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Title: Vehicle mass, size and safety

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Abstract:

A review of the international literature was undertaken to examine the relationship between a vehicle's mass or size and its influence on occupant protection. A number of specific objectives were addressed on this relationship and its consequence for vehicle down-sizing in Australia. There was considerable evidence that occupants in larger cars that crash have superior protection to those in smaller cars. However, the precise relationship between size, mass and safety was complex and not totally clear from this review. While mass appeared to be more relevant in multi-vehicle crashes, size seemed to be important in rollovers and single vehicle collisions generally. The question of whether mass or size has greatest influence on safety is relevant if future car construction emphasises lighter composite materials. Safety features act to offset mass effects with a suggestion that they have greatest importance for occupants of smaller cars. While down-sizing was apparent during the seventies, the vehicle fleet mix has remained relatively stable since then. During this time, down-sizing seemed to have been driven more by changes in vehicle ownership and two-car families than world-wide oil shortages or economics in this country. Current and proposed design rules do not appear to have much influence on down-sizing. Economic analysis could throw additional light on the costs and benefits of changes to the Australian fleet.

Key Words: Vehicle type, Dimension, Vehicle Weighting, Safety, Crashworthiness, Accident, Vehicle design, Vehicle Occupant.

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The Biomedical and Hargraves libraries of Monash University and the libraries of the Australian Road Research Board and VIC ROADS were also most helpful in providing references used in this review.

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Executive Summary

An extensive review of the international road safety literature was undertaken by the Monash University Accident Research Centre for the Federal Office of Road Safety to examine the relationship between vehicle mass or size and occupant safety. More than 70 references on this topic were uncovered, essentially from the United States of America, but also from Sweden, Germany, the United Kingdom, France and Canada. One or two Australian references were also found.

The review set out to clarify issues of importance for Australian vehicles, to consider whether it is size or mass that is the dominant factor, to reflect on the safety consequences of changes to the vehicle fleet, and examine the Design rule implications for small and large vehicles It was not intended to make specific recommendations but rather to raise relevant issues for discussion and identify areas that might require further research effort.

Mass and Size Effects on Occupant Safety

The literature on the crashworthiness relationship between vehicle mass, size and safety is rather ambiguous. There was general consensus by most authors that bigger cars were inherently more safe than smaller ones in a collision. However, trying to define this relationship more precisely from the literature is problematic, in part, because of the number of confounding influences and definitional differences.

It was concluded in general terms that mass is probably a more important safety feature than size for most car-to-car collisions, although there was a suggestion that size may predominate more in rollover crashes and single-vehicle accidents generally

There was large variability in the mass and size effects reported in the literature. One report claimed that differences of only 45kg (100 pounds) can have a marked influence on fatality rates in multi-car crashes. Given the wide spread of effects reported, though, it would be extremely difficult to quantify precisely the consequences of down-sizing in terms of reduced occupant safety.

Very few of the reports claiming size effects were also consistent in terms of the amount of this effect. This may be a function of the different ways vehicle size was measured in these studies (overall dimensions, wheelbase, cabin size, etc). Given that the space inside the cabin will have a marked influence on the likelihood and severity of injury, it might be worthwhile in future examining size effects in terms of occupant space.

The level of restraint has been shown to have a marked influence on the mass (size) and safety relationship. One study reported that an unbelted driver in a 2000kg car had the same amount of protection as a belted driver in a 1140kg car. It was further claimed that drivers of small cars gained more from being restrained that those of larger ones. It is too early yet to confirm if there is any disproportionate benefit of driver airbags by vehicle size.

The relationship between vehicle mass and size and likelihood of collision is very much confounded by driver effects. Any effect of vehicle size on risk taking behaviour is at best only speculative at this time.

Down-Sizing and the Australian Fleet

Down-sizing in the Australian fleet seems to have occurred mainly during the seventies and early eighties. While it is often claimed that down-sizing occurred because of the oil crisis at that time, one local vehicle manufacturer argued that increased purchasing by women and increases in the rate of second vehicles at that time was the main motivation for down-sizing in this country.

Annual fleet and sales statistics show that the mix of small and large vehicles has been relatively stable throughout most of the 1980's and 1990's.

It seems that vehicle design rules in this country have had little if any effect on down-sizing in the past. New crash performance regulations recently introduced in Australia (ADR69) may have some marginal (upward) influence on car mass in future, although this influence will at best only be minimal and likely to apply generally across the whole vehicle fleet.

Likely Changes in Future Vehicle Size or Mass

There are two major developments world-wide which may have consequences on fleet down-sizing in the years ahead.

First, there were reports of a growing interest in the use of light-weight materials such as aluminium and plastics in car construction. While the shell body of a car contributes less than half the total weight, nevertheless any substantial reduction in mass by the use of lighter materials could have some consequence on the safety of its occupants in multi-car crashes.

Second, the trend towards the use of finite element analysis (FEA) in car design to reduce mass while improving structural stiffness has the potential to influence the degree of safety for the vehicle's occupants.

Both these trends need to be closely monitored to ensure that occupant safety is optimised and to highlight the need for future regulations aimed at improving vehicle safety in this country.

Areas For Further Research

In the absence of a shift towards smaller vehicles in this country, it is difficult to point to specific areas requiring further research in down-sizing in Australia.

A cost-benefit study of the likely effects of down-sizing (and up-sizing) would be difficult at this time, requiring many assumptions and different scenarios of likely fleet changes and the effects on the community. Nevertheless, such an analysis could highlight what are the critical issues and the likely consequences of fleet size changes in the future.

Assessing in more detail the motivation for down-sizing both within the community and among local and overseas manufacturers would be helpful in demonstrating the need and directions for further research.

1. INTRODUCTION

1.1 VEHICLE MASS AND SIZE

There is potential for conflict between the competing demands for increased vehicle safety to improve occupant protection and the need for smaller lighter vehicles to reduce energy consumption and minimise pollutants. Indeed, overseas reports by researchers and research organisations, such as Leonard Evans of General Motors Research Laboratories, Bob Campbell formerly of the North Carolina Highway Safety Research Centre, The Insurance Institute for Highway Safety, and Claes Tingvall, Folksam Insurance have all reported an apparent linear relationship between increased occupant protection with increasing vehicle mass. It has been assumed that mass is a proxy for increased vehicle size, although Evans (1992) has recently argued that mass is the dominant causative factor.

However, very little local research has been conducted to show whether this relationship exists among the Australian car fleet. One local report by Cameron, Mach, Neiger et al (1992) noted a similar trend from Victorian and N.S.W. crash involvement data when conducting a retrospective crashworthiness analysis by vehicle make and model for Australian passenger car crashes between 1983 and 1990. They found that the risk of injury was well correlated with vehicle mass when speed zone of the crash was controlled, although the severity of injury seemed to be less affected Moreover, the question of whether it is size or mass that is the dominant causal factor does not seem to have been addressed in Australia.

1.2 PROJECT AND OBJECTIVES

The Federal Office of Road Safety recently commissioned the Monash University Accident Research Centre to conduct a review of the effects of vehicle mass and size on occupant safety. The objectives specified for this review included the need to:

1. examine the relationship between injury and vehicle size or mass for a variety of different crash types from the overseas literature;
2. contrast the findings from local reports and available data to the extent possible to see whether the overseas findings are relevant for Australian vehicles and crashes;
3. consider if possible whether vehicle size or mass is likely to be the dominant causal factor in downsizing safety and whether other factors also need to be considered;
4. reflect on the overall consequences of downsizing assuming the eventual vehicle fleet was made up of a high proportion of smaller vehicles; and
5. examine the likely Design Rule implications for small and large vehicles.

1.3 PROJECT DESIGN

The project called for a review of local and international literature to address these objectives. The main aim of the review was to question the likely effects that changes in passenger car mass and size will have on occupant protection in Australia.

A number of questions of specific interest were raised in the outline for this review. While the review was to attempt to answer as many of these questions as possible, it was recognised that existing knowledge and local data may not be sufficient to provide definitive answers to all these questions.

Hence, the project was to identify local existing data sources that could also be used for a more detailed analysis of the effects of vehicle down-sizing on crashworthiness in this country.

1.3.1 The Literature Review

The literature review included a critical assessment of any local and overseas data which investigated the relationship between vehicle size and mass with occupant protection. There were a number of data sources available for this review. Initially, searches were conducted on a number of local and international road safety information sources. Computer searches included the International Road Research Documentation (IRRD), The Australian LASOR system maintained by the Federal Office of Road Safety and MEDLINE database through Monash University. In addition, periodicals such as Injury, Journal of Trauma, and Accident Analysis and Prevention were accessed.

The INMAGIC occupant protection database at MUARC had over 1000 references specific to vehicle safety entered onto this system comprising papers and reports from key international conferences (ESV, AAAM, IRCOBI, STAPP, etc), publications from key safety organisations (NHTSA, TRL, INRETS, etc), as well as from traditional road safety information sources (Medical and Human Factors literature through on-line searches, AAP and TRB journals, other international journals, personal copies from overseas visits, and ARRB and FORS publications). Preliminary analysis revealed more than 50 publications on the INMAGIC database that address various aspects on the topic of vehicle safety and car mass or size.

Other internal MUARC and special purpose publications, such as crashworthiness reports by Cameron, Mach and Neiger (1992), Folksam car model safety rating system by Gustafsson et al (1989), and transport statistics report on cars by make and model (Department of Transport in UK, 1991). MUARC had copies of all these relevant and important publications for inclusion in the review. The Australian Bureau of Statistics (ABS) vehicle census surveys every three years provided *snapshot* data on the vehicle fleet over the last 10 to 15 years while Paxus Australia published yearly statistics on vehicle sales over the same period.

1.3.2 Structure of the Report

Suitable papers were critically examined during this review to extract meaningful and relevant findings that bear on the project objectives. Overseas findings were interpreted in terms of their likely relevance and usefulness for predicting likely safety consequences of down-sizing the Australian fleet. The review also considered the policy ramifications of aspects of the review where issues have general implications for the community at large. The report is essentially a technical discussion of relevant road safety issues of down-sizing and was not able to make specific recommendations for countermeasure development or action in this area.

The report is intended to help identify gaps in our current state of knowledge in this area and further work required to help clarify the likely consequences of down-sizing in terms of clean, safe and environmentally friendly vehicles for Australia.

2. BACKGROUND TO DOWN-SIZING AND SAFETY

2.1 CRASH COMPATIBILITY

There is a large body of research which suggests that occupant safety is highly related to the change in velocity per unit of time (deceleration) experienced by the vehicle during the collision. Banthia, Miller, Valisetty, and Winter (1993) suggest that, in two car crashes, the change in velocity during impact is determined by three ratios, the vehicles' mass, energy absorbing properties, and crush zone lengths. In the case of a single vehicle accident the mass, energy absorbing properties and crush lengths of the striking vehicle and the struck object must be considered.

It is obvious that, to a large extent, the injury outcome for vehicle occupants is determined by the compatibility between the striking vehicle and the struck object or vehicle. In the US crash performance standard FMVSS 208 (and the recently mandated ADR 69), all passenger cars must meet certain minimum human injury tolerance levels in a impact test against a rigid barrier. While this standard may only represent a subset of real world accidents, it is the most common legislated measure of vehicle safety For this crash configuration, the three crash ratios described by Banthia et al (1993) all approach maximum values because the rigid barrier has a very high mass, zero energy absorbing properties and zero crush zone length.

Given that the barrier is rigid and unyielding, the striking vehicle has to absorb all of the collision energy. The collision energy dissipated in this case is equal to the kinetic energy of the vehicle as it approaches the barrier, and is all transformed into deformation of the vehicle front. To perform adequately on the barrier test the deceleration that the vehicle undergoes and the restraint system must be optimised to ensure the human tolerances specified are not exceeded.

This is achieved by manipulating the stiffness of the front of the vehicle and the design of the restraint system. Vehicle deformation is balanced against the need to maintain the integrity of the passenger cell and achieve the three human performance criteria of head injury, chest deceleration and femur loading.

In vehicle design terms, this means that larger cars are usually softer than smaller cars. Their weight disadvantage resulting in higher kinetic energy on impact can be offset by allowing their larger physical structure to absorb this energy through its larger crush zone. Smaller cars must absorb their impact energy (albeit of less amount than for large cars) over a physically smaller structure which usually leads to stiffer structures and higher impact forces on the occupants of these vehicles. Current rigid barrier crash requirements do not take into account any mass effects.

2.1 REAL-WORLD DISADVANTAGE FOR SMALLER CARS

Apart from differences in design characteristics between small and large cars, there are other ramifications for these vehicles that collide in the real-world. In a fleet of passenger cars of mixed mass and size, the safety outcome always favours larger cars over their smaller counterparts. This is best explained by way of an example.

In a collision, both energy and momentum are subject to the laws of physics which dictate that both are "conserved" (the *Principle of Conservation of Momentum* for instance states that in any system of bodies which act and react on each other, the total momentum remains constant). Figure 2.1 shows an idealised head-on collision between two cars, one smaller (of lower mass) and one larger (of greater mass) The crash is assumed to be inelastic and the vehicles, remaining together after the impact, have a common final speed V.

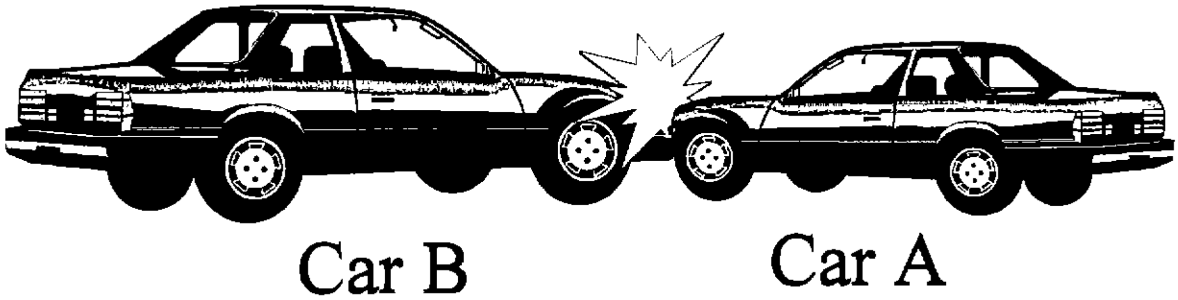

Figure 2.1 Two cars of unequal size colliding head-on
(Car A=500Kg speed=V^A; Car B=1000Kg, speed=V^B)

Equating momentum,

$(m^A v^A - m^B v^B) = (m^A + m^B)V = MV$, where M is the combined car masses

If delta v^A and delta v^B are the changes in velocity of the two cars, it follows then that:

$$\text{delta } v^A/\text{delta } v^B = m^B/m^A.$$

In the example shown in Figure 2.1, therefore,

$$\text{delta } v^A = 1000/500 \text{ delta } v^B\text{, that is, } 2 \times \text{delta } v^B$$

As delta-v is one of the factors which determines the forces the occupant has to withstand in a collision, those in heavier cars will always better off than those of lighter ones (all other factors being equal). If the collision takes place over time delta t, the average acceleration of car^B, a^B = delta v^B /delta t, and for car^A, a^A = delta v^A/delta t.

Then a^A must also be $2 \times a^B$.

Since the forces on the cars are (ideally) balanced, ie; $F^A = F^B$, the total energy dissipated $E = FD^A + FD^B$, where D^A and D^B are the crush distances. Thus, the proportioning of energy depends on the respective crush distances of the two cars. Given the physical differences in size, it is likely, therefore, that a greater proportion of the energy will have to be absorbed by the smaller car but this is not necessarily so (consider the limiting case of a car colliding with a large firmly anchored energy-absorbing barrier in front of a highway obstruction). In attempting to manage this, manufacturers can manipulate the crush profiles of their cars.

Ernst et al (1991) maintained that it is possible to optimise vehicle design for car-to-car collisions by stiffening the structure of smaller vehicles while at the same time ensuring that the stiffness of large vehicles underwent a linear increase in stiffness (starting soft and getting stiffer). This, they argued, would increase collision compatibility. In the event of a collision between two such cars, the softer portion of the larger vehicle will absorb the initial impact energy after which both vehicles deform (and absorb collision energy) equally. There are costs associated with increasing vehicle-vehicle compatibility, namely the rigid barrier (single vehicle) collision performance of both cars is compromised. The stiffer small vehicle will undergo less deformation, resulting in higher decelerations. Concurrently, the larger vehicle with linearly increasing stiffness has surrendered energy absorbing potential through softening the structure. This is offset to some degree by new regulations which set injury limits requiring manufacturers to optimise restraint systems and crash zone performance. While a mass ratio of two might seem extreme, this example demonstrates the compatibility trade-off between occupant protection in vehicle-vehicle collisions and occupant protection in single vehicle collisions.

2.2 THE SIZE AND SAFETY DEBATE

Research has demonstrated that the physical characteristics of passenger vehicles affect the injury outcome for occupants in the event of a collision. Vehicle size, and its association with occupant safety, is one such vehicle characteristic that has received a good deal of research interest. The nature of the relationship between these two vehicle attributes is complex. While the causal relationships are poorly understood, there is general consensus among researchers that vehicle size and occupant safety are positively related. That is, as vehicle size increases, so too, does the safety of its occupants in most collision situations.

It is suggested above that vehicle occupant safety in the event collision is highly related to the change in velocity per unit of time (deceleration) experienced by the vehicle, determined by its mass, crush zone length, and energy absorbing properties. Discussion of energy absorbing characteristics of passenger vehicles is commonly restricted to the safety features of the vehicle interior (eg. seat belts, airbags, energy absorbing steering columns, etc), presumably because the vast majority of the current passenger vehicle fleet are constructed using the same materials and methods of manufacture (steel monocoque). The current debate regarding the association between of the physical characteristics of passenger vehicles and occupant protection therefore focuses largely on the mass and crush zone lengths of the striking vehicle and the object struck.

