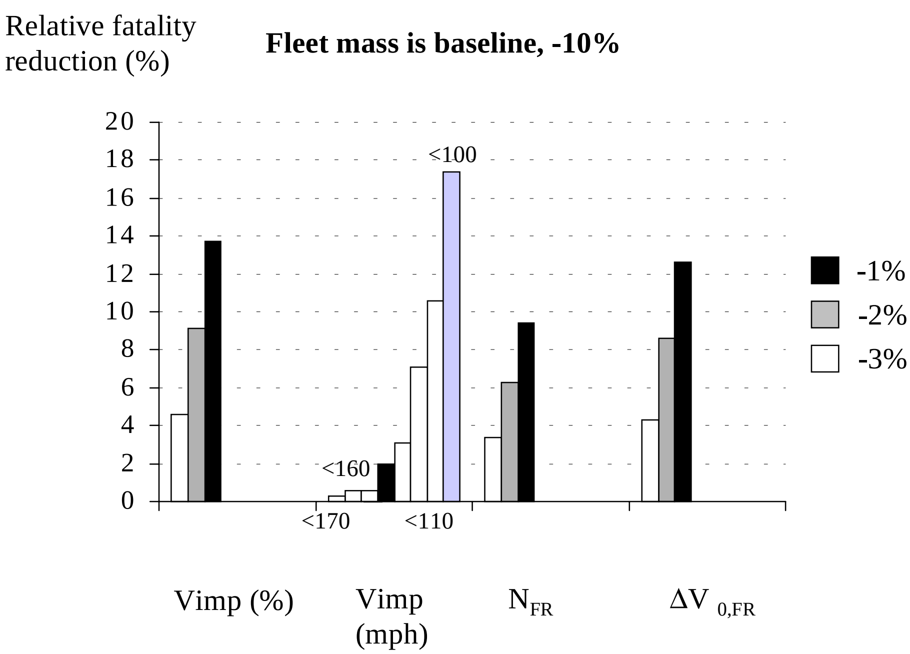

Figure 4a. Fatality effects of impact speed reductions (Vimp), or inherent vehicle protection parameters N_{FR} and $\Delta V_{0,FR}$ for the baseline or 10% downsized vehicle fleet. The impact speed of all crashes was reduced by 1-3% (Vimp (%)) or the crashes with impact speeds over 100, 110, 120, 130, 140, 150, 160 or 170 mph were eliminated (Vimp (mph), < 100, <110,… < 160, <170).

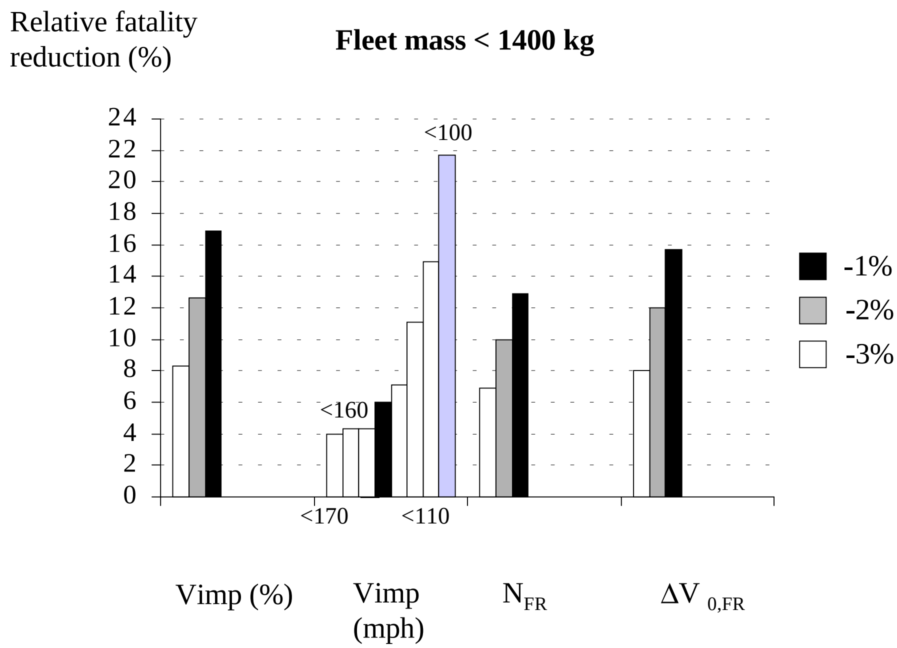

Figure 4b. Fatality effects of impact speed reductions (Vimp), or inherent vehicle protection parameters N_{FR} and $\Delta V_{0,FR}$ for the fleet with maximum vehicle mass of 1400 kg. The impact speed of all crashes was reduced by 1-3% (Vimp (%)) or the crashes with impact speeds over 100, 110, 120, 130, 140, 150, 160 or 170 mph were eliminated (Vimp (mph), < 100, <110, …, < 160, <170).

