THE COMPATIBILITY OF MINI CARS IN TRAFFIC ACCIDENTS

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ABSTRACT

The compatibility problems of the mini car in car-to-car frontal collision and car-pedestrian accident are discussed using accident data and computer simulations.

In our analysis of the accident data in Japan, the number of fatalities was investigated using the vehicle masses and classes. It was found that the cars with identical mass are most compatible since the injuries per accident are minimal and injury risks to the driver in both cars are the same. The analysis of the car class indicated that the mini car and the sports utility vehicle are the most incompatible car types, with low and high aggressivity, respectively.

Our accident analysis in the present study shows that the safety of mini cars is the key point in achieving the compatibility in Japan. Computer simulations using MADYMO were carried out of crashes of mini car into a rigid wall and into a large car. It was found that either stiffening mini car with an optimized restraint system or modifying the large car with additional crush space can reduce the injury risk to the driver in the mini car.

The analysis of car-pedestrian accidents in Japan shows that the mini car has higher aggressivity in relation to the pedestrian than other bonnet-type cars. Computer simulation revealed that the head velocity of the pedestrian at impact is high since the pedestrian head contacts the body of the mini car in the early phase.

INTRODUCTION

In vehicle-to-vehicle collisions, the protection of all occupants in the subject and other vehicle should be considered. This compatibility problem was first discussed in connection with the Experimental Safety Vehicle (ESV) in 1970 and has not been solved yet. EC/EEVC has a leading responsibility for vehicle compatibility, which is one of the harmonized research activities of ESV [NHTSA 1996]. In the United States, the National Highway Traffic Safety Administration (NHTSA) has started a research program on this subject [Hollowell and Gabler 1996]. However, in Japan, there seems to have been little research on vehicle compatibility in the past decade. One reason is that it has been difficult to obtain accident data in Japan.

Thus, the Institute for Traffic Accident Research and Data Analysis (ITARDA), established in 1992, provides some accident data.

Compatibility means that passenger vehicles of disparate size provide an equal level of occupant protection in car-to-car collisions [NHTSA 1996]. The field data show there are many vehicles which are incompatible with other vehicles. This incompatibility is induced by the difference in the mass, stiffness, geometry and structure of both vehicles [Buzeman 1997]. An incompatible vehicle induces high injury risks for the occupants in the other vehicle, which can be defined as aggressivity. The influences of mass, stiffness and geometry are combined and have aggressivity to other cars.

One purpose of the present study is to identify the compatibility problems of car-to-car and car-to-pedestrian collisions in Japan based on the accident data using vehicle masses and classes. The compatibility problem should be examined for each country because the traffic environment differs in each country in terms of vehicle size, population, velocity, travel distance and the road environment.

In car-to-car collisions, the injury risk to the occupants in a mini car is high due to high delta-V and large intrusion based on its small mass and size. To achieve the compatibility of this type of a car, a low mass vehicle (LMV) with a mass of 600-650 kg and length of 2.5-3.0 m was proposed [Waltz et al. 1991; Kaeser et al. 1992, 1995; Frei 1997]. The front structure of a LMV is designed to be stiff in order to reduce the intrusion into the passenger compartment. As the acceleration of a LMV becomes high due to the stiff structure, it needs a specially designed restraint system to ensure the occupant's safety. Optimum restraint system was analyzed using the crash victim simulation program MADYMO [Kaeser et al. 1995; Muser et al. 1996]. However, this analysis was conducted only for a crash with a deformable barrier. The analysis of the compatibility in a car-to-car collision is necessary to show the injury-reducing effect of high stiffness and the optimized restraint system of a LMV.

The safety of the occupant of a small car in a car-to-car frontal collision has been investigated in many studies by a mathematical model. The force–deformation characteristics of both cars were examined in order to decrease the acceleration and deformation of the small car

using a simple spring-mass model [Ventre 1972, 1973; Appel et al. 1994; Tarrière 1994]. Finite element analyses of a car-to-car frontal collision were also conducted to describe the interaction of components of both cars [Maurer et al. 1996; Tarrière 1996]. These analyses of car-to-car collisions focused mainly on the car characteristics, and the model consists only of a vehicle without an occupant. Therefore, the influence of the car stiffness on the injury risk of the occupants by a combination of acceleration and intrusion in car-to-car frontal collision is not clear.