Efforts to determine the essence of the size-safety relationship have been driven to a large extent by demands for increased fuel economy. Proponents of the need for increased fuel economy argue that increased kilometres per litre of fuel will result in reductions in environmental damage caused by engine emissions, consumption of natural resources, and dependency on foreign oil markets (a dependency demonstrated in the recent war in the Persian Gulf). In response to calls for increased fuel economy, the average vehicle size overseas has supposedly been declining since the seventies. For example, down-sizing in the General Motors (US) car fleet was supposed to have occurred between the mid-seventies to the mid-eighties which is claimed to have resulted in a 27% increase in fatalities attributed to the newer, smaller, lighter models (Consumer Research Magazine, 1991). However, while this was the case in the US during the 1970's and 1980's, it is not clear whether down-sizing is still occurring in that country today.

2.2.1 The Consequences of Reduced Size

The ambiguity of terms like "*down-sizing*" and "*vehicle size*" create difficulties and cause misunderstanding in discussions regarding the association between vehicle size and safety. The term "*vehicle size*" can correctly be used as a description of weight, external dimensions (such as length, width and height), engine capacity, and many other indicators of car size. For the purpose of this discussion the term "*external size*" will be used as a descriptor of a vehicles' external dimensions (typically wheelbase), and mass as a descriptor of vehicle weight. Down-sizing results in shorter, narrower, and often lighter cars. While these vehicle attributes are highly correlated, researchers have attempted to isolate the individual contribution of each to occupant safety. Most prevalent in the literature are estimates of the effects of vehicle mass, and to a lesser extent, external size (wheelbase, total length, track-width), on occupant safety. The influences of vehicle weight and external size on occupant safety, have each been thought of as dominant by different researchers at different times.

These two vehicle characteristics are highly correlated and therefore are equally well encapsulated in the rather nebulous term "*vehicle size*". Because most cars are of similar steel monocoque construction, heavier cars tend to be longer and wider than lighter ones. Kahane (1991) calculated the correlations between these attributes for the 1970-1982 US. car fleet. The correlations between vehicle weight and wheelbase, weight and track width, and wheelbase and track width were 0.93, 0.92, and 0.91 respectively.

More recent analyses conducted by Wood, Mooney, Doody, and Riordain (1993) reported a correlation of 0.86 between vehicle mass and overall length for the 1990 US. car fleet. This apparent decrease in the strength of association between mass and length may simply be attributable to the higher variability of overall lengths than wheelbase lengths. Alternatively, such an observation would be expected as result of diversification of design and manufacturing techniques as the car manufacturers develop new and innovative designs in order to met the many demands of the market (to optimise occupant protection, passenger comfort, fuel economy, aesthetic appeal, affordability, etc.) Nonetheless, it is apparent that the many descriptors of vehicle size are highly related, even for the current vehicle fleet The extent to which the same can be said of the Australian fleet is not known.

Vehicle size and safety are related via several quite conceptually different mechanisms, each of which will be presented more fully in the following discussion. In short, size and safety are related through the associations between size and crashworthiness, size and crash aggressiveness, and size and crashproneness.

The association between vehicle size and occupant protection, or "*crashworthiness*" as it has come to be known, is such that larger cars offer more protection to their occupants in the event of collision. Some debate surrounds the issue of whether the increased protection is afforded by virtue of the larger vehicles' external size, crush space (the amount of material available for absorbing collision forces before the occupant space is intruded), other safety features, or mass which of course is correlated to these other dimensions.

The term "*aggressiveness*" is used to describe the extent to which a vehicle transfers collision energy to the struck object in preference to absorbing it itself (a share of which is apportioned to the occupants). Vehicle aggressiveness is directly related to vehicle mass. For a given velocity, heavier cars transfer more energy than lighter ones to a fixed object. Similarly, in multiple vehicle crashes, heavier cars hit the other vehicle with more force than do lighter cars, for example, a 1200kg car travelling at 60km/h has the same energy at impact as an 800kg car travelling at approximately 73km/h. Put simply, the laws of conservation of momentum dictate that occupants in heavy cars are subject to less severe decelerations than occupants in lighter ones.

Vehicle size is also related to safety through its effects on crashproneness, or propensity to be involved in a collision. Cars that are lighter and smaller tend to have a higher centre of gravity (this is explained in more detail further on) and, therefore, more likely to roll-over than larger, heavier cars. Cars that are more likely to roll-over are more likely to cause occupant injuries.

2.2.2 Mass as a Proxy for Size

Given that the vehicle size and safety debate is usually driven by demands for increased fuel economy, it is not surprising that vehicle mass is the most common proxy for vehicle size encountered in the literature. Of all descriptors of vehicle size, mass is the one most closely related to fuel efficiency (General Accounting Office, 1991). In a review of past research of the association between vehicle size and safety, Evans (1985d) stated that:

In all cases, we characterise car size by the physical variable mass as measured by the curb mass of the car. We then determine relation between probable driver death (or injury) and car mass. Such relations do not imply that car mass, as such, is the causative factor. Clearly, a wide variety of vehicular characteristics are strongly correlated with car mass (eg., wheelbase, track, size in general, hood length, trunk size, engine displacement, etc.). (Evans 1985d, p. 548)

It cannot be denied, though, that in the case of two car crashes, mass figures prominently in the laws and equations used to describe the dynamics of the collision (Evans, 1991).

There are safety trade-offs associated with vehicle weight in that increased weight generally protects the occupants of the heavier vehicle often to the detriment of the other vehicle struck Unlike the trade-offs associated with vehicle weight, increased vehicle size does not increase the risks of other road users. There is some controversy regarding the issue of whether or not increased vehicle size provides increased occupant protection over and above the effects of increased weight and changed structural design. Because the manufacture of nearly all passenger vehicles involve similar materials and methods, reductions in size are necessarily associated with changed design and/or changed weight.

It is known however, that weight has a greater effect on fuel economy than size. Therefore, its conceivable that reductions in weight that are not associated with reductions in size may result in less safety losses and better fuel economy (Consumer Research Magazine, 1991). This is based on the assumption that size has safety enhancing effects apart from those attributable to associated mass effects (this will be discussed further in a later section).

2.2.3 Problems Defining Mass and Size

Various definitions of car weight are used in investigations that relate vehicle size and safety. The "*unladen car weight*" is that specified by the manufacturer (with or without a quantity of fuel), the term "*car weight*" as defined by Aldman, Gustafsson, Nygren, and Tingvall (1984) is the unladen car weight plus 75 kilograms

Joksch and Thoren (1984) distinguished six different car classes using definitions of car size described by Insurance Institute for Highway Safety (IIHS). The six categories described by IIHS are defined in terms of wheelbase, in roughly five inch increments, as small and large subcompacts, small and large compacts, intermediate, and large cars. Of course these categories are relative, and defined by the distribution of wheelbases of the fleet at the time that they are defined. As the car fleet has slowly reduced in size, so to has the size (range of wheelbases) of car that is described in each category. For example, some ten year old cars that were considered intermediate ten years ago, would now fall within the large car category. They noted that the size categories that they employed were not those currently used by the US. automobile industry. The size categories used in preference to those described by the IIHS, are defined by the Environmental Protection Authority (EPA) in terms of interior volume rather than any linear dimension of the car. The two definitions, although making use of many of the same category labels, do not correspond perfectly.

Partyka and Boehly (1989) and Partyka (1990) demonstrated that large differences exist between reported vehicle weights in fatality data (the Fatal Accident Reporting System file maintained by the National Highway Traffic Safety Administration) compared to registration data (R.L. Polk & Co.'s National Vehicle Population Profile files) The observed discrepancy between these two data sources is of particular concern to the many US. researchers that use them. Partyka demonstrated that systematic differences in car weight coding complicate the use of FARS and Polk registration data to calculate fatality rates (number killed per registered vehicle).

Overall the registration data were found to describe any particular make model and model year car as approximately one hundred pounds heavier than described in the fatality data. The effects of this discrepancy is to bias analyses of fatalities per registered vehicle against lighter cars. To demonstrate the effect of the observed discrepancy on fatality rate estimates, Partyka and Bowhly (1989) and Partyka (1990) compared fatality rates calculated using the two different sources of vehicle weight information. Using the uncorrected data, the number of fatalities per registered vehicle was approximately five times greater for the smallest size class (under 1950 pounds) compared to the largest size class (over 3950 pounds), whereas estimates based on the corrected weight data indicated that the fatalities per registered vehicle was only two times greater for the same smallest size class compared to the largest size class, a huge difference.

The relationship between injury levels and car size is also confounded by the fact that larger cars typically carry more occupants than smaller ones. This can also lead to a bias against larger cars because of the greater number of occupants who can be injured. One way of dealing with this bias is by considering only driver injury rates (Evans, 1992). A problem created by this "*occupancy rate bias*" not controlled for in driver only injuries is the differential effects that occupancy rates have on the crash weight of small and large vehicles. All vehicles have a crash weight that exceeds the official weight of the car by the weight of its payload. As we are discussing passenger vehicles, one would assume that the payload consists predominantly of its occupants. As larger vehicles tend to have higher occupancy rates, the discrepancy between the official weight and the crash weight is likely to be largest for large cars. Partyka and Boehly (1989) and Partyka (1990) demonstrated the dramatic effects that a mere 100 pound bias in vehicle weights can have on relative safety assessments. The extent to which this *occupancy rate bias* influences the strength of association between size and safety is hitherto unknown and is worthy of further investigation.

2.2.4 Car Size Versus Mass

Evans and Frick (1992b) set about determining which of a vehicle's attributes, external size (wheelbase) or mass, has the greater influence on occupant safety. Their analyses were conducted on 1975-1989 FARS file data for two car crashes in which the mass and wheelbase of both cars was known. In two similar publications, Evans and Frick (1992a; 1992b) used mass ratios and wheelbase ratios to assess the influence of these variables on fatality rates. When cars of the same wheelbase but different mass collided, the driver of the lighter car was more likely to be killed than the driver of the heavier car. When cars of similar mass but different wheelbase collided, any effect due to differences in wheelbase were too small to be detected by the same method that clearly demonstrated effects dependent on car mass. Based on these findings, they concluded that mass is the dominant causative factor in the large dependence of driver fatality risk on "size" in two-car crashes, with external body size playing at most a secondary role.

They argued that the only crash situations where mass does not play an important role are those involving a crash between two cars of the same mass and those involving fixed object collisions of essentially infinite mass. In these situations, they conceded that mass effects were more likely dependent on some other property of the vehicle that varies with mass, most likely its external size.

Further, evidence that car characteristics other than mass mediate the crash outcome in terms of occupant injury is found in the changing association between mass and injury risk for different vehicle ages.

In contrast to effects of mass observed for crash configurations in which mass is not expected to play a role in the crash outcome, large effects of mass that are observed when cars of dissimilar mass collide appear to be largely, if not intrinsically related to mass and its crucial role in the laws of conservation of momentum

Banthia, Miller, Valisetty, and Winter (1993) present an alternative viewpoint to the one held by Evans. These researchers (who incidentally work for Alcoa) claimed that the widely held view that lightweighting cars is detrimental to safety stems from the fact that efforts to reduce weight have usually meant down-sizing structure. Banthia and his colleagues claimed that findings such as those reported by Evans and Frick (1992a) who compared the safety of cars with similar wheelbase but different mass, promote the notion that lightweighting and crashworthiness represent competing and contradictory demands on design.

This assertion is based on comparisons between cars that employ similar materials and methods of construction, and rightly so, as these represent the current state of play in passenger vehicle manufacture. Nonetheless, these findings should not be extrapolated to assert that lightweight aluminium cars would be less safe than steel cars (Banthia et al, 1993). Such extrapolation would be based on two fundamentally invalid assumptions, (1), that the energy absorption properties of steel and aluminium are equivalent, and (2), that design would not be adapted to take advantage of aluminium's characteristics

Banthia et al (1993) discuss the safety advantages of lightweighting cars, particularly in regard to two-car crashes. By virtue of their momentum advantage, they argued, heavier vehicles pose a greater risk to the occupants of lighter vehicles. This inherent "*aggressiveness*" of the heavier vehicle can, and should, be reduced by reducing the weight, and hence momentum advantage, of heavy vehicles (Bauman, Goesch, Holtze & Schwede, cited in Banthia et al., 1993). While increased mass may be aggressive to other road users, this is not the case for size which is always (potentially) protective. They claimed that design standards should specify ranges of aggressiveness that ensure reasonable and acceptable levels of risk for the more vulnerable occupants of small cars (Banthia et al 1993).

Banthia cited two pieces of research that concluded vehicle size (wheelbase) was more influential than mass in the relationship between size and safety.

> "*...Graham (1992) attributed reduced occupant injury in heavier cars to the larger size. O'Neil et al. (1974) considered both car size and car mass separately in an analytical regression of a traffic set and found that, of the two effects on occupant injury, car size is more pronounced than inter-vehicular weight difference*" (Banthia et al 1993, p2).

Banthia and his colleagues concluded that front end structures with longer crush zones that crush progressively result in lower decelerations, which in turn result in lower loads on the occupants and hence, lower injury severity Their contention was that large lightweight cars can provide this protection, while at the same time pose less threat to other road users. In support of this assertion, Banthia et al reported the weight saving achieved by various vehicle manufacturers through research and development programs that employed aluminium in the primary body structure Weight savings in the order of 30% percent, on the body structure and some panels, were achieved with relative ease. These weight savings can be compounded by reductions in the weights of other systems, for example, the demands placed on both the engine and the brakes would be reduced in the lighter car allowing these systems to be reduced in size and weight.

O'Neil, Joksch and Haddon (cited in McLean, 1980) examined the role of vehicle size as opposed to vehicle weight using police reported accident data from North Carolina. They reported that, in the event of a two-car crash, vehicle size has a greater influence on the likelihood of occupants sustaining injuries, where larger vehicles were associated with lower rate of injury.

It is conceded that many facts regarding the association between vehicle size and risk of occupant injury continue to elude clear definition. For example, in 1992 Leonard Evans, the singly most prolific author of research in this area, stated:

> *''We do not know with much precision the relative contributions of weight and [external] size to effects found for different types. More precise quantification is desirable for all relationships''.*

However, it is Evans' (1992) contention that our knowledge about the relationship between reduced vehicle size and increased fatalities is as well known (and with the same degree of confidence) as that of the relationship between increased speed limits and increased fatalities or increased safety belt wearing rates and decreased fatalities.

2.3 CRASHWORTHINESS AND CRASHPRONENESS

Vehicle safety performance can be measured in many ways. From the safety viewpoint, we are generally interested in the ability of the vehicle to assist in breaking the road trauma chain, shown in Figures 2.2 and 2.3 from Cameron, Mach, Neiger, et al (1992). The vehicle's safety performance can reflect the various risks shown in these figures and we are interested in knowing the vehicle characteristics for which these risks are relatively high or low, either in terms of its crashworthiness or crashproneness.

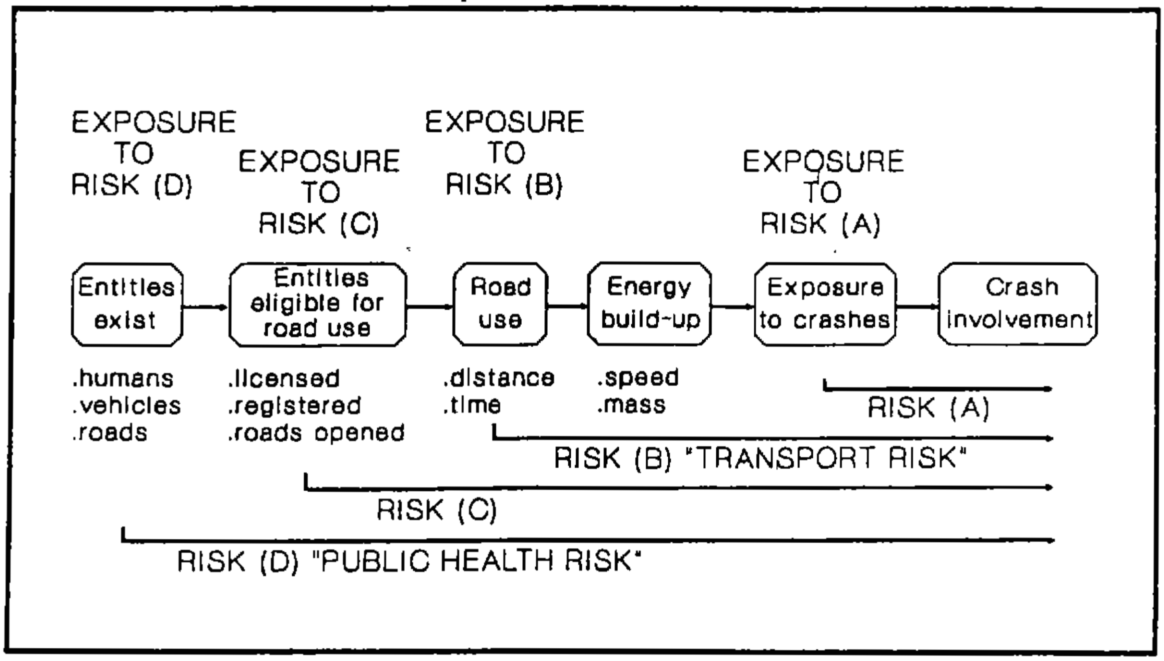

Figure 2.2 The pre-crash road trauma chain *(from Cameron et al 1992).*

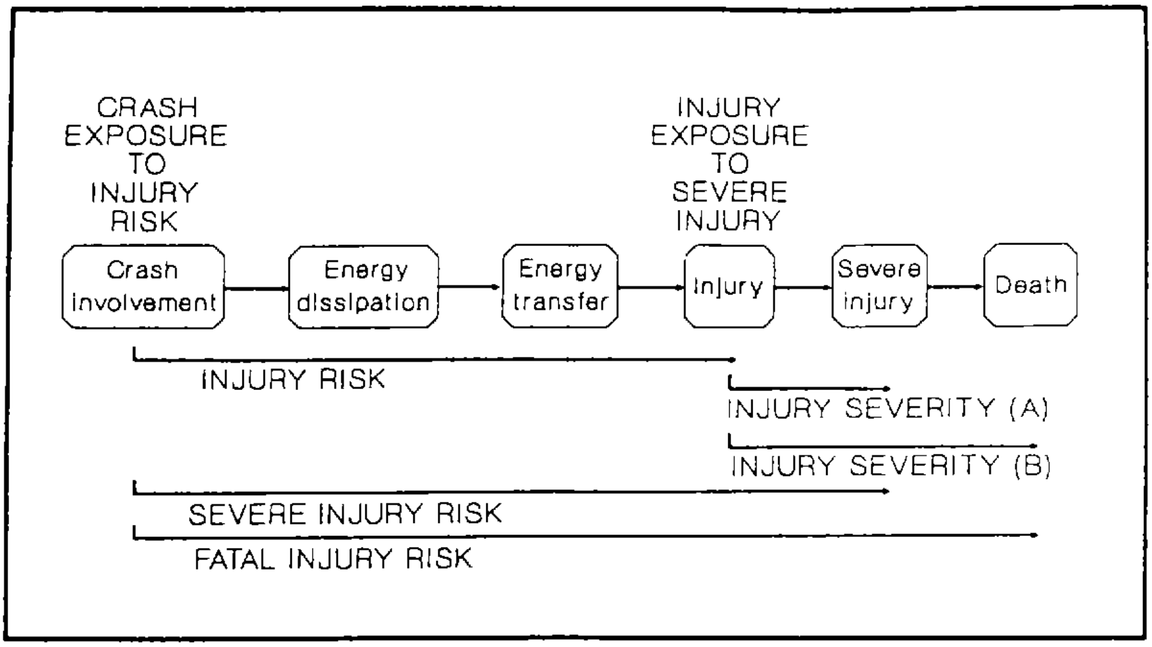

Figure 2.3 The crash and post-crash road trauma chain
(from Cameron et al 1992).