ANALYSIS AND DISCUSSION

METHOD – The goal of this paper was to study the individual effects and interactions of vehicle mass, impact speed and inherent vehicle protection on the average injury and fatality rates in frontal car-to-car crashes. The vehicle mass could be isolated from impact speed and inherent protection by assuming that the impact distribution and inherent protection (fatality or injury risk curve) are equal for all vehicles. In reality, these parameters are related to vehicle mass and design differences, causing a higher fatality rate in crashes between two light vehicles than in crashes between two heavy vehicles (Dreyer et al. 1981, Ernst et al. 1991, Evans and Wasielewski 1987, Evans 1991, Evans 1994b, Fountaine and Gourlet 1994, Marumo et al. 1974, Tarriere et al. 1994, Wood and Mooney 1996, Wood 1997). The isolation of vehicle mass from impact speed and inherent protection helped in determining the relative significance of these parameters on fatality and injury rates. Furthermore, the method used in this paper was a useful tool in finding safe downsize strategies and set priorities to increase safety for downsized fleets.

The vehicle fleet mass was not based on the US fleet, which caused that a validation of the model was limited. However, the calculated fatality rates were similar to the rate of passenger cars involved in fatal real-world crashes in the US, which was assumed to be a good estimate of the real-world driver fatality rate in the US. The reasonable prediction of this fatality rate indicates the applicability of the model.

The model assessed only frontal car-to-car collisions, which covers about 30% of all car crash injuries and fatalities (Evans 1989, Official Statistics Sweden 1996, Korner 1996). Single car crashes however, are not affected by mass in case of the assumed uniform inherent vehicle protection, and are therefore implicitly included in this paper. This results in the assessment of approximately 50% of all car crashes.

The estimates of injury and fatality rates were based on the fatality risk versus delta-V curve. Delta-V was considered to be the best available crash severity parameter, since a combination of acceleration and crush or intrusion amount is reflected by this parameter, in case the delta-V is caused by a collision. However, the analysis would be improved if acceleration time-histories and intrusion data would be available for car crashes. The use of crash recorders (Kullgren et al. 199??) and post-impact intrusion measurements would enable the development of a relationship between delta-V and acceleration and/or intrusion, resulting in a more accurate reflection of injury or fatality-risk increase with crash severity.

The input risk curve was based on all frontal car crashes of the complete passenger car fleet (Evans 1994a), and reflects the average inherent vehicle protection of vehicles in the time-frame of the late 1980's. The risk curve, however, may vary with car mass and model since heavier and newer cars have safer driver behavior and improved designs (Marumo et al. 1974, Dreyer et al. 1981, Evans and Wasielewski 1987, Ernst et al. 1991, Fountaine and Gourlet 1994, Tarriere et al. 1994, Evans 1994, Wood and Mooney 1996, Wood 1997). Also, fatality risk may vary with crash configuration and object, due to stiffness and geometrical incompatibility. Finally, fatality risk may differ for drivers and passengers. These risk variations between vehicles caused highly variable fatality risk versus delta-V data, to which an exponential curve was fitted by Evans (1994a). The large effects of parameters N_{FR} and $\Delta V_{0,FR}$ indicate that other adequate curve-fits might lead to substantial changes in the magnitude of the calculated effects. The model could be more accurate and could be extended to overall traffic safety by determining fatality risk curves for various crash directions, collision objects and vehicle characteristics. Malliaris et al. (1997) presented a method to determine the significance of these factors and Wood (1997) explained how to apply the different risk curves to estimate overall safety effects. Furthermore, the use of crash recorders (Kullgren et al. ??) may provide more accurate measurements of delta-V, which would improve the input data for the fatality risk curve. Therefore, crash recorder data would contribute to a higher quality of fatality predictions.

EFFECTS OF MASS – Environmental concerns have initiated governments in Europe to support a downsized vehicle fleet to lower CO2 emissions. However, many researchers predicted higher injury and fatality rates for a downsized vehicle fleet (Evans 1991, Klein et al. 1991, Korner 1996, Hertz 1997), though others reported that downsizing may improve traffic safety (Dreyer et al. 1981, Richter and Zobel 1982, Tarriere et al. 1994, Thomas et al. 1990 and Broughton 1995, 1996a). In this paper, the individual mass effects showed that traffic safety can be maintained when all vehicles are reduced by a mass proportional to their original mass. Using this downsizing strategy, the average mass ratio of the fleet remains the same, while Buzeman et al. (1998) showed that fatality rate monotonously increases with average mass-ratio. A lighter fleet can even result in fewer casualties and fatalities by removing the heaviest cars. Removing the heaviest vehicles reduces the mass range and thus the average mass ratio, which causes the lower the number of fatalities (Buzeman et al. 1998). This was in agreement with Dreyer et al. (1981) and Richter and Zobel (1982) and Broughton (1995, 1996b). However, this approach may be quite infeasible as the heavier vehicles are often used for commercial purposes. It would be good to prioritize downsizing of large vehicles. The results in this paper were partly inconsistent with those of Broughton (1995, 1996b). He predicted more injuries in light-to-light car than in heavy-to-heavy car collisions, due to an effect of combined mass. This was in contrast with our estimates of individual mass effects as reflected in the equal fatality rate for the baseline and 10 or 20% lighter fleet. However, this paper showed that the effect of inherent vehicle protection (as represented by the parameters N_{FR} and $\Delta V_{0,FR}$) was dominant over vehicle mass, which may explain for Broughton's findings.