The compatibility of a mini car in a collision with a large car has to be achieved without increasing the injury risk to the driver of the mini car in a single-car crash. In the current study, the crash of a mini car into a rigid wall with full overlap, and the collision with a large car with a 50% overlap are simulated using MADYMO. The influences of front stiffness and the restraint systems of the mini car on the injury risk to the driver are studied to achieve the compatibility of the mini car in frontal collisions.

Since mini cars are mainly used in the city, car-pedestrian accidents are of great importance. The front geometry of the vehicle affects the pedestrian injury risk [Ishikawa et al. 1991]. Therefore the injury risk to the pedestrian struck by a mini car was examined by the analysis of the accident data and also computer simulation using MADYMO.

METHODOLOGY

Accident Analysis of Mini Car Crash

Distribution of Fatalities by Accident Type - The distribution of fatalities can be expressed for all types of accidents by fatalities related to the subject car [Appel 1996]. The fatalities can be distinguished as internal and external in relation to the car. Fatalities of the subject car in car-to-car collisions and in single car accidents are classified as internal fatalities, while those of other cars, motorcyclists, cyclists and pedestrians are classified as external fatalities. Fatalities in all types of accidents are estimated by the number of internal and external fatalities per registrations of the subject car.

Compatibility in Car-to-Car Frontal Collision - The goal of vehicle compatibility in car-to-car frontal collisions is to minimize the number of fatalities while the injury rates of the occupants in each car remain the same. Thus, in the current study to estimate compatibility in a car-to-car frontal collision, one method is employed to determine the total number of fatalities in both cars per accident when comparing the ratio of the fatalities occurring in each car.

To estimate the aggressivity in car-to-car frontal collisions, the following methods can be used:

1. (Number of fatalities in other cars) /(Number of fatalities in subject cars)

2. Percentage of fatalities in other cars

3. Number of fatalities in other cars per million subject car registrations

Methods 1 and 3 were suggested by Hollowell et al. [1996]. Using method 1, the aggressivity of a car without influence of human factors can be described. If the crash velocity of the subject car is high, the injury risk to the occupants in other cars as well as in the subject car is high. Thus, the influence of crash velocity on the aggressivity estimated by method 1 will be small. On the other hand, the aggressivity of the car including influence of crash velocity is estimated when the injury rate of the driver in the other cars is used in method 2. If the crash velocity of the subject car is high, the aggressivity obtained by method 2 will be higher because the number of fatalities in the other cars will increase. The aggressivity estimated by method 3 includes the effects of travel distances, vehicle velocities and accident rates, reflecting how they are used (Table 1.).

Table 1.
Effect of Crash Velocity and Accident Rate on Aggressivity Using Each Method

◀— Aggressivity

Other car   Subject car
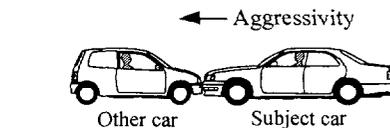
Method	Crash Velocity	Accident Rate
1	X	X
2	O	X
3	O	O

O = large effect   X = small effect

The method of examining aggressivity depends on the problem under investigation. For example, car manufacturers can use method 1 to estimate aggressivity of cars because this method is related to the car itself. Method 2, which includes the velocity effect, is usable in studies dealing with driver behaviors. Method 3 expresses the aggressivity of each registered car, so it can be used when insurance problems are investigated. In the current study, only method 1 is used to discuss the aggressivity of the car itself.

The law enforcement accident data for the four years from 1992 to 1995 were used. The analysis is conducted only for cars with a model year of 1988 or later. In the current research, cars are categorized in eight classes: mini, sedan A, sedan B, sedan C, sports & specialty, wagon, 1BOX and Sports Utility Vehicle (SUV). Only injuries to drivers are examined to simplify the analysis.

Computer Simulation of Mini Car Crash

Car Model - The car model used in the computer simulations is based on a currently produced mini car. Figures 1 and 2 present a model of a car used to simulate crashes into a rigid wall and large car. The mass of the mini car is 700 kg, which is slightly larger than the average mini car (639 kg; Mizuno et al. 1997), and the mass of the large car is 1400 kg.
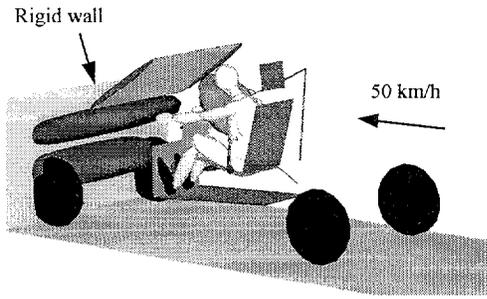