The concepts of "*crashworthiness*" and "*crashproneness*" are fundamentally different and need to be clarified in this context. "*Crashworthiness*" is taken to mean a vehicle's secondary safety performance in a collision (McLean, 1982). Implicit in its use is an understanding of human tolerance to impacts. It involves two structural properties or requirements in crash protection. First, a crashworthy vehicle is one which minimises intrusion of its own structure into the passenger compartment. Severe intrusions can often results in injury to the vehicle's occupants from direct contact with the intruding structure (Fildes et al 1991). Second, a crashworthy vehicle is one which aims to absorb much of the energy of the crash in its own structure, thereby reducing the level of impact forces on the occupants.

"*Crashproneness*", on the other hand, is taken to mean the susceptibility of vehicle to crashing, which is more akin to the primary safety concept of crash involvement and avoidance. It involves a vehicle's ability to avoid collisions by features, such as its stability, resistance to failure, and braking capacities. Not surprisingly, driver's abilities (or more correctly inabilities) are often intimately associated with crashproneness. That is, a vehicle which is over-involved in terms of collisions rates may be prone because of some vehicle defect or simply because it is attractive to drivers known to be over-involved in collisions. This raises the possibility that vehicles that attract those over-involved in collisions (say young drivers) may require superior handling and braking characteristics

2.3.1 Vehicle Safety Ratings

Organisations in Scandinavia, UK and USA regularly publish performance figures on vehicle crashworthiness and crashproneness by make and model to guide consumers when purchasing new cars. More recently, Australia, too, has published similar figures. The overwhelming effect of the vehicle's mass or size on these figures has been noted by several of the publications (c f., Gustafsson et al 1989; Cameron et al 1992).

Crashproneness ratings measure one of the pre-crash risks shown in Figure 2.2. Which of these risks is measured depends on the type of exposure used as the denominator of the involvement rate. For mass accident data comparisons of makes/models, it is most common to use numbers of vehicles registered as the denominator and to measure risk (C) by the involvement rate. It would be preferable to measure risk (B), but road use data by make/model is not always available to calculate the appropriate rate. Risk (A) may be even more preferable as it would measure the ability of the vehicle to assist the driver to recover from some critical pre-crash situations (eg. skidding out of control).

Crashworthiness ratings measure the risks shown in Figure 2.3. The starting event is the crash involvement and there are various risks of injury depending on the severity level specified. Injury risk is measured by the injury rate, which is the number of persons killed or injured divided by the number involved in crashes. Since many of our data sources have some minimum level of injury as the entry criterion, it is useful to define injury severity as the risk of severe injury (given that the vehicle occupant is injured). Injury severity can also relate to the risk of death, for occupants who are injured. The number of crash involvements forms the exposure to injury risk and is known as "*crash exposure*". In injury data collections, the event of being injured (to a level providing entry to the data system) represents the "*injury exposure*" to the risk of severe injury.

Vehicle ratings for different makes/models have been developed to measure each of the risks defined above. Whether the observed differences measure differences in vehicle safety characteristics can depend on how the ratings are calculated. Differences in the driver and passenger characteristics, in the crash speed, in environmental factors, and in the crash type, could potentially hide any vehicle design differences. If the aim of vehicle ratings is to measure true differences in vehicle safety, then the analysis needs to take into account these other differences. This can be done by normalisation, ie. making the exposure distribution the same for all makes/models, or by estimating the expected rating of a specific make/model (taking exposure into account) for use as a reference figure against which the actual rating should be compared.

2.3.2 Relative Role of Worthiness and Proneness

Johnston (1984) noted that vehicle factors have been estimated in several studies to be the cause of about 10% of crash involvements (road user factors cause about 90% and environmental factors cause about 30%; multiple causes are common). At least some of these vehicle-related causal factors are due to vehicle condition rather than to vehicle design. Thus there is much less potential for finding make/model differences in vehicle design related to crash involvement.

Cameron et al (1992) argued that the development of crashworthiness ratings should be given priority in vehicle safety ratings because of their greater potential to find significant differences in vehicle design between makes and models of cars. Crash involvement ratings are constrained by the relatively small role that vehicle design plays in causing crashes (assuming that its effects can be separated for the factors affecting the risk of crashes).

2.3.3 Estimating "Rates" and the Problem of Exposure

A challenge that must be met by all investigations that employ real world accident data to estimate either involvement rates or risk of injury, is that of exposure or opportunity to be involved in an accident. A measure of exposure is mandatory if the aim of analysis is to understand the influence of a particular variable on observed behaviour. For example, no amount of data on the number of accidents involving male and female drivers will allow insight into the question of which sex is at greater risk of being involved in an accident. Such insight will only be afforded by a measure of exposure, enabling a comparison of accidents per unit of exposure. Various units of exposure are commonly used in the literature (eg , per driver, per registered vehicle, per unit of distance of travel), however most are open to the criticism that they do not take account of all of the influential variables.

Evans (1985e) describes exposure as "*all the factors that might affect the accident rate, with the exception of the particular factor whose effect is being investigated*", such that in an investigation of the effects of vehicle mass, vehicle age would be a component of exposure and vice-versa, in an investigation of the effects of vehicle age, vehicle mass would be a component of exposure.

2.3.4 Vehicle Age

The effects of vehicle age on the association between vehicle size and safety is complex. First, vehicle size has been decreasing since the 1970's therefore many older are relatively large. However, these older and heavier cars have higher fatality rates than their newer, lighter counterparts (the later being more likely to employ designed characteristics that have been demonstrated to offer more advantageous collision energy dissipation).

Evans and Frick (1993) used ratios of vehicle mass and relative driver fatality risk in two vehicle crashes to analyse 1975 to 1989 FARS file data. They conducted analyses in which the model year of crash involved cars was unrestricted, restricted to pre-1980, and restricted to 1980 and later. Post-1980 model year cars demonstrated a smaller mass effect than pre-1980 model year cars. The relationship between car mass and driver fatality risk was stronger for pre-1980 year model cars than it was for all year models. Conversely the relationship between car mass and driver fatality risk was not as strong for 1980 and later year model cars as it was for all year models. Evans and Frick suggested that the critical differences between newer and older cars were most likely to be broad differences in vehicle design that are correlated with vehicle age.

Similarly, analyses conducted by Evans and Frick (1992a) investigated the nature of the effect that vehicle age has on the association between vehicle mass and driver fatality risk. Using 15 years (1975-1989) of FARS file data, they revealed that the relationship between vehicle mass and driver fatality risk decreased monotonically from 1975 to 1984 This decline was followed by an increase to 1989. Evans and Frick argued that these data contained every indication of a mass effect on relative driver fatality risk for future year models returning to levels similar to that seen in the 1970's. They speculated that the decline of the mass effect was most likely attributable to differences in design between large and small cars, whereby small cars were subject to structural redesign to better manage the dissipation of collision energy before larger cars. Later, when large cars too were subject to redesign, mass effects returned to levels seen previously.

Ernst et al (1991) acknowledged the contribution of vehicle age in determining the outcome of the collision for the occupants and accounted for such effects through case selection criteria. Vehicle age was restricted to a maximum of ten years, on the basis that older cars were more likely to be heavier and stiffer, creating compatibility problems for newer lighter cars Also, older cars were considered likely to be more severely corroded, possibly affecting collision consequences.

2.3.5 Driver Age and Sex

A vast body of road safety research has demonstrated the extent of the "*young driver problem*", whereby younger inexperienced drivers are considerably over-represented in the accident statistics (Drummond 1989). Evans (1985b) reported that the over-involvement of young drivers in accidents to the order of 400 percent means that any vehicle or class of vehicles that preferentially attracts or repels young drivers will have an anomalous involvement rate in accidents. Obviously, the age of the driver has a more marked influence on a particular vehicle's crashproneness than its crashworthiness. The sex of the driver, too, has been shown to influence this relationship (Evans 1991) However, as ageing leads to frailty, then cars that are attractive to the older population may also have higher injury risk and severity of injury rates which also need to be controlled for.

Joksch and Thoren (1984) examined the effects of driver sex and age, on driver fatality rates per vehicle mile of travel. The effects of these variables were described by these workers as interacting on three levels: the risk of accident involvement, the severity of the accident, and the risk of an injury being fatal. The risk of accident involvement and the severity of the accident are both higher for younger drivers, while the risk of fatality given a collision increases with increasing age. Joksch and Thoren reported that young male drivers had more than twice the involvement rate for single-vehicle accidents than their female counterparts, however the difference decreased with increasing age to the extent that the pattern was reversed for those aged 70 years and over The oldest drivers demonstrated higher involvement rates than the middle aged drivers, but still lower than the young drivers. They acknowledged that the observed effects of sex and age were not only due to differences in driver behaviour, but also to differences in exposure between drivers of different sex and age.

Evans (1985b) stressed the importance of removing driver age, and subsequently developed a method of adjusting exposure data to allow for any age effects. He fitted a linear relation between driver age and mass of car driven using seven pre-existing data sets to develop an average relationship that can be used to supplement exposure data with the ability to disaggregate by driver age. One problem with Evans' analytic relation is that it is really only useful for adjusting data from the US. fleet at the time that it was calculated.

The confounding effects of driver variables, age and sex, in the association between vehicle size and fatality risk were confirmed by Evans and Frick (1993). Analyses based on only those crashes in which drivers were the same sex and within five years of the same age revealed stronger effects of mass than analyses using all crashes. Indeed, female drivers were found to be 1.16 times as likely to be killed as their male counterparts, in any given collision. Older drivers (40+ years) were 3.1 times more likely to be killed than younger drivers (under 25 years), in any given collision.

Others, too, have demonstrated the effects of driver age on the association between vehicle size and fatality risk. For example Aldman, Gustafsson, Nygren, and Tingvall (1984) reported that young drivers showed the highest frequency of injury in each car weight group. Ernst et al (1991) controlled for the effects occupant age in their analysis as the seriousness of injuries sustained in a given accident are greater for elderly drivers. On the other hand, collisions involving younger drivers are more likely associated with excessive speeding.

Smith and O'Day (1982) reported an incidence of the phenomenon referred to as "*Simpson's Paradox*", whereby aggregate data mask, or misrepresent a real effect. These researchers conducted an analysis of two consecutive years (1975-1976) of Texas, police reported, single vehicle, fatal, passenger car accidents to compare fatality rates for these crashes as a function of both car weight and driver age. Analyses conducted on aggregate data suggested that car size has little or no effect on fatality risk in single vehicle crashes. However, when the data were disaggregated with respect to driver age, the association between fatality rates and car weight for each of the two subsets of drivers (young, less than 35 years, and old, 35 years plus) was stronger than that exhibited in the aggregate data. The analysis of the disaggregated data revealed that older drivers show a decrease in fatality risk with increasing car size, such that if these drivers all changed to the smallest weight class, a 40% increase in fatalities would be expected This was true also, but to a lesser extent, for younger drivers, whereby if these drivers all changed to the smallest weight class, a 17% increase in fatalities would be expected.

Fontaine (1992) conducted an analysis of French road accident data and reported that driver age potentially influenced the association between vehicle factors and safety on two levels. Young drivers, particularly those in high power-to-weight ratio vehicles, tended to be over-involved in loss of control accidents, and indeed all accidents. Also, given an accident involvement, younger drivers were more resilient. She stressed the need to employ accurate and reliable exposure data in such studies.

Having conceded that driver age can have an enormous effect on the likelihood of a vehicle being involved in an accident and the outcome of the accident, care must be taken in choosing a method to account for such effects. For example in an effort to account for driver age effects Evans (1982) assumed that drivers and owners were the same people, as owner age data rather than driver age data was available. There are two problems associated with this assumption. The first was demonstrated by Gustafsson, Nygren, and Tingvall (1984), compared these two ages for an accident data set and reported that the age of the driver and the age of the owner were the same 72% of the time, in a further 16% of cases the age of the driver and the age of the owner were within 5 years. The second, is that the inaccuracy in this data could reasonably be expected to show a unidirectional bias whereby average owner age would exceed average driver age. With regard to young drivers this would be expected on the grounds that children driving their parents' cars would be more likely than the reverse.

2.4 SOLUTIONS TO THE EXPOSURE PROBLEM

It is stated above that a measure of exposure is critical if the aim of analysis is to understand the influence of a particular variable on observed behaviour, such that a comparison of accidents per unit of exposure can be made. Various units of exposure are commonly used in the literature (eg., per driver, per registered vehicle, per unit of distance of travel) Invariably these methods of estimating exposure involve the melding of several different sources of data which is at best a difficult process.

Evans (1982), for example, used data from three different sources to enable estimates of fatality risk broken down by vehicle mass. Fatality data from the FARS file, registration data from registration files, and owner age data from a random sample of driver in one US. State were merged together to arrive at a breakdown of fatality risk per registered vehicle by driver age and vehicle mass. The practice of blending two different sources has been shown to be fraught with danger (Joksch & Thoren, 1984), particularly the FARS file and registration data (Partyka, 1990). Moreover, such methods of estimating exposure are all, to some extent, open to the criticism that they do not take account of the numerous other factors that may be influencing the accident rate. Alternatives to these techniques have been developed to allow comparisons of, for example, injury risk in a way that either accounts for, or is independent of, driver exposure.

2.4.1 The Pedestrian Exposure Approach

Evans (1984) developed an innovative new pedestrian exposure approach to allow analysis of fatality data, in this case, the FARS file. A problem intrinsic to fatality data is that no conventional measure of exposure is contained within the data as only fatal accidents are coded. Evans' new approach was developed in an effort to better account for the multitude of factors that have an unknown influence on the association between vehicle size and safety, using only data internal to the file. The vast majority of passenger car collisions are not coded in fatality statistics because the majority do not result in a fatality. On the other hand, crashes that involve pedestrians and motor cyclists are coded when this pedestrian is killed.

Generally speaking, the method hinges on the assumption that pedestrian fatalities are proportional to pedestrian crashes, and that cars strike pedestrians with the same frequency as they strike all other objects. Then the number of pedestrian fatalities that a particular class or group of cars is involved in, can be taken as a measure of that group or class of vehicle crashes in general. Central to this estimate of exposure is the assumption that in crashes in which either a pedestrian or motorcyclist is killed, the fatality is not related to car mass, and that the ratio of the number of people killed in mass dependent crashes to the number killed in mass independent crashes gives an estimate of how car mass affects the likelihood of driver fatality. Because driver behaviour effects are presumed to be included in both pedestrian and occupant fatality rates, this estimate of the "*mass effect*" is asserted by Evans to be a pure measure of how the likelihood of driver fatality depends on the factor under investigation, all other factors being equal.

A critical assumption of exposure approach is that when a car and non-occupant (pedestrian or motorcyclist) collide, the probability that the non-occupant is killed does not depend on the vehicle attribute (in this case, mass). It is assumed that the likelihood of a pedestrian or motorcyclist fatality is not dependant on driver age, and that exposure of cars of different mass to both type of fatality and crash location is homogeneous (ie., it denies any effects from the time of day, speed of impact, urban or rural location, etc.).

2.4.2 Mass and Driver Fatality Risk

An alternative method used extensively by Evans and Frick (1992a; 1992b; 1993) to investigate fatality data for the effects of mass on fatality risk involves the use of ratios of vehicle mass and relative driver fatality risk in two vehicle crashes. In this method, a study is made of the association between the fatality ratio (the ratio of driver fatalities in the heavier car to driver fatalities in the lighter car) and the mass ratio (the ratio of the mass of the heavier car to the mass of the lighter car, always greater than one), and further, the influence of various other vehicle, driver and crash configuration factors can be evaluated. The advantage of such an approach is that no measure of exposure is required as all factors other than the one under investigation is included in both the denominator and numerator of both ratios.