EFFECTS OF IMPACT SPEED AND INHERENT VEHICLE PROTECTION ON DOWNSIZED VEHICLE FLEETS – Uniform impact speed reductions and an increase in the parameters N_{FR} and $\Delta V_{0,FR}$ strongly reduced injury and fatality rates of downsized vehicle fleets. These influences were relatively large compared to those of vehicle fleet mass distribution changes. The parameters N_{FR} and $\Delta V_{0,FR}$ in equation (IIIa) were assumed to reflect three phenomena. First, they may be related to the design of restraint systems and other safety features. This was indicated by Evans (1991), who found that belt-use increased the parameter N by 23%. Furthermore, the different of vehicle characteristics, like front stiffness and geometry, and crash configuration may cause different acceleration and compartment intrusion for crashes of equal delta-V, which entails a variation in injury and fatality risk. Thus, the parameters N_{FR} and $\Delta V_{0,FR}$ may also be influenced by the fleet's variation in stiffness and geometry. A more compatible fleet would result in less variation of acceleration and intrusion in crashes of similar conditions, and a higher value of N_{FR} might be expected. Finally, the risk curve parameters reflect the tolerance level divergence between occupants of different age and gender. The large effect of impact speed reductions and improvements of the inherent protection parameters N_{FR} and $\Delta V_{0,FR}$ indicate that a more compatible fleet and lower impact speeds may further enhance fatality reductions for downsized vehicle fleets.

Impact speed reductions can be achieved by application of different strategies, like focus on speed limit reductions on highways, increased speed limit controls in cities, or implementation of speed control or crash avoidance devices. The latter two strategies could reduce the impact speed in the majority of car crashes, while the focus on high-way speed limits would mainly reduce the number of crashes at high severity. The results of this study showed that speed reductions throughout the impact speed range would lead to far greater fatality reductions than eliminating crashes over 140 mph impact speed or 70 mph average delta-V, which reflects the low crash exposure in high speed ranges (figure 2). Crashes of this impact severity may represent frontal crashes on two-lane highways with speed limits between 65 and 75 mph, or 100-120 km/h as applied in the US and in Europe. Speed limit controls in congested areas may be a goal of higher priority than reducing the number of crashes in speed ranges over 70 mph. However, the proportion of crashes increases non-linearly for impact speeds (considering impact speeds > 25 mph, figure 2), which causes the fatality rate to decrease non-linearly with reduced maximum impact speeds (figures 4a and b). Consequently, a reduction of the maximum impact speed to 100-110 mph led to 17.4-21.7% fewer fatalities, which was the most pronounced fatality reduction. The model may be used to determine which speed limit strategy should be prioritized to more effectively improve traffic safety. It should be noted that FARS calculates the delta-V from the damage of the involved vehicles, using a constant stiffness. Most vehicles, however, show force saturation at high crush levels. The higher range of delta-V's may therefore have been overestimated. Improved calculations of crash delta-V would benefit this type of analyses.

CONCLUSIONS

- The model is a valid tool to predict injury and fatality consequences of changes in the vehicle fleet, impact speeds or inherent protection, provided that an adequate risk versus delta-V curve is available for the examined crash conditions.
- Vehicle downsizing can maintain or improve traffic safety, provided that the average mass ratio remains the same or is reduced. Reducing all vehicle masses had no safety consequences, when the mass reductions were proportional to the original car weight. Safety improvements were achieved by removing the heaviest cars.
- Impact speed reductions in all crashes resulted in relatively large fatality rate reduction in comparison to mass. Similarly, the consequences of improvements in inherent vehicle protection or compatibility dominated mass effects.
- Eliminating the highest speed crashes hardly contributed to traffic safety, for maximum impact speeds of 140 mph, due to the low crash proportion of this high severity. However, further reduction of maximum impact speeds to 100-110 mph (average delta-V of 50-55 mph) caused the most pronounced fatality reductions of 17.4-21.7%. The results show that intensified speed controls are most beneficial for traffic safety if applied in areas with the greatest number of crashes.
- The model is a helpful tool to determine the priorities of safety strategies like vehicle downsizing, impact speed reductions, improved inherent vehicle protection and car-to-car compatibility for frontal car-to-car crashes.
- The model can be extended to other crash configurations and crash objects, in case risk versus delta-V data are available for all crash situations considered.

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