2.4.3 Double-Pair Comparison Method

Yet another method developed by Evans and Frick (1986) is termed the double pair comparison method. Evans first conceived of the double pair comparison method as a method of examining the contribution of driver factors, such as age, sex or safety belt use, to the association between vehicle size and safety. This was achieved by comparing the injuries sustained by a "*target*" occupant to those sustained by an "*other*" occupant of the same vehicle involved in a collision, where the only difference between these two occupants is the particular characteristic under investigation. The double pair comparison methods is based on the assumption that when two occupants of a crashed car are compared, equivalent in all respect except one, the contribution of that difference to occupant safety can be assessed.

Swedish researchers at Folksam (Gustafsson, et al, 1989; Krafft, Kullgren, Lie, Nygren, and Tingvall, 1991; Koch, Kullgren, Lie and Tingvall, 1991) extended the double pair comparison method from one that gives insight into the effects of driver factors to one that allows comparison of different car models. The Folksam researchers started with the proposition that for each car model the probability of injury varies as a function of accident severity, and that each car model has an unknown accident severity distribution. However when two different car models collide the severity for each is equal, assuming a mass ratio of one (approximated by weight classes). Under these circumstances the relative injury risk associated with each of the models was compared. It is conceivable that this same extended double pair comparison method could be used to assess the influence of specific vehicle characteristics such as external size or mass.

3. REVIEW OF AUSTRALIAN LITERATURE

Very little research into the effects of down-sizing on occupant protection has been conducted in Australia. One of the few pieces of early research was conducted at the Road Accident Research Unit at the University of Adelaide by Dr. Jack McLean and his colleagues.

3.1 ADELAIDE IN-DEPTH STUDY

McLean (1982) undertook a study into the relationship between energy conservation and road safety in Australia using data he collected as part of the Adelaide "*In-Depth*" study by McLean and Robinson (1979). As part of this review, he reported on the effect of car size by distribution of driver's injury severity, measured by Abbreviated Injury Severity (AIS) score compiled into total Injury Severity Score (ISS) An analysis of these data revealed that occupants of larger cars were generally less likely to be injured or less likely to sustain severe injuries than those in smaller cars in either single-vehicle or car/heavy vehicle collisions. A summary of these results in shown in Figure 3.1 below.

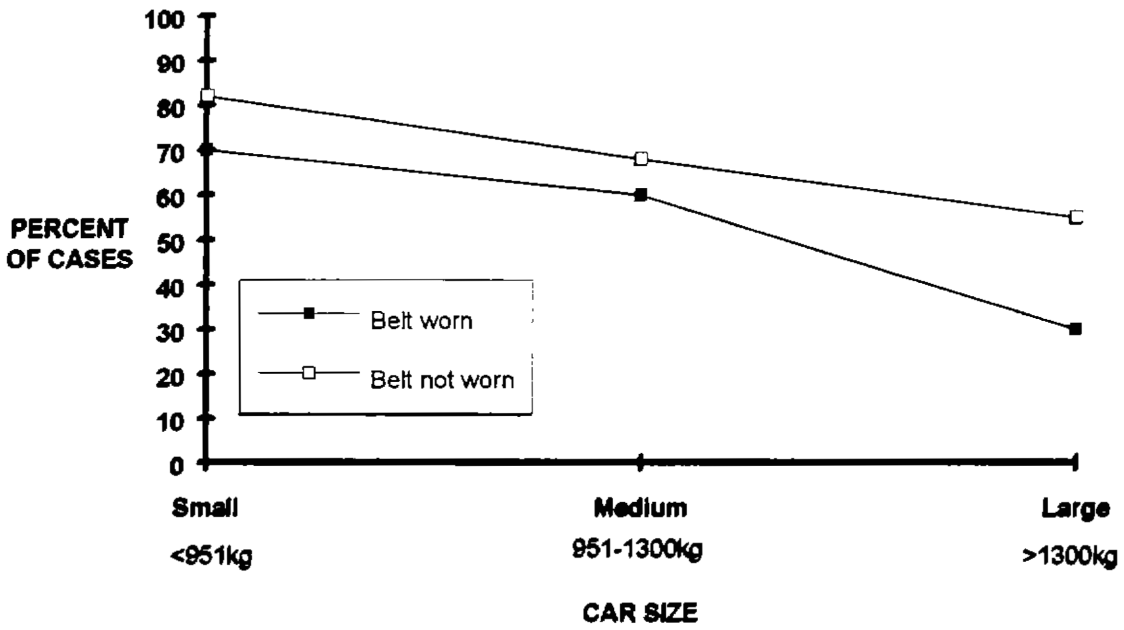

Figure 3.1 Car size by likelihood of an injury in a severe crash
(replotted from data presented by McLean 1982).

These findings were somewhat remarkable as McLean's data only included casualty crashes (that is, urban collisions in which an ambulance was called to the scene). Even so, there was still an apparent relationship between size and safety in these data. Furthermore, this relationship was shown to apply to both belted and unbelted drivers in this early study.

3.2 THE MUARC CRASHWORTHINESS STUDIES

More recently, the relationship between vehicle mass (size) and safety in Australia for cars manufactured during the 1980's was reported by Cameron, Mach, Neiger, et al (1992) in their study of the relative safety of cars offered for sale as a way of encouraging manufacturers to improve the crash performance of their products. While the main thrust of this report was on providing consumer advice on relative safety, they nevertheless provided a detailed account of the effects of vehicle size on safety in Australia.

3.2.1 Australian Database and Analysis

The database used in Cameron et al's study was derived from Victorian and New South Wales police crash reports and insurance injury records. In Victoria, detailed injury data have been collected by the Transport Accident Commission (TAC) and its predecessor, the Motor Accidents Board, as part of their responsibilities to provide road transport injury compensation in Victoria. Details of the vehicle occupied were added from the VIC ROADS vehicle registration system and this information was in turn decoded to determine vehicle makes and models.

In NSW, the Roads and Traffic Authority (RTA) collect similar data comprising Police reported crashes resulting in death or injury or a vehicle being towed away. As these data do not contain details on vehicle make and model normally, the National Roads and Motorists' Association (NRMA) derived this information from matching the NSW vehicle register with the vehicle's registration number and then the vehicle identification number. In total, the file covered vehicles manufactured during the period 1982-90 involving 74,000 injured drivers.

Crashworthiness ratings measure the risk of serious injury to the drivers of each specific model car when it is involved in a crash. This comprised injury risk (the risk of injury for drivers involved in crashes) and injury severity (the risk of serious injury for drivers who are injured). Following the method used by Folksam Insurance (Gustafsson et al 1989), an overall combined crashworthiness rating was also produced.

3.2.2 Relationship with Car Mass

Cameron et al reported that Krafft et al (1991) had found a statistically significant inverse relationship between the Folksam combined rate and the weight of 47 car models ($R = -0.50$) However this relationship was not homogeneous. A number of small car models had very low combined rates and that some large car model rates were similar to those of smaller cars. Cameron et al pointed out that this suggested that while car weight was an important factor in determining crashworthiness, there was also a residual component which may be explainable by other factors such as vehicle design.

From their own results, Cameron, Mach, Neiger, et al (1992) reported that, ignoring car makes that could not be disaggregated into specific models, their was a highly significant correlation between vehicle mass and combined injury score in their data such that the rating score falls by 6.0% per 100kg increase in the mass of the car. This is shown in Figure 3.2 above. On closer inspection, they argued that this relationship was much stronger for injury risk (see Figure 3.3) than it was for injury severity (see Figure 3.4). For injury risk, the relationship between these two variables appeared almost linear and risk fell by 4.7% per 100kg increase in car mass. This apparent effect of car mass in crashes in general should be compared with that observed in multi-vehicle crashes. When analysing Victorian crashes alone using Folksam's method to estimate the driver relative risk of injury in two-car crashes (following Gustafsson et al 1989), there was a 9.1% decrease in injury risk per 100kg increase in mass. An effect of this magnitude is confirmed from results given by Gustafsson et al (1989) (a 10.2% decrease per 100kg increase).

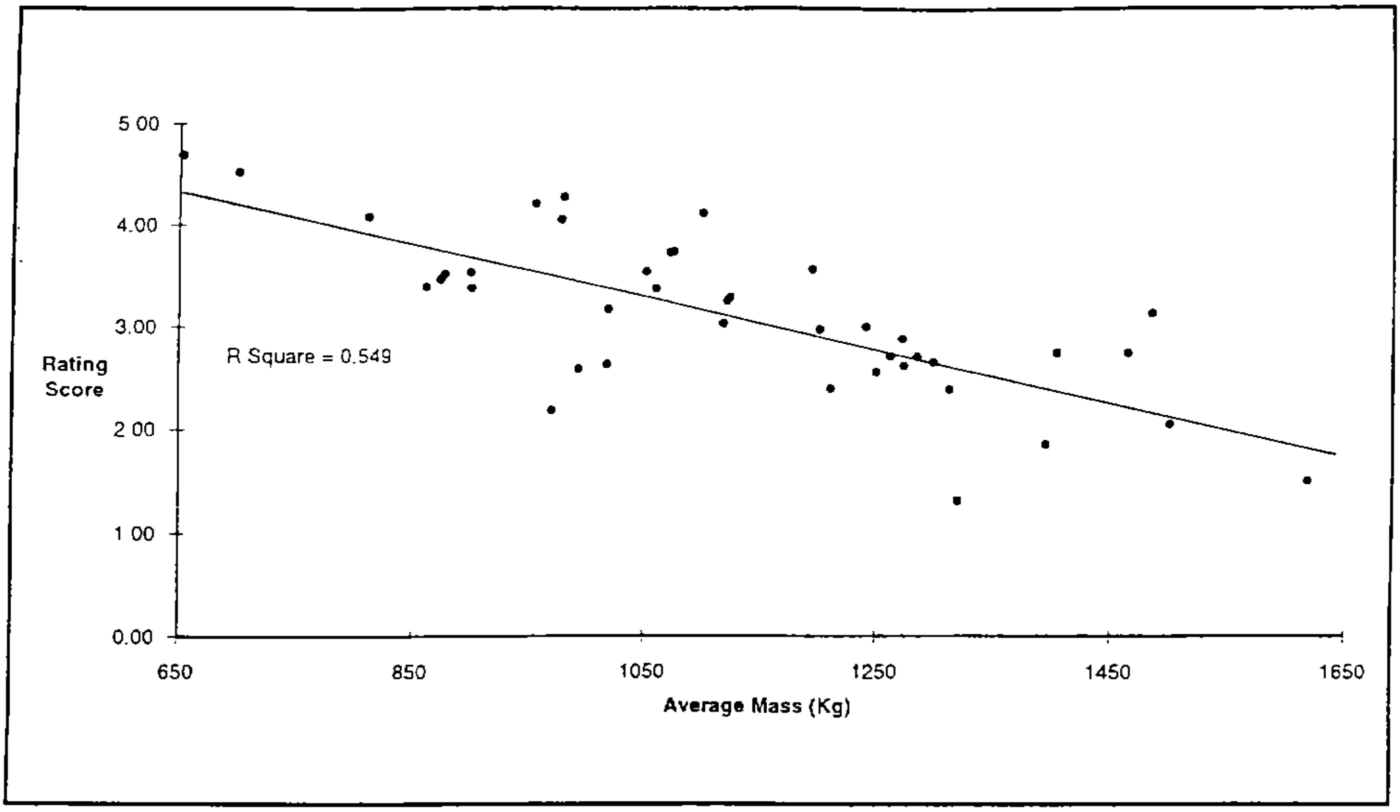

Figure 3.2 Crashworthiness combined rating score by average mass of vehicle model
(from Cameron, Mach, Neiger, et al 1992)

They concluded that there was a strong relationship between the rating scores and the mass of the passenger car models, where the lowest risks of driver death or hospital admission occurred in cars of greatest mass. This apparent effect of car mass was strongest in its effect on the risk of driver injury (particularly in multi-vehicle crashes) compared with the effect on the injury severity of injured drivers. They maintained, however, that at least among the car models which they analysed in Australia, that greater mass may be correlated with superior designs which still further reduce the risk of driver injury.

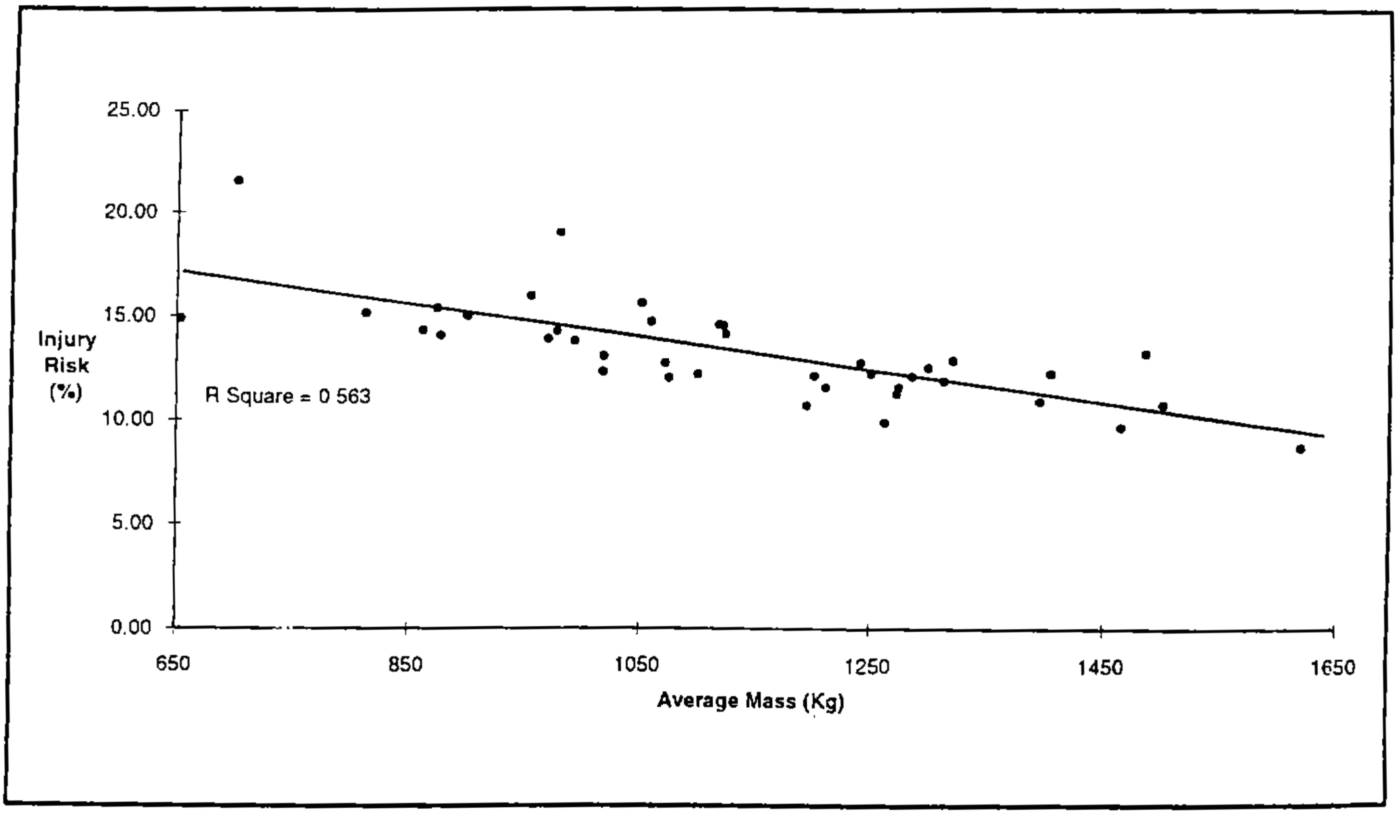

Figure 3.3 Injury risk score by average mass of vehicle model
(from Cameron, Mach, Neiger, et al 1992)

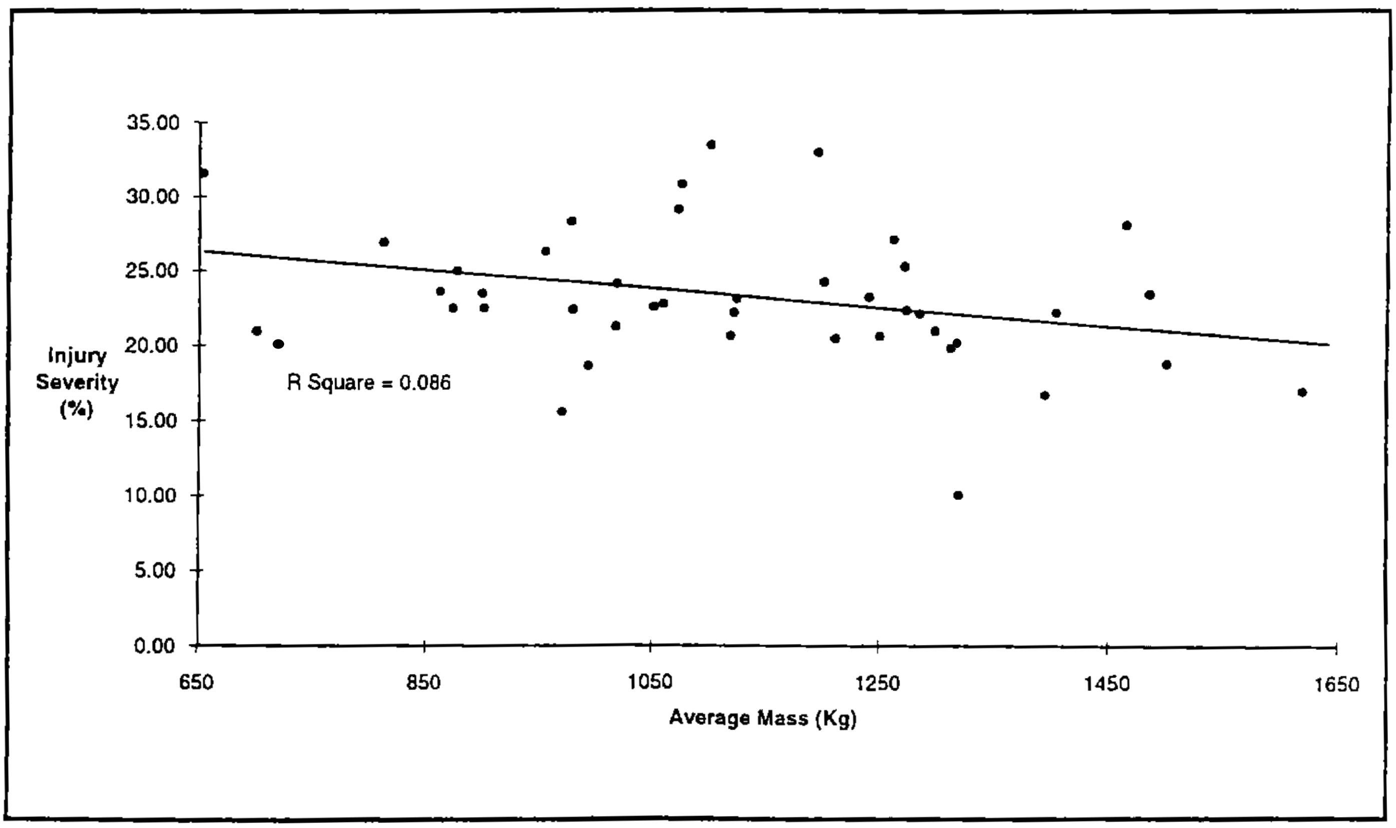

Figure 3.4 Injury severity score by average mass of vehicle model
(from Cameron, Mach, Neiger, et al 1992)

4. OVERSEAS LITERATURE ON DOWN-SIZING

Most of the literature on the association between vehicle size and safety has emanated from overseas, predominantly the United States of America However, other countries including Canada, the United Kingdom, Germany, France and Sweden have also undertaken some work in this area. These studies have been reviewed in terms of their findings summarised by type of crash, impact direction and vehicle characteristics.

4.1 SINGLE-VEHICLE CRASHES

Campbell and Reinfurt (1973) were among the first to undertake the task of trying to identify the safety consequences by vehicle make, model and weight from police reported crashes in North Carolina in the late 1960's and early 1970's No association was subsequently observed between vehicle weight and relative injury frequency for single vehicle, run off the road crashes in this study. However, Stewart and Stutts (1978) subsequently analysed data from three years of police reported accidents from 1973 to 1975 in the state of North Carolina using linear categorical modelling They found that in single vehicle crashes, unrestrained drivers in small cars (under 1300kg) were 14% more likely to sustain serious or fatal injuries than those in cars of more than 1750kg For belted drivers, the observed difference was 67 percent.

As noted in the previous chapter, research conducted at the Road Accident Research Unit at the University of Adelaide by McLean (1982) was the first to reveal an inverse relationship between vehicle weight and injury severity for single car crashes in Australia. While this analysis involved casualty crashes only, nevertheless it was able to demonstrate reductions in injury severity and increases in a non-injury outcome for occupants of large cars over those of smaller ones.

In 1984, Joksch and Thoren conducted analyses on two years (1981-1982) of Fatal Accident Reporting System (FARS) file data. They suggested that single vehicle crashes give the best indication of how well a vehicle protects its occupants because no other vehicle has an effect in these crashes. After adjustment of the data, only the smallest cars (small and large sub-compacts) differed significantly from any other size class. The fatality rate associated with the smallest size class was 75 percent higher than those of the largest class. No differences in fatality rates were observed between any of the other size classes (small and large compacts, intermediate, and large cars).

Most significantly, in single vehicle accidents, large cars (wheelbase greater than 120 inches) were not found to offer any more occupant protection than small compacts (wheelbase between 101 and 106 inches). They noted that plotting death rate as a function of wheel base displayed a much smoother relationship than did plotting death rate as a function of mass (average mass within each of the size classes). This observation led Joksch and Thoren to concluded that weight *per se* does not provide occupant protection in single vehicle crashes, but rather that wheelbase, and the crush space it provides, is needed for protection. However increasing the wheelbase beyond that of the small compact did not appear to provide increased protection (Joksch and Thoren, 1984).

Jones and Whitfield (1984) analysed four years (1979-1982) of accident data from police reported one and two car crashes from Washington State to examine the association between occupant injuries, vehicle mass and restraint use After controlling for the confounding effects of driver age and sex, and to a lesser extent crash severity, it was reported that injury risk was dependant on both vehicle mass and restraint use. An increase in vehicle weight of 1000 pounds was associated with a 25 percent decrease in injury risk for restrained drivers, and a 34 percent decrease in injury risk for unrestrained drivers.

Evans (1982) investigated the association between vehicle mass and the likelihood of fatality using the US Fatal Accident Reporting System (FARS). The effects of mass were most evident; in single-car crashes, they found a rather high 1.7 fatality ratio with a increase at a rate of 0.04% per kg reduction in vehicle mass. Other analyses of the FARS file have also been conducted by researchers at the National Highway Traffic Safety Administration in Washington (c.f. Partyka, 1988; Partyka, 1989; Partyka & Boehly, 1989; Partyka, 1990). In an examination of the 1986-1987 FARS file data describing, for each car class, the proportion fatalities that occurred under various conditions, Partyka (1989) reported that only a small mass effect was evident. However, small car fatalities were more likely to have occurred in speed zones under 50mph and in multiple vehicle crashes.

In a collection of analyses into vehicle weight and safety, Klein, Hertz and Borener (1991) reported that down-sizing of the US vehicle fleet from 1970 to 1982 (on average, from 3700 to 2700 pounds) resulted in increased injury rates from both car-to-car and single vehicle non-rollover crashes. They also noted that down-sizing of the vehicle fleet in Texas was associated with a 10 percent increase in the injury rate for single vehicle non-rollover crashes.

Fontaine (1992) reported that in single vehicle crashes, high powered medium weight vehicles were over-represented, though these findings were confounded by the effects of driver's age. She noted that driver age potentially influenced the association between vehicle factors and safety on two levels. First, younger drivers, particularly those in high power to weight ratio cars, tend to be over-involved in all crashes, especially those involving loss of control. Second, given accident involvement, younger drivers are less vulnerable to injury. Fontaine concluded that her analyses had demonstrated the influence of the driver-vehicle combination and therefore the need to conduct disaggregated analyses. This, however, would have seemed obvious from the earlier accounts.

4.1.1 Summary

A summary of the mass/safety relationship for single vehicle crashes is shown in Table 4.1. A number of studies in the USA, France and Australia have reported on the relationship between vehicle mass and safety for single vehicle crashes involving fatality and serious injury measures. The range of mass penalties varied from 1.5% to 8.0% increase in injury for every 100kg decrease in vehicle mass, although two studies failed to find any noticeable finding. These findings suggest that the mass of the vehicle involved in a single vehicle collision is generally important for occupant protection, although the relationship may not be totally based on the vehicle's mass or relevant for all crash types. This will be reviewed in greater depth in later sections of this chapter.

Table 4.1 Summary of Studies Reporting on Single Vehicle Crash Effects

STUDY	COUNTRY	MEASURE	PENALTY (per 100Kg)
Campbell & Reinfurt (1973)	USA	Casualty Injury	unavail.
McLean (1982)	Aus	Casualty Injury	-1.50%
Evans (1982)	USA	Fatality	-5.30%
Joksch & Thoren (1984)	USA	Fatality	-8.00%
Partyka (1989a)	USA	Fatality	not sig.
Klein, Hertz & Borener (1991)	US (Texas)	Injury	-2.20%
Fontaine (1992)	France	Fatality	not sig.

4.2 TWO-CAR CRASHES

By far, the vast majority of the research uncovered in this review was focussed on the safety consequences of cars crashing into each other, and especially situations involving vehicles of different sizes and weights. The characteristics of these crashes will be discussed separately.

4.2.1 Cars of Similar Mass

In 1978, Grime and Hutchinson analysed accident statistics from Great Britain for the years 1969 to 1972 to determine the effect of the mass ratio in determining injury outcome (per collision) for drivers in police reported two-car collisions. Significant associations between mass ratio and injury severity were observed for both two-vehicle and single-vehicle accidents. For a mass ratio of two, the percentage of deaths was about seven times greater in the lighter vehicle. The influence of the mass effect on injury rates decreased with decreasing injury severity. Generally speaking, for two-car collisions, both head-on and perpendicular, there was no effect of mass on injury rates, over and above that explained by mass ratio. In single vehicle accidents there was little or no effect of mass for either overturning or non-overturning crashes.

The compatibility of vehicles of similar mass striking each other was also examined in the Folksam research. When cars of the same weight collided, the relative frequency of injuries was significantly lower for large and medium sized cars than it was for small cars The weight of both the struck and striking car affected the crash outcome in terms of the number of injuries. For those in the bullet vehicle, the relative frequency of their injuries increased as the weight of the striking car decreased. As the weight of the struck car decreased, so too, did the frequency of occupant injuries in the striking car (Aldman et al, 1984).

Evans (1985e) reported that small cars were less likely to be involved in two car crashes generally than larger cars and interestingly, were less likely to be crashed into by all other cars. In terms of collisions between cars of similar mass, collisions between two small (900kg) cars were only 0.3 times as likely to occur as collisions between two large (1800kg) cars. Given such a crash, the driver in the ''*small-small*'' crash was 2.3 times as likely to be seriously injured or killed as the driver in the ''*big-big*'' crash. The product of these two numbers (0.3 x 2.3 = 0 7) gives the involvement rate per registered car and suggests that this serious and fatal injury involvement rate for drivers in ''*small-small*'' crashes is 0.7 times that of ''*big-big*'' car crashes. That is, the serious injury-fatality rate is 30% lower for small-small crashes than big-big crashes despite the fact that given a crash, small-small crashes are more than twice as likely to result in injury.

This finding was interpreted by Evans (1983;1985e) to reflect driver behaviour feedback, originating from the perceived vulnerability of drivers of small cars in the presence of larger cars. Consequently, Evans suggested that removing large cars from the vehicle fleet may lead to an increase in danger if drivers of small cars were to adjust their risk taking behaviour in response to lower perceived risk. Taking a slightly different tack, while still pursuing the association between vehicle mass and occupant safety, Evans and Wasielewski (1984) analysed FARS file data from 1975-1980, focusing on driver fatalities in head-on crashes between cars of similar mass. They used non-occupant fatalities as a general measure of accident involvement or ''*exposure*'' as described by Evans (1984). This research showed that the likelihood of driver fatality when two cars of similar mass collide head-on increases with decreasing car mass. Additional analyses were conducted on injury severity data from New York State and North Carolina to investigate the generality of these findings to non-fatal injuries. There was general concordance among the various analyses, a driver of a 900kg car involved in a head-on collision with another 900kg car was about twice as likely to be seriously injured or killed as a driver of a 1800kg car colliding head-on with another 1800kg car. This could be interpreted as a size effect as well.

Evans and Frick (1991) revisited the FARS file to investigate the relative risk of driver fatality in two-car crashes between 1980 and 1989 for cars manufactured after 1980. The pedestrian exposure approach (previously described in Chapter 2) was employed which showed that driver fatality risk increased with decreasing mass for both the striking and struck vehicle. When cars of similar mass collided, the fatality risk was lower when the two cars were heavier. The risk of driver fatality in a light-light crash was 25% greater than that in a heavy-heavy crash (compared to the earlier findings that driver fatality in a light-light crash was approximately twice that in a heavy-heavy crash (Evans and Wasielewski, 1984). Some of the various results published by Evans and his co-workers over the years is summarised in Table 4.2.

A number of simple mathematical formulas were proposed by Hirsch (1983) for use in estimating collision forces. Hirsch reported that the severity of a two-car crash is directly proportional to the relative velocities of the cars, whereas the relative severity for each car is inversely proportional to its weight (relative to the other car).

TABLE 4.2 SUMMARY OF CAR MASS EFFECTS
(reported by Evans 1992)

Number of cars involved	Quantity measured	Description of crash	900 kg to 1800 kg ratio
TWO-CAR CRASHES	Driver fatalities per crash	Into each other	
		All directions	13
		Head on	14
	Driver serious injuries (including fatalities) per crash	Into car of similar mass	
		All directions	2.2
		Head on	2.0
	Driver fatalities per crash	Into "average" car in 1978 car mix	4
	Driver fatalities per registered car	All driver fatalities in two-car crashes	1.9
	Police-reported crashes per registered car	Into car of similar mass	0.3
SINGLE-CAR CRASHES	Driver fatalities per crash	Unbelted drivers	2.4
	Driver fatalities per registered car	Belted drivers	2.3
	Police reported crashes per registered car	All single-car crashes	1.5
		Rollover only	1.8
		Non-rollover only	1.15
		Assumed to be the same as for all crashes	0.72
ALL CAR CRASHES	Driver fatalities per crash	All crashes	2.8
	Driver fatalities per registered car	All crashes	1.7
	Police-reported crashes per registered car	All crashes	0.72

Fontaine (1992) examined the relationship between vehicle weight and safety in France. She confirmed that in two-car crashes, increased mass improved occupant safety and increased the likelihood of *external aggressiveness*. An analysis of collisions between vehicles in the same weight category, however, did not reveal any differences in the likelihood of serious or fatal injury for different levels of vehicle weight in this analysis, due no doubt to the injury criterion entry into this study.

4.2.2 Cars of Unequal Mass

Campbell and Reinfurt (1973) reported an inverse relationship between vehicle weight and relative injury frequency (of serious injury for a given make and model year compared with that expected on the basis of injuries sustained by the total sample) for car-to-car crashes involving vehicles of disparate mass. The strength of this association declined with later model years which these researchers assumed reflected progressive improvements in crash-energy management systems. Joksch and Thoren (1984) reported that occupant fatality rates increased with both decreasing mass and wheelbase and concluded that the increased occupant protection offered by larger cars in two-car crashes must be attributable to their heavier weight distributing more of the collision energy to the other car.

Grime and Hutchinson (1978) reported significant associations between mass ratio and injury severity were observed for both two-vehicle and single-vehicle accidents. For a mass ratio of two, the percentage of deaths was about seven times greater in the lighter vehicle. The influence of the mass effect on injury rates decreased with decreasing injury severity. Generally speaking, for two-car collisions, both head-on and perpendicular, there was no effect of mass on injury rates, over and above that explained by mass ratio.

Jones and Whitfield (1984) in their analysis of four years accident data in Washington State. After controlling for the confounding effects of driver age and sex (and to a lesser extent crash severity) they noted that injury risk was dependant on both vehicle mass and restraint use. An increase in vehicle weight of 1000 pounds was associated with a 25 percent decrease in injury risk for restrained drivers, and a 34 percent decrease in injury risk for unrestrained drivers.

Aldman et al (1984) described trends in vehicle safety in terms of the frequency and severity of injuries sustained by passenger car occupants (particularly drivers) over a five year period in Sweden. The severity of injuries decreased significantly with increasing car weight, and this was true for all injury severity groups, from slightly injured to fatally injured. The relative frequency of injured or killed drivers was dependent on car weight. Drivers of cars in the smallest weight class (less than 950 kg) were 1.9 times as likely to be killed, 2.2 times as likely to be severely injured, 1.9 times as likely to be moderately injured, and 1.8 times as likely to be slightly injured as those in the largest weight class (more than 1250 kg). The basic nature of these relationships remained unchanged for belted and unbelted drivers and all impact directions.

The Swedish research started with the proposition that for each car model, the probability of injury varies as a function of accident severity and that each car model has an unknown accident severity distribution. However when two different car models collide the severity for each is equal, assuming a mass ratio of one (approximated by weight classes). Under these circumstances the relative injury risk associated with each of the models was compared. These researchers reported that injury risk was related to vehicle weight, with just less than twice the relative risk of death or medical disablement in the smallest weight class (750-950kg) compared to the largest weight class (1250-1550kg). Injury severity was not related to vehicle mass ***per se***. In a similar study of rear seat occupants, Krafft, Nygren and Tingvall (1989) reported that the risk of injury was approximately 50 percent higher in the rear seat of cars in the smallest weight class (750-950kg) compared to those in the largest (1250-1550kg).

As noted previously, Leonard Evans of the General Motors Research Laboratories has published a number of papers addressing the relationship between vehicle mass (size) and safety. A significant inverse relationship between vehicle mass and risk of an occupant or drivers fatality was first reported by Evans (1982) for cars of unequal mass that collide. When comparing the ratio of a fatality in a 900kg car to that in a 1800kg car, he reported a value of 4.0 in all two-car crashes. Furthermore, he calculated that the likelihood of an occupant fatality increased at a rate of 0.14% per kg reduction in vehicle mass in two-car crashes. He subsequently noted that in crashes between 900kg cars and 1800kg cars, eight times as many occupants of the smaller cars were killed compared to the larger cars (Evans 1983). Using his method of demonstrating magnitude of the mass effect, he noted that the accident involvement rate for 900kg cars was 0.72 that of 1800kg cars, which he attributed to behaviour changes arising directly out of drivers' perception of how their safety varies with vehicle size.

Using estimates of exposure based non-occupant fatalities, Evans (1984) further reported a large and consistent increase in the likelihood of a driver fatality as car mass decreased. In this report, he noted that driver fatalities were 2.6 times as likely in a 900kg car as in an 1800kg car. Further, for crashes between 900kg cars and 1800kg cars, 13 times as many occupants of the smaller cars were killed as larger car occupants (14 for head-on crashes only). Because driver behaviour effects were presumed to be included in both the numerator and denominator of this ratio, this estimate of the "mass effect" was taken by Evans to be a *pure measure* of the mass effect on driver fatalities. Subsequent analyses conducted by Evans (1985a) using FARS file data have revealed that the relationship between vehicle mass and driver fatality is similar for both belted and unbelted drivers.

Evans and Frick (1991) revisited the FARS file, investigating the relative risk of driver fatality in two-car crashes between 1980 and 1989, in which both cars were manufactured after 1980. The pedestrian exposure approach as previously described in Chapter 2 was employed again where, generally speaking, driver fatality risk increased with decreasing mass of both the striking and struck vehicle. Evans and Frick (1993) were able to investigate the influence of many parameters on the vehicle "size" (mass) and safety association that had previously received little attention. In crashes between 900kg cars and 1800kg cars, 11.5 times as many occupants of the smaller cars were killed.

Post-1980 model year cars demonstrated a smaller mass effect than pre-1980 model year cars (Evans and Frick, 1993). Post-hoc analyses conducted to aid understanding this phenomenon offered two possible explanations First, as newer cars are generally lighter, the fatality ratio may have varied as a function of both mass and mass ratio. Subsequent analyses that compared the relationship between fatality ratio and mass ratio for different ranges of vehicle mass, suggested that mass *per se* had no real effect.

The second explanation offered was that newer vehicles were more likely to use front wheel drive than older ones. However, only a nominal indication (high uncertainty) of a larger mass effect for rear wheel drive cars was found by these investigators. It was suggested that the critical differences between newer and older cars were more likely to be broader differences in vehicle design that facilitate better collision energy dissipation, and that these too were correlated with vehicle age. The confounding effects of driver variables, age and sex, in the association between vehicle size and fatality risk were confirmed by Evans and Frick (1993). Analyses based on only those crashes in which drivers were the same sex and within five years of the same age revealed stronger effects of mass than analyses using all crashes.

Analyses were also conducted by Evans and Frick (1992a) using 15 years (1975-1989) of FARS file data for two-car crashes with at least one fatality. This analyses revealed that the relationship between vehicle mass and driver fatality risk was monotonic decreasing between 1975 and 1984. This decline was followed by an increase to 1989, with every indication that the effect of mass on relative driver fatality risk for future year models may become similar to that observed in the past.

Partyka (1989) examined the 1986-1987 FARS file data describing the proportion of fatalities that occurred under various conditions for each car class in car to car crashes also. Only a small mass effect was evident for cars of unequal mass in this report, however fatalities in small cars were more likely to have occurred in urban areas, with speed limits under 50mph and in multiple vehicle crashes than was the case in large cars.

In a collection of analyses of the association between vehicle weight and safety, Klein, Hertz and Borener (1991) reported that down-sizing of the U.S. vehicle fleet from an average of 3700 pounds to an average of 2700 pounds from 1970 to 1982, had resulted in increases in injury rates from both car-to-car and single vehicle non-rollover crashes. In Texas, down-sizing of the vehicle fleet was associated with a 14 percent increase in the injury rate resulting from car-to-car crashes, and a ten percent increase in the injury rate resulting from single vehicle non-rollover crashes. In Maryland, an increase in the injury rate resulting from car-to-car crashes of four percent was attributed to down-sizing of the vehicle fleet.

Dalmotas (1983) conducted analysis of the injuries sustained by Canadian passenger car occupants in near- and far-side impacts in which at least one, three-point-restrained occupant was injured at AIS 2 or greater severity. Injury severity and injury probability were inversely related to mass of the vehicle for occupants on the near-side (the side where the vehicle is struck). However, there was no evidence to suggest that the mass of the striking vehicle had any significant effect on injury probability or severity for occupants on the far-side They used the proportions of belted drivers in each car size class as a basis of comparison to control for exposure effects.

Ernst et al (1991) investigated occupant safety in passenger cars (not station wagons), involved in 15,207 head-on collisions (fatals, personal injuries, and serious material damage). Multi-dimensional analysis revealed that when cars of different or equal mass collide, the consequences are always more serious for the occupants of the smaller car. Fontaine (1992) demonstrated a similar relationship between vehicle mass and safety for French vehicle fleet, where with increasing vehicle mass, both occupant safety and external aggressiveness subsequently increased.

4.2.3 Cars of Similar Wheelbase

Joksch and Thoren (1984) reported that occupant fatality rates for car-to-car collisions in the USA during the late 1970's and early 1980's increased with ***both*** decreasing mass and wheelbase (see Figure 4.2 below). However, in single vehicle crashes, they found the fatality risk was influenced strongly by vehicle size, claiming that weight seemed to have had little direct influence. It should be noted that 15 to 25% of single-vehicle accidents involved the car rolling over. They concluded that the increased occupant protection offered by larger cars in two-car crashes must be attributable to their heavier weight distributing more of the collision energy to the other car while single car crash occupant protection was more a function of the space around the occupant.

Evans and Frick (1992b) set about determining which of a vehicle's attributes, size (wheelbase) or mass, has the greater influence on occupant safety. Their analyses were conducted on 1975-1989 FARS file data for two car crashes in which the mass and wheelbase of both cars was known. In the same way that Evans and Frick (1992a) used mass and fatality ratios, Evans and Frick (1992b) used wheelbase ratios where necessary to assess the influence of this variable. When cars of the same wheelbase but different mass collided, the driver of the lighter car was more likely to be killed than the driver of the heavier car. When cars of similar mass but different wheelbase collided, any effect due to differences in wheelbase were too small to be detected by the same method that clearly demonstrated effects dependent on car mass. Based on these findings, Evans and Frick concluded that mass is still the dominant causative factor, with size playing at most a secondary role.

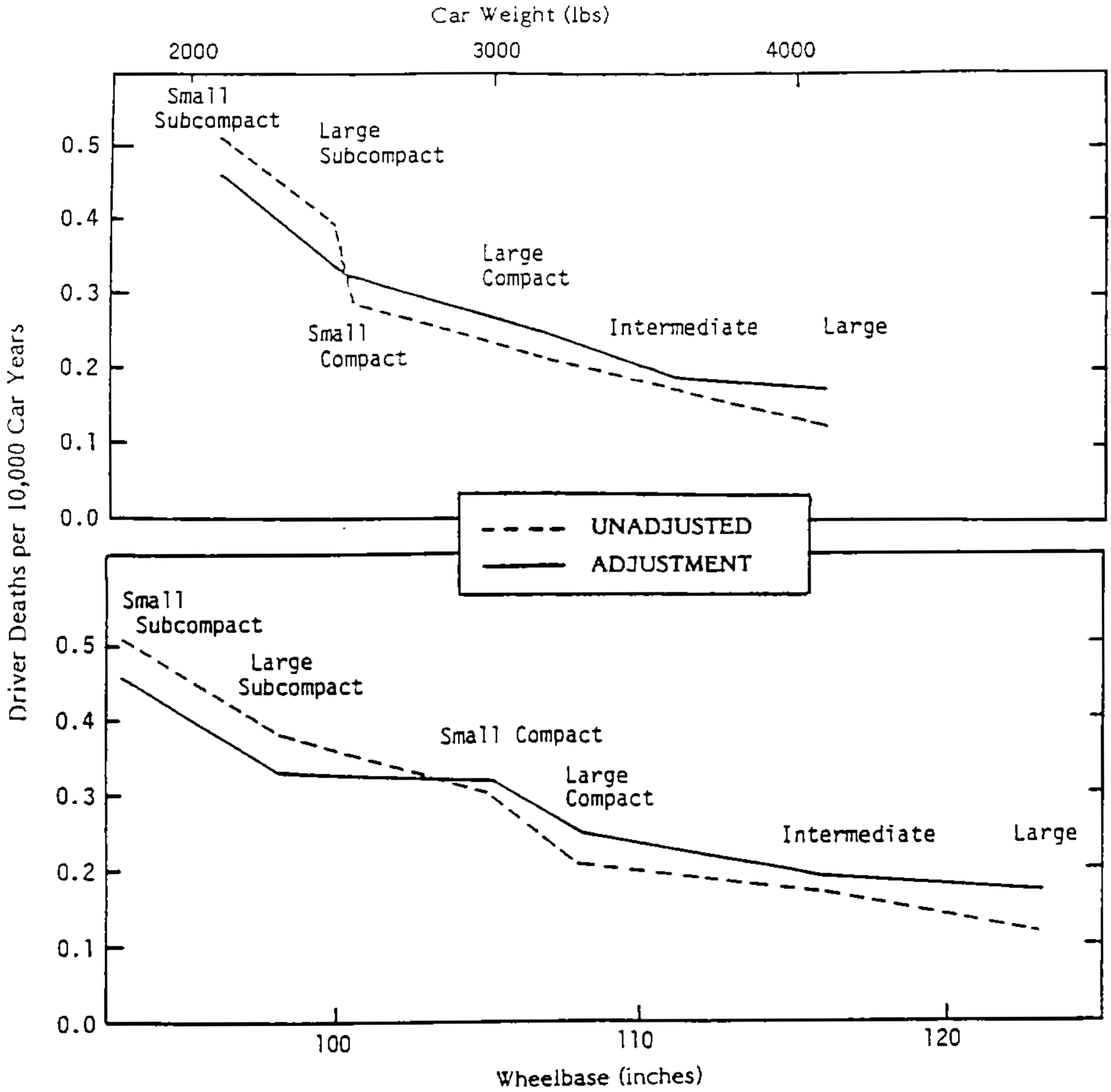

Figure 4.2 Driver death rate in car-to-car collisions
(from Joksch and Thoren 1984).

The upper and lower part of the figure present the same death rates. However, in the upper part, car classes are arranged by average weight, and in the lower part, by average wheelbase. Adjustments were made for differences in the fatality rate per vehicle mile of travel by type of driver and use of the vehicle.

The Highway Loss Data Institute (HLDI 1992) conducted a recent analysis of insurance claim data in the US to examine the role of vehicle size, as defined by six wheelbase classes, in injury and collision losses. The insurance claim data included all claims pertaining to the first three years service of 1979 to 1989 year model cars. Over the ten years for which data was examined, the market share of cars in the largest size class (wheelbase in excess of 114 inches) halved in size, from 18 percent to 9 percent. In terms of both personal injury and collision claim frequencies (per insured vehicle years), larger cars were associated with lower claim rates than smaller cars. They concluded that passenger car down-sizing has had a negative safety effect in the US across the 1979 to 1989 model years. Unfortunately, though, this report failed to address the size versus mass issue, simply assuming that the effects they observed were all size related.

4.2.4 Summary

The various safety implications of the relationship between down-sizing and occupant safety in all and two-car crashes is shown in Table 4.3. It is clear from the outset that there is a much stronger relationship between vehicle mass and safety when two cars collide than for single vehicle crashes. Across all vehicle crashes, the range of injury penalties per 100kg decrease in mass reportedly varied from as little as 5.5% to a maximum of 20% for a range of different outcome measures and seatbelt wearing conditions. For two car crashes only, the penalty range was from 2.5% to 21%. These ranges are too large to permit a meaningful interpretation of the size of the relationship (they are obviously very dependent upon a number of extraneous features such as driver variables, type of collision, crash speed, different vehicle fleets, and so on). Nevertheless, they confirm the injury benefit of crashing in a larger car. Whether mass or size is the prominent feature is not clear from these findings, although from the studies reviewed here, it seems there may not be a simple answer to this question.

4.3 IMPACT DIRECTION

Campbell and Reinfurt (1973) also reported that crash configuration plays a mediating role in the mass, size and occupant safety debate. Indeed, crash configuration effects were evident after controlling for the relative vehicle masses in many of the studies reported above. In "*front-to-side*" crashes Campbell and Reinfurt noted that drivers of "*side-struck*" vehicles were seriously injured more frequently compared to their "*side-striking*" counterparts. Similarly, in "*front-to-rear*" crashes drivers of "*front-striking*" vehicles were seriously injured more frequently than those who were "*rear-struck*".

As noted earlier, Grime and Hutchinson (1978) analysed accident statistics from Great Britain for the years 1969 to 1972. They reported significant mass and injury severity findings for head-on and perpendicular impact directions for single-vehicle and car-to-car collisions. However, they claimed there was little or no effect of mass for overturning crashes.

Dalmotas (1983) conducted analysis of the injuries sustained by Canadian passenger vehicle occupants in near- and far-side impacts in which at least one, three-point-restrained occupant was injured at AIS 2 or greater severity. It was reported that both injury severity and injury probability were inversely related to mass of the vehicle occupied (side-struck). However, there was no evidence to suggest that the mass of the striking vehicle had any significant effect on injury probability or severity for the non-struck side. The proportions of belted drivers in each car size class were used to control for exposure effects, although impact speed and urban or rural crashes were not controlled for in this analysis.

Table 4.3 Summary of Studies Reporting on All and Multiple Vehicle Crash Effects

STUDY	COUNTRY	MEASURE	PENALTY (per 100kg)
ALL VEHICLE CRASHES			
Jones & Whitfield (1984)	US(Washington)	Casualty Injury	-5.5% rest. -7.5% unrest.
Gustafsson et al (1989)	Sweden	Casualty Injury	-10.2%
Partyka (1989)	USA	Fatality	-6.7%
Evans (1991)	USA	Fatality	-20.0%
Cameron et al (1992)	Aus	Casualty Injury	-9.1%
CAR-TO-CAR CRASHES			
Grime & Hutchinson (1978)	UK	Fatality Serious Injury	-9.0% -2.5%
Evans (1992)	USA	Fatality Injury + Fatals	-14% rest. -15% unrest. -13% all 2 car -11% head-on
Klein, Hertz & Boremer (1991)	USA	Serious Injury	-2.5% to 3.0%
Ernst et al (1991)	Germany	Serious Injury	-21.0%
Fontaine (1992)	France	Severe Injury	-9.5% heavy -18% light

The Traffic Safety Group at Folksam reported on impact direction effects in Sweden (Aldman et al 1984). They demonstrated differences in outcome for small, medium and large cars dependent upon impact direction. Small cars seemed to be particularly over-represented in rear-end and near side impacts, while larger cars in far side impacts and rollovers. However, even though there were reasonable numbers of cases in most of these comparisons, there was no attempt to control for area or speed zone of the crash suggesting that these findings might be confounded by urban and rural influences. The higher propensity of small cars in city areas and large ones in rural areas has been previously reported in Australia by Monash University Accident Research Centre (1992) and Cameron et al (1992).

4.3.1 Rollover Crashes

Although investigation of the rollover process was first undertaken as early as 1959 (Shoemaker, 1959), it has only been intermittently studied since, with most of the intensive research only in recent years.

From an analysis of a sample of 249 rollovers by solid top cars, Huelke et al (1972) identified the following as characterising rollovers: rural more than urban locations, curves rather than tangent road sections, single than multi-vehicle, smaller than larger cars, younger than older drivers (especially impaired), and a tripping mechanism initiating the roll.

Since most rollovers are single vehicle accidents, considerable investigation has been directed towards vehicle factors related to the risk of overturning. Cohen et al (1989) found that rollovers accounted for 16% of serious and fatal casualties in cars, but 42% of similar casualties in light trucks. Over-representation of particular classes of cars or vehicle types, shown in Figure 4.3, directs attention to vehicle characteristics such as dimensions.

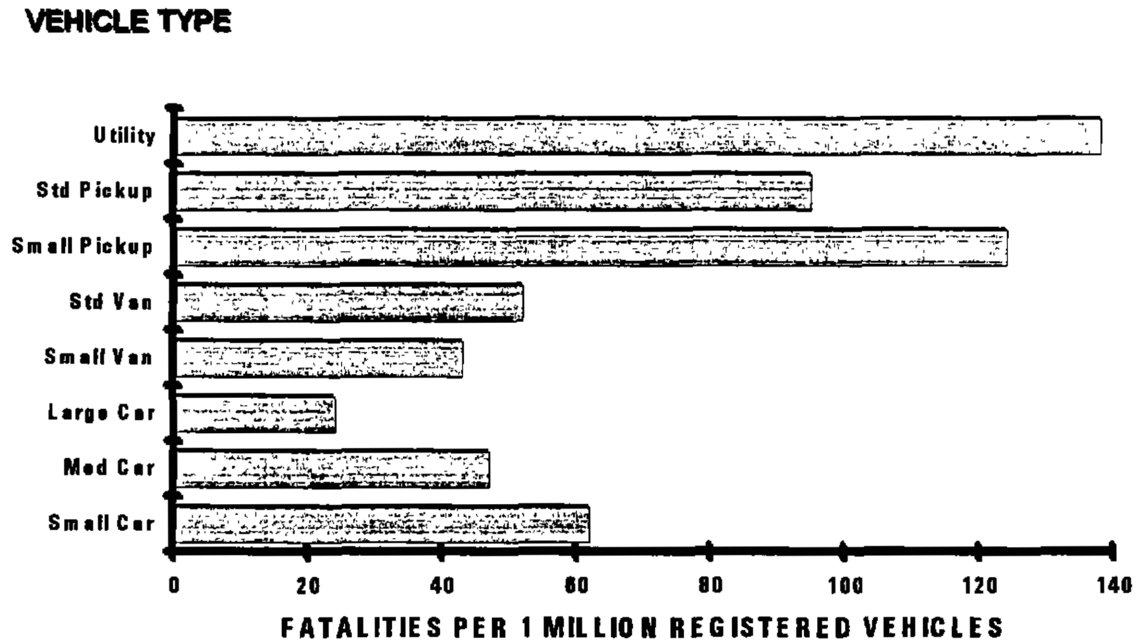

***Figure 4.3 Relative rollover rate by vehicle type** (from Hinch, et al 1992).*

Variables that have been studied include track (width), wheelbase, mass, the ratio of half-track to centre of gravity height, and roll moment of inertia. The first four are all highly inter-correlated. As early as 1968, Garrett defined a rollover factor as the ratio of rollovers to all other single vehicle crashes. In general, shorter, narrower, lighter vehicles have higher rollover rates than longer, wider and heavier cars.

Mengert et al (1989) analysed more than 39,000 accidents by logistic regression and showed that the vehicle safety factor (VSF = track/2CG height) predicted rollover propensity best, but including wheelbase improved the prediction marginally. The wheelbase factor is probably related to the poorer directional stability of shorter (smaller) cars and hence their greater likelihood for entering a potential rollover situation.

Partyka and Boehly (1989) showed that the rollover fatality rate per 100,000 vehicle years was equal to 8.01 minus .00123 times the car weight in pounds. According to Kahane (1991), this effects is due to rollover propensity. The ratio of fatal rollovers to fatal front impacts with a fixed object increased during the 1970's in the USA, especially since 1975 when it was thought that down-sizing was most prevalent in that country. The effect is separate from the better crashworthiness associated with larger cars. The net effect of size reduction in the car fleet was calculated to be about 1340 extra rollover fatalities per year in that country

A number of authors have noted the generally higher speed of rollover crashes compared with other crash modes (eg: Malliaris 1985). As noted above, Mengert et al identified VSF as a main factor in predicting rollover rate (the other main factor being the location of the crash) Other vehicle factors likely to be involved in rollover crashes. either separately or interrelated with the mass or size of the vehicle, include the suspension, centre of gravity, and rollover stability metrics.

The propensity to roll over, for a given vehicle model, is therefore the product of two probabilities:

1. The probability of getting into as situation which makes rollover possible, typically losing directional control, a function of wheelbase, and

2. The probability of rolling, which is a function of track and centre of gravity height.

Both these factors are associated with vehicle size rather than mass. But if an analysis is made of rollover rate by vehicle mass, the rate will appear to be related to mass, because of the high correlation between vehicle mass and vehicle size.

4.5 EFFECTS OF SAFETY FEATURES

Generally speaking, injury severity for a car occupant is related in an uncomplicated crash to delta-V. In two-car collisions, the respective delta-Vs are determined by the mass ratio of the vehicles (Evans, 1993). The actual injuries sustained by occupants, for a given delta-V, will be modified by whatever characteristics or features their vehicle possesses that influence the management of delta-V (Aldman 1984). One such feature is the linear dimension of the car, particularly that portion ahead of the firewall and generally associated with wheelbase (Wood et al 1993). Another important feature is the presence of adequate restraint when used.

The effect of restraint in relation to vehicle mass was noted as early as 1974 by Scott, who found that the risk of serious or fatal injury was more than three times greater for unrestrained drivers of small cars (less than 900 kg) as for heavy cars (1800 kg or more), but the risk was greatly reduced if the driver was wearing a seat belt. The relative difference in risk for small and heavy cars was only slightly diminished by seatbelt wearing.

Stewart and Stutts (1978) in single car crashes found the benefit (reduced death or serious injury) from belts to be substantial (50% to 60%), but it was not greater for small cars compared with three higher weight categories.

Jones and Whitfield (1984) examined injury data for drivers from the State of Washington police-reported crashes with respect to a number of variables: age, sex, use of restraint, car mass, posted speed limit and the interaction of restraint and mass. The significant variables were speed limit (a proxy for travelling speed), mass, sex, use of restraint and the interaction of restraint and mass. The interaction term indicates a differential effect of restraint use on the effect of mass.

They found that a belted driver gains a reduction in injury odds for each additional thousand pounds of car mass. This figure is 34% for unrestrained drivers. To gain the same reduction in injury odds afforded to the belted driver of a 2500 pound car, an unbelted driver requires a 4325 pound car. The driver of a small car gains more from being restrained than does the belted driver of a large car, but the use of restraint in a very small car cannot overcome the weight disadvantage.

An examination of 1982-1987 FARS files by Partyka and Boehly (1989) yielded estimates of belt effectiveness, against fatality, across six weight classes, indicating a modest gradient from lightest to heaviest vehicles (Table 4.4).

TABLE 4.4 Belt Effectiveness by Fatalities for Cars of Different Weight

CAR CATEGORY	WEIGHT RANGE	EFFECTIVENESS
Mini-compact	<1949 lbs	65%
Sub-compact	1950-2449 lbs	57%
Compact	2450-2949 lbs	52%
Intermediate	2950-3449 lbs	55%
Full size	3450-3949 lbs	49%
Largest	3950 plus lbs	50%

A multivariate analysis was made also by Lui et al (1988) from material in the FARS files of 1984 and 1985. Here the variables included impact direction, car mass (at four levels), belt use, driver age and sex and car deformation. The independent variable was the death (or survival) of the driver. The main effects were: use of belt and increased car mass, both decreasing risk, and deformation, increasing risk. Interestingly, in this analysis, there was no significant interaction term for belt by mass, implying that the benefit of belt-wearing was more-or-less constant across car mass categories.

Thus, there is no question about a substantial benefit from wearing a belt across all sizes (masses) of cars. Whether there is a differential effect (more benefit from belts in smaller cars), however, is uncertain.

Airbags have only recently become a standard fitting in the US, principally as a *passive* restraint. In an early evaluation of the benefits of airbags for a mainly unrestrained population, Zador and Ciccone (1991) reported larger reductions in fatalities for occupants of larger cars and smaller benefits for occupants of smaller models. While all occupants benefited from these devices, this result seems counter-intuitive and may simply reflect exposure differences across the vehicles studied (different impact speeds, different age groups, differences in unrestrained occupants, etc.). It is reasonable to assume that there are, qualitatively, similar benefits from air bags, though these are likely to have a smaller effect in a largely belt-wearing population of car occupants.

While restraint cannot fully compensate for smaller mass, the benefits from belts across mass categories lends encouragement to any other measures for managing the effect of delta-V on injury production in small cars.

5. OTHER ASPECTS OF DOWN-SIZING

While the thrust of this review has been aimed primarily on the safety aspects of vehicle down-sizing, there are a number of other (additional) consequences that also need to be considered in this context This is not meant to be an exhaustive review of these issues but rather recognition of the fact that there are other than safety consequences involved in down-sizing. Other studies currently planned or underway are aimed at a more detailed examination of these other issues (refer Environmental Study 4.5, Car Size, Efficiency and Safety, by the Australian Road Research Board, 1993-94 program).

5.1 ENVIRONMENTAL ASPECTS

Down-sizing in the USA in the 1970s was commonly believed to have been driven by the fuel crisis and the likely environmental benefits from a vehicle population containing smaller vehicles. It is argued that smaller vehicles mean fewer resources for their manufacture and a reduced need for running expenses

The Royal Automobile Club in Victoria frequently publishes estimates of vehicle running costs which indeed show that smaller vehicles cost less to run than larger ones (see Table 5 1).

Table 5.1 Private Vehicle Reimbursement Rates
(Royalauto magazine, June 1992)

Vehicle Size	Up to 5 years old (cents per km)	5 to 10 years old (cents per km)
Small (<1600cc)	35.63	26.13
Medium (1601-2200cc)	43.17	29.63
Upper Medium (2201-3000cc)	49.63	33.67
Large (>3000cc)	48.37	33.59

While engine capacity is not necessarily a good measure of vehicle size (cars of small size sometimes come with very large, powerful engines), nevertheless, these figures illustrate the fact that in general, motorists with an eye for economy will be persuaded to choose smaller than larger cars. As price is a proxy for community resources in this area, it is often taken that smaller cars can mean *"more environmentally friendly"* vehicles, although this is not necessarily the case.

Of course, this logic disregards any consideration of safety consequences. If larger cars result in fewer injuries for a given crash, then it follows that there will be injury benefits (fewer costs to the community) from bigger vehicles. Thus, the so-called *environmental benefit* from down-sizing needs to be offset somewhat by any safety disbenefits to the community.

5.2 MANUFACTURING PLANS AND TRENDS

It is always difficult uncovering manufacturer's plans for future production trends in new cars because of their marketing needs for confidentiality. However, one local manufacturer was quite forthcoming in terms of their historical experience and various other sources of information were uncovered that provide indications of down-sizing trends that have occurred over the last decade or so and reasons for this shift.

5.2.1 Fleet Trends in Vehicle Size

The Australian Bureau of Statistics conducts regular census of the type and size of vehicles on the register for the year in which the census was undertaken. The census years of 1979 to 1991 were of particular interest as they provided the opportunity to monitor changes in the vehicle fleet since the late 1970's.

5.2.2 Census Data

Data were obtained from the Australian Bureau of Statistics from their 3 yearly census of passenger cars listed on the vehicle register for all Australian States and Territories between 1979 and 1991. The individual makes and models were collapsed into 5 categories of Tare weight (unladen kg) representing small to large vehicles and the results shown in Table 5.2.

The results of this analysis show that the market segments across the vehicle registers for the whole of Australia is exceptionally stable and not indicative of down-sizing at all. The proportion of small cars (less than 1100kg) has if anything slightly reduced from 1979 to 1991 (48% to 44%) while large cars (more than 1300kg) has increased marginally from 22% to 27%. It must be borne in mind that the average vehicle age in Australia is 9.7 years (ABS 1991 census), thus any likely fleet effects of down-sizing would take a long time to show.

Table 5.2 Proportion of Passenger Cars on Register by Tare Weight
(ABS, Australia, 3year census, 1979 to 1991)

CENSUS YEAR	<900kg	901/1100kg	1101/1300kg	1301/1500kg	>1500kg
1979	25	23	30	18	4
1982	21	24	30	20	5
1985	21	27	28	19	5
1988	19	27	30	19	5
1991	16	28	30	20	7

(Figures show the percentage of vehicles in each mass category.)

5.2.3 New Car Sales

If down-sizing is a fairly recent phenomenon and not apparent in the census figures of the Australian vehicle fleet, it should be more apparent in recent sales trends in this country. Paxus publish annual sales figures of new cars each year which show trends by market segment. While these figures are different to the fleet effects in that they do not allow for scrappage, they do nevertheless provide indicative trends in recent buyers preferences for vehicles of differing size.

Table 5.3 shows the market segment trends for passenger cars every 2 years from 1970 to 1989. There is strong evidence of down-sizing occurring in new passenger sales over this period with small and lower medium vehicle sales going from 17% in 1970 up to 29% in 1989 and upper medium and large car sales from 69% down to 42% over the same period. Interestingly, however, most of the change seems to have occurred during the 1970's with relatively stable market segments throughout the 1980's.

Table 5.3 Market Segment Trends, 1970-1989
(Paxus new registration data)

CATEGORY	1970	1972	1974	1976	1978	1980	1982	1984	1986	1988	1989
SMALL	3	2	1	1	1	1	2	3	1	2	2
L/MEDIUM	14	16	21	27	22	26	30	28	30	27	27
INTERMED.	15	18	19	20	30	35	30	33	29	31	28
U/MEDIUM	12	9	12	13	11	6	6	4	4	6	6
LARGE	57	55	47	39	35	33	32	32	36	35	36

Figures listed are percentages, rounded off to nearest whole percentage.

5.2.4 Motivation for Down-sizing

It has been maintained that the world-wide push for smaller vehicles over the last 10-20 years was prompted by two crises that occurred during the 1970's. Indeed, this may have been a motivation for some people to down-size, but there are alternative explanations for this trend A major Australian vehicle manufacturer has in fact suggested that such down-sizing as occurred in the seventies was more a function of an increase in the proportion of women car buyers, partly associated with the rise in female participation in the workforce and to some extent reflected in the growth of multiple car households.

Table 5.4 shows the proportion of men and women aged 15 to 99 owning cars from 1970 to 1985, derived from regular car ownership surveys conducted by that manufacturer. These figures show that the rate of women owning cars to men has gone from 0.24 to 0.84 over that time period and would be presently approaching 100%. For women to ***own*** an increasing proportion of cars relative to men, they must have ***bought*** an increased proportion of cars. As women, on average, buy smaller cars than men, the car market in the seventies shows a tendency towards down-sizing, independent of other pressures. One reason women tend to buy a smaller car is that they are on average physically smaller than men and accordingly do not on average need the same sized car to experience the same degree of comfort, while at the same time, especially in the days before power assistance, a smaller car would have had greater appeal to women, because it was much easier to handle, i.e. to steer or stop. Moreover, particularly in the seventies, the cars bought, for instance, by married women tended to be the second car in the household, which gave rise to increased demands for economy in terms of purchase price and running costs, both of which considerations encouraged a reduction in vehicle size.

Table 5.4 **Car Ownership as Percent of Population 15 and over**
(Data based on 3 year surveys by one large Australian manufacturer)

SURVEY YEAR	MALES	FEMALES	PERSONS	SEX RATIO
1970	66%	16%	41%	0.24
1976	73%	27%	50%	0.37
1982	70%	41%	55%	0.58
1985	63%	53%	58%	0.84

One reason women tend to buy smaller cars is that they are, on average, physically smaller than men. Accordingly, they do not need the same space to experience the same degree of comfort. In addition, a smaller car during this period would have been easier to handle as power assistance was less common. During the seventies, many cars purchased by women were second cars which would give rise to greater demands for economy in terms of purchase price and running cost, both of which considerations would have encouraged a reduction in vehicle size or mass.

The cost of fuel would have been less of an influence in down-sizing in Australia because of its relative cheapness by international standards. Figure 5.1 shows that the cost of fuel in this country compared to most other western countries, where Australian prices are the second cheapest behind the US. As petrol prices have effectively fallen in relative terms compared with other cost of living increases, the importance of the price of petrol in motorist's decisions about car purchase is probably less today than it was during the 1970's and 1980's.

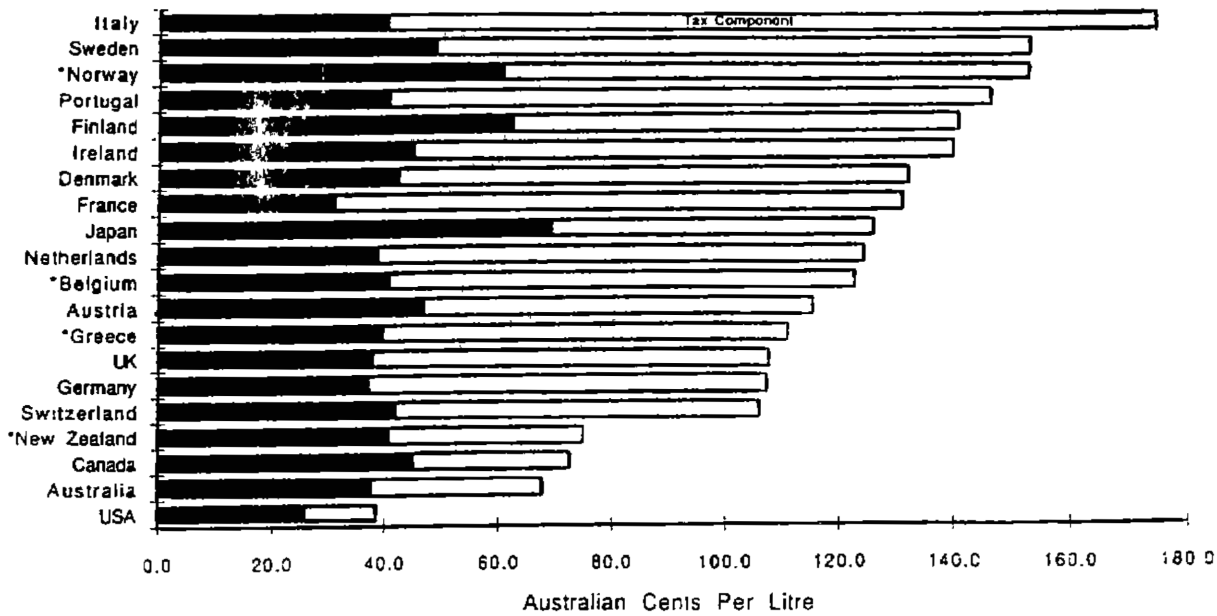

Figure 5.1 Comparison of petrol prices and taxes in IEA countries - March Quarter 1991
(from Australian Institute of Petroleum, OPIE from data supplied by IEA)

5.2.5 Changes to Regulations

The control of vehicle emissions is often cited as a reason for down-sizing among the vehicle fleet. Australian Design Rule ADR37/00 specifies emission control for light vehicles and the current standard was first issued in December 1986. Following a detailed review of the standard by Nelson English Loxton & Andrews (1991) a revised standard has been prepared (Draft ADR37/0X) which specifies more stringent controls on the levels of emission for new vehicles This standard is due to be introduced for application to new models on 1 January 1997 and existing models 1 January 1998

The degree to which these emission control standards have influenced the trend to vehicle down-sizing is based on opinion. However, as the revised standard is likely to have only minimal impact on fuel economy, vehicle weight, and the cost of new vehicles, it would seem highly unlikely that ADR37/0X will lead to further down-sizing of the fleet.

Safety performance design standards such as ADR69/00 will no doubt have some effect on vehicle size and mass in future cars. However, these effects are likely to be only minimal and will probably lead to slightly heavier, not lighter, cars. Side structural improvements, expected as side impact legislation becomes operative in the USA and eventually Europe may also lead to a minor increase in mass. As these effects are likely to apply uniformly to all vehicles sold in Australia, it is unlikely to penalise any one manufacturer or vehicle and result in a slight shift upwards for the whole vehicle fleet.

5.3 THE USE OF COST-BENEFIT ANALYSIS

Benefit-Cost analysis is becoming more important for providing advice to governments trying to make rational community decisions where there are competing options. In recent times, BCR analysis has been used in road safety to indicate the feasibility of occupant protection measures (Monash University Accident Research Centre 1992) and the effectiveness of black-spot treatments (Ogden 1992)

As down-sizing is likely to have both costs and benefits to the community, clearly there is scope for the use of benefit-cost analysis for helping to clarify issues in this debate. The question to be resolved, however, is whether there are sufficient data available to permit a thorough analysis.

5.3.1 Down-Sizing Benefits

The benefits of down-sizing were briefly alluded to earlier in this section. They include such possibilities as:

- reduced need for materials for smaller cars,
- reductions in labour and allied costs of manufacturing,
- reductions in fuel,
- reductions in road maintenance costs,
- reduced parking requirements,
- lower repair costs,
- less emissions, etc.

While many of these environmental benefits may not have been costed to date, it should be possible to arrive at reasonable estimates of these benefits by a systematic examination. The costs and benefits to the environment in terms of such factors as Greenhouse effects would be almost impossible to cost for any one country.

However, it may be feasible to undertake a limited study to determine the likely savings to the community from a proportional reduction in vehicle size Compounding factors, such as the use of different materials (eg; plastics and aluminium) and manufacturing techniques would need to be considered. Sensitivity analyses would also be desirable to allow for variations of these factors.

5.3.2 Down-Sizing Costs

While it may be possible to determine the likely benefits of down-sizing, arriving at the prob costs would be more difficult. The major costs of down-sizing to the community would . terms of increased trauma from smaller vehicles. It would be extremely difficult ***a prio*** . assess the consequences of down-sizing in terms of likely vehicle mix. A number of different scenarios might be possible such as:

- a proportional shift in the vehicle fleet towards the smaller or lighter vehicles (ie; a movement away from big cars altogether so that the present relative differences in vehicle size are maintained), or
- a stretching of the distribution towards smaller vehicles, with big cars are relatively unaffected and the middle group of cars moving downwards.

Obviously, both of these scenarios have safety consequences: The first scenario would mean that the relative injury patterns currently experienced are maintained but that there is likely to be a constant increase in trauma from the absolute size reduction. Scenario two would see a non-linear increase in small vehicle trauma, dependent upon increases in relativities as well as the number of small cars involved in crashes.

Establishing the safety consequences would require considerable assumptions about the likely mix of small and large cars in the vehicle fleet in future and the associated injurious effects.

5.3.3 Conclusions

Cost-benefit analysis would be an important input into the down-sizing debate, providing rational information to help guide future decisions. Whether it would be possible to arrive at accurate estimates of the likely benefits and costs is not clear. A partial solution might be to look at a matrix of possibilities based on various scenarios and arrive at a range of possible outcomes. While this may not be too definitive, it could at least help focus on what are the relevant issues and the likely consequences.

6. GENERAL DISCUSSION AND CONCLUSIONS

The literature review has pointed to a number of important findings in regard to the relationship between vehicle mass, size and occupant safety, as well as a number of unresolved issues. This Chapter summarises these findings and identify areas that still require further attention It ends by listing the main conclusions emanating from this review.

6.1 DOWN-SIZING AND SAFETY

The literature on the relationship between vehicle mass, size and safety was a little unclear and seemed to be subject to a number of confounding influences. There was general consensus by most researchers that bigger cars were inherently more safe than smaller models. However, problems arose when trying to be more specific about this relationship, in part because of a number of definition ambiguities.

Vehicle size is often interpreted to mean differences in the vehicle's external dimensions, its cabin space, or its engine size. Vehicle mass can refer to its curb weight, unladen weight, its weight with and without fuel or with and without occupants or load. Small variations in some of these characteristics can lead to a marked difference in outcome and mask the full extent of the relationship between a vehicle's mass or size on safety.

These problems aside, however, the one clear message to come from this review is that occupant safety is very much dependent upon the type of vehicle one is in during the crash. Whether its mass or size (structure) that offers improved protection is yet to be positively shown. The role of cabin size would also seem to be worth closer scrutiny, although it, too, is not totally independent of other dimensions. The overriding complication is of course impact velocity for, beyond some critical speed, the debate becomes irrelevant. However, as a large body of evidence shows that the vast majority of crashes today still occur at potentially survivable speeds, it is worth pursuing the importance of these vehicle dimensions in improving vehicle safety.

6.2 CRASHWORTHINESS AND CRASHPRONENESS

The concepts of ''*crashworthiness*'' and ''*crashproneness*'' and how vehicle design influences them was also reviewed. It is clear that crashworthiness (how well a vehicle performs in a crash) is quite a separate concept to crashproneness (whether the crash can be avoided), the implications of each needing careful consideration These terms are akin to the notion of ''*primary*'' and ''*secondary*'' safety, normally credited to William Haddon.

Vehicle safety ratings which assess fleet crashworthiness have demonstrated statistically robust differences between makes and models of different size and mass. While in general the larger the car the better its crashworthiness, there is some evidence that performance within similar size (mass) categories can be influenced by other characteristics. Vehicle safety feature differences would seem to be one possible source of within-size variation

Crashproneness differences, on the other hand, are inherently difficult to interpret because of the overwhelming influence of driver factors. As various models appeal to different motorists, so factors such as driver age, sex, distance travelled, travel speed, and injury susceptibility all play a part in influencing these assessments. The likelihood of a vehicle rolling over seems to be the only aspect of vehicle crashproneness essentially outside these exposure effects.

6.3 THE ROLE OF MASS AND SAFETY

The vast majority of the literature published on the effects of down-sizing on safety have focussed on the influence of the vehicle's mass. Overall, it appears that the mass of the vehicle has a pronounced effects of the level of safety for occupants of passenger cars that crash, although there appeared to be a much stronger relationship between mass and size in multi-car crashes than single vehicle collisions The precise nature of the relationship, however, is not at all clear or proven from these studies.

There were large differences reported in the magnitude of the mass effect across the various studies reviewed here, both between and within countries. Some of this variation would be accounted for by differences in driver and crash conditions as these were not controlled for consistently across the studies. The type of crash and the impact speed were also not consistent in many of the studies (if known at all) and these factors would inevitably have a sizeable influence in injury outcome. The crash periods also varied from the 1970's until the late 1980's during which time there were a number of improvements in vehicle design and occupant protection.

It is apparent that would be a difficult task indeed to try and predict what the consequences of down-sizing alone would be in terms of occupant safety, given the number of variables involved and their interactive effects.

6.4 VEHICLE FLEET EFFECTS

One or two researchers have remarked on the fact that in crashes involving similar mass vehicles, the injury outcome for the occupants is still significantly different dependent upon whether they are *small-small* or *large-large* crashes (Evans 1985c, for example, reported that drivers of small cars were 2.3 times more likely to be seriously injured or killed if 900kg pairs of cars collided compared to those in 1800kg pairs in the US).

He subsequently argued, however, that as small-small car crashes were only 30% as frequent as large-large car crashes in the US, then the risk of injury for small car drivers is only 70% (ie., 0.3 times 2.3) that for drivers of large cars overall. Thus, removing large cars from the fleet through down-sizing, he maintained, could lead to an increase in injuries if drivers adjust their risk taking behaviour in the absence of these large threatening vehicles (the so-called "*risk homeostasis*" theory of driver behaviour).

This is a curious argument indeed as Evans has ignored several important and seemingly critical aspects. First, there needs to be more definitive evidence that drivers in smaller fleets elsewhere are at a higher risk of collision than they are in the US. International comparisons are possible, although there are several other sources of difference (roads, traffic volumes, speeds, behaviour, etc) that could explain any differences here. Second, it ignores what the current proportion of small and large cars are in the US and what the risk of a collision is for both these size categories. Suppose for instance that drivers of small cars generally have fewer crashes than drivers of large ones. Then, there is potential for a reduction in the number of injuries from down-sizing as removing large cars will inevitably reduce the overall risk of crashing.

The theory of risk homeostasis has long been disproved by the continuous fall in the international road toll rate per 10,000 vehicles. This does not preclude, however, the possibility that drivers might still adjust their driving slightly in the face of different driving conditions.

In any event, trying to predict the safety consequences of down-sizing would be very much dependent on a number of local factors which Evans did not seem to address

6.5 THE ROLE OF SIZE AND SAFETY

There were conflicting accounts of whether size or mass is the critical safety factor. Evans and his colleagues in the USA argued that variation in mass between colliding vehicles was paramount and that size was only a relevant feature when vehicle mass was constant between two cars that collide or in single vehicle crashes. This finding was also confirmed by Joksch and Thoren (1984) of the National Highway Traffic Safety Administration in Washington.

Banthia and his co-workers at Alcoa argued the reverse. They maintained that differences in mass intimately involved structural differences and that size and structure was the principle feature They argued that cars built of lighter materials while maintaining size would be both safer and more fuel efficient (although coincidently this view supports the interests of their employers). The Insurance Institute for Highway Safety recently reported that passenger car down-sizing between 1979 and 1989 in the US was related to increases in occupant casualties which they attributed to size differences. However, this study failed to address whether size or mass decreases had the stronger association

To some degree, it will always be a matter of contention whether size or mass is the critical factor associated with the safety disbenefit of down-sizing because they are so interrelated with each other. The use of lighter materials such as aluminium in car structures means that the consequence of mass versus size takes on more importance than simply academic interest. The degree to which the use of light-weight materials in body construction will effect safety is not clear, given the relatively small contribution of the weight of the body shell generally to the total weight of the vehicle. However, as Partyka demonstrated, differences of only 100 pounds (approximately 45 kilograms) can have a sizeable influence on multiple vehicle fatality rates

The use of Finite Element Design (FEA) in streamlining body design is also of interest in the size or mass debate. This relatively new design procedure enables designers to focus on essential members and components in designing new vehicles and eliminate the need for redundant structures in meeting crash performance requirements in future car bodies. This procedure is expected to lead to even lighter car bodies than current models. It is important to monitor the use of light-weight materials in body construction and FEA in streamlining body structures for assessing their impact on occupant protection in the years ahead.

6.6 THE EFFECT OF CRASH TYPE

The role of crash type is important for specifying the relationship between mass (size) and safety. Researchers such as Evans showed that mass effects were more pronounced for frontal and rear impacts where the size or structure of the vehicle is maximal and the impact energy can be absorbed in a more controlled manner. However, there appeared to be little if any mass or size benefit for larger cars in the Canadian side impact study reported by Dalmotas. This is not too surprising, given the relative lack of structure in the side of most cars irrespective of their size Design opportunities for improving occupant protection in side impacts might lead to benefits more from structural improvements rather than mass effects, although there are only limited opportunities for such improvements, given present day vehicle designs and styles.

Vehicle rollover is known to be an extremely severe type of crash and one more likely to involve a single vehicle. Smaller, lighter vehicles tend to have higher rollover rates than larger, heavier ones, largely because of the relation of track and height of the centre of gravity, which is in turn related to linear dimensions. According to Kahane, the severity of injury outcome is related to rollover propensity rather than crashworthiness. This effect is mitigated, to some extent, because larger, heavier cars tend to have their (less frequent) rollovers at higher speed than smaller, lighter vehicles. Again, with lighter materials or composite bodies in the future, there may be some scope for improving the rollover characteristics of smaller cars by lowering the centre of gravity or widening the track.

6.7 THE INFLUENCE OF SAFETY FEATURES

The preceding discussion has shown that in a simple car-to-car crash, occupant safety is related to the change in velocity during impact (delta-V) which is determined in part by the mass ratio. However, there are several reports which illustrated crashworthiness variations within particular mass categories seemingly determined by other design aspects such as the amount and type of safety features fitted to the vehicle (Cameron et al 1992)

The level of restraint use has been shown to markedly influence the mass (size) and safety relationship in a number of studies The study by Jones and Whitfield in 1984 demonstrated that an unbelted driver in a 4325lb (2000kg) car had the same amount of protection as a belted driver in a 2500lb (1140kg) vehicle. Moreover, they claimed that drivers of small cars gained more from being restrained than did their large car counterparts. Stewart and Stutts in 1978 failed to find an asymmetrical mass effect for seat belt use as did Jones and Whitfield, although they were principally concerned with single vehicle crashes.

The only study to report size differential effects for airbags was less than definitive. It would seem reasonable to assume qualitative benefits for occupants in head-on crashes from airbags and that these might favour occupants in smaller vehicles. However, the study reported the opposite. This could have been because of a number of confounding factors which were uncontrolled in this report. Given that airbags are a recent development, it is still too early yet to assess whether they will offer disproportionate benefits based on vehicle mass or size.

6.8 DOWN-SIZING AND THE AUSTRALIAN VEHICLE FLEET

Fleet down-sizing certainly appears to have been a real phenomenon during the 1970's and early 1980's in most western countries. While this was said to have resulted from the oil crisis during the mid-1970's, it may also have been the result of other forces such as increased purchases by women who had a preference for smaller vehicles. This has been reported by one vehicle manufacturer in this country.

There are certainly financial benefits to owners of smaller cars from cheaper running costs (cars with less than 1600cc engines cost only 74% that of 3000cc vehicles to run, presumably heavily influenced by the cost of petrol). However, given the relatively low prices of fuel in this country, it could hardly be the major push for down-sizing in Australia.

Importantly, however, government statistics revealed that the proportion of smaller cars in Australia (those with a mass of 1100kg or less) has been relatively stable throughout the 1980's and early 1990's. Furthermore, trends of increased sales of these vehicles in the 1970's have not continued recently in this country. There is little evidence of any real or lasting trend towards lighter or smaller cars in Australia. Nevertheless, this may change in the years ahead if only from the use of lighter materials in car construction.

6.9 DESIGN RULE IMPLICATIONS

Vehicle emission regulations may have had some minor effect towards down-sizing, but on the evidence considered here, hardly a significant effect Moreover, recent amendments to ADR37 to come into effect in December 1996 are not expected to have any noticeable effects on vehicle down-sizing and hence on occupant safety from mass or size influences.

Vehicle performance legislation aimed at specifying acceptable levels of safety may have some influence on vehicle mass and size as manufacturers design cars to meet these levels. More features such as airbags, belt pretensioners and webbing clamps, stronger seats, etc will have some marginal (upward) influence on the cars weight. However, these influences will at best only be minimal and are likely to apply to the whole vehicle fleet.

It has been argued that the most effective means of improving occupant protection for all Australians would be to up-size the vehicle fleet (rather than down-size). The consequences of this are not immediately apparent in terms of what the benefits and disbenefits would be, based on the literature available. There may be an overall improvement in vehicle trauma but at some cost (higher purchase and running costs for those least able to afford it as well as environmental consequences). Whether such legislation would be acceptable to the majority of motorists is also questionable.

6.10 THE USE OF ECONOMIC ANALYSIS

Cost-benefit analysis would make an important contribution to the down-sizing debate, providing rational information to help guide future decisions. It would be possible to undertake a cost benefit study of the consequences of down-sizing (or up-sizing for that matter) of the future Australian fleet. However, it would not be an easy task, requiring a number of assumptions and estimates of fleet effects both short term and long term.

It was argued that a partial solution might be to look at a matrix of possibilities, based on various scenarios to arrive at a range of possible outcomes. While this may not provide definitive answers, it could at least help focus on what are the relevant issues and likely consequences and demonstrate areas requiring further work in this area.

6.11 CONCLUSIONS

A number of conclusions can be drawn from this review of the relationship between vehicle mass, size, and safety.

1. There is little doubt that larger vehicles are inherently more safe than smaller ones. However, the precise relationship between mass, size and safety is not entirely clear.

2. A number of confounding factors will influence the crash performance of a vehicle apart from mass or size advantages These include driver involvement, crash type, impact speed, and safety feature differences. These must be controlled for to enable meaningful comparisons of vehicle crashworthiness to be made.

3. Mass seems to be an important feature in multi-vehicle crashes while size is more relevant in single vehicle crashes. The high correlation between these factors and the lack of well controlled studies in this area makes it difficult to separate mass and size effects.

4. The consequence of whether mass or size has greatest influence on vehicle safety is paramount if manufacturers continue to use lighter materials and/or composite structures in their vehicles.

5. The degree to which driver behaviour interacts with vehicle mass is unclear. While down-sizing might lead to drivers of smaller cars changing their risk characteristics, one would hardly expect massive changes through down-sizing.

6. Mass or size effects are more pronounced in frontal crashes. Side impacts offer little opportunity for mass (size) effects because of limits in available space. Rollover benefits for larger cars are dependent on size, not mass.

7. Safety features do influence vehicle safety, independent of the vehicle's size or mass. Seatbelts act to enhance safety for occupants in all car masses and may have greater benefits for small car occupants in multi-vehicle crashes. While airbags also offer benefits for all occupants, it is too early yet to know whether they have differential effects for any particular vehicle mass or size.

8. There has been little evidence of down-sizing in the Australian fleet since the late 1970's apart from the advent of some very small cars. The traditional economic motivation for down-sizing has been challenged, suggesting that changes in buying patterns, emphasising increased female ownership has had a much greater influence in down-sizing in this country than economic factors.

9. Current or proposed Australian design rules have had (or will have) only marginal influence on down-sizing. While it would be possible to legislate for a larger vehicle fleet, such a step does not seem warranted at this time.

10. Economic analysis is a suitable means of examining the costs and benefits of down-sizing. At this time, a cost-benefit analysis would need to focus on a matrix of possible outcome scenarios, given the number of assumptions needed to arrive at BCR's.

6.12 AREAS FOR WHICH FURTHER RESEARCH IS NEEDED

It is difficult to point to specific areas requiring further research into down-sizing in this country, given the apparent lack of a shift towards smaller vehicles in Australia. This is not to say that future trends might not see a push for light-weight smaller cars world-wide which would have some flow-on effect in Australia. Some areas that might be useful for future research in this area are listed below.

1. There might be some value in assessing what motivation there is for smaller, light-weight vehicles in Australia. This could entail assessments of demand trends among the population for smaller vehicles now and in the future, as well as examining local and overseas developments in manufacturing smaller and lighter cars generally. Industry plans for using lighter and composite materials, more sophisticated design approaches and future trade-offs between lighter materials and larger size cars would be particularly important information if available.

2. Merged databases are currently available of both NSW's and Victorian police and injury data over the last 5 to 10 years containing over 100,000 records supplemented with vehicle make and model descriptors which would permit a more detailed analysis of the relationship between vehicle mass, size and safety Exposure control techniques are available to permit a degree of control of many of the confounding factors reported in several of the studies reviewed here

3. A cost-benefit study could be attempted of the likely effects of down-sizing and up-sizing the Australian vehicle fleet. While this analysis would entail a number of assumptions and predictions about future size trends, it could nevertheless highlight critical aspects of fleet size changes for the future. Such an analysis should not attempt to predict a single outcome but rather a range or matrix of possibilities to demonstrate these effects.

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