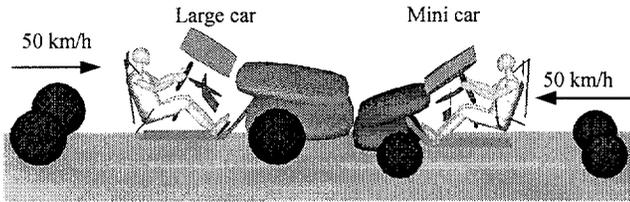**Figure 1. Simulation model of a mini car in a frontal crash into a rigid wall.**

Figure 2. Simulation model for a frontal collision between a mini car and a large car with a 50% overlap for mini car.

Car front structures are represented by the ellipsoids. In the current model, the force–deformation characteristics of the mini and large cars are approximated by a straight line. The regression of the stiffness of the car (k) is expressed using car mass (m) as follows [Ishikawa 1990]:

$$k = 78m^{1/3} \text{ (kN/m)}. \tag{1.}$$

Using Eq. (1), the stiffness of the current mini car (700 kg) is evaluated as 693 kN/m. The stiffness of the mini car is changed from 500 to 1000 kN/m in order to examine the effect of the stiffness in crashes into a rigid wall and into a large car. The stiffness of the large car (1400 kg) is calculated as 872 kN/m by Eq. (1), which is used in the simulation of a car-to-car collision.

In an offset crash, the damage profile of the car is classified into direct damage and induced damage. Due to the induced damage, the stiffness of the car in the offset crash increases by 30% per width of the car [Ishikawa 1995]. Thus, the front stiffness of the car in an offset

collision is estimated as:

$$k_{offset} = 1.3k \times (overlap\ ratio) \tag{2.}$$

where k_{offset} is the stiffness of the car in the offset crash and k is that in the full overlap crash. In car-to-car collisions, the forces acting on both cars have the same magnitude but a different direction. The deformation of each car is calculated using force–deformation characteristics according to this force.

According to Matsumoto et al. [1990], the intrusion of the firewall ($x_{firewall}$) can be approximated as:

$$x_{firewall} = 0.75(x - x_0) \tag{3.}$$

where x is the deformation of the car and x_0 is the car deformation when the engine contacts the firewall. The deformation x_0 of the mini car is smaller than that of the large car due to its small size. In the current model, x_0 is estimated as 0.175 m for a mini car and 0.350 m for a large car. Based on the experimental results (Figure 3.), the longitudinal displacement of the steering column ($x_{steering}$) can be expressed by the intrusion of the firewall ($x_{firewall}$) as:

$$x_{steering} = 0.772(x_{firewall} - 0.0566). \tag{4.}$$

In the model, the movements of the firewall and steering column are simulated as the displacement of translational joints based on Eqs (3) and (4). To express the intrusion of the firewall, the toe pan is designed to rotate first, and upon becoming perpendicular moves in the driver's direction.
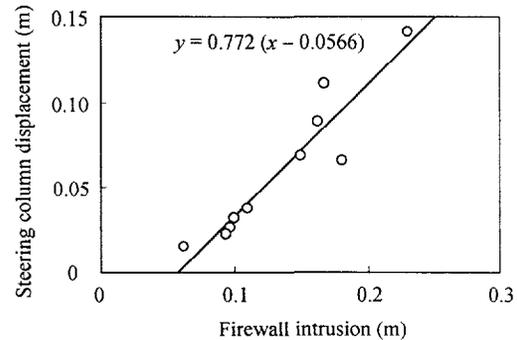

Figure 3. Relation between the firewall intrusion and longitudinal displacement of the steering column.

The HYBRID III database from MADYMO is used for the driver. The seat belt (10% webbing) and airbag (35*l*) is used for the basic restraint system for drivers in mini and large cars. This combination of restraint systems is commonly used in the current cars.

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Mini Car Crashes into Rigid Wall and Large Car -

The fatalities of the driver in single-car and head-on collisions account for a large portion of the driver fatalities in mini car accidents. Crashes into a rigid wall and car-to-car frontal offset collisions are representative of many cases of single-car and head-on collisions. In the present study, the simulations of the crash of the mini car into a rigid wall and the crash between mini and large cars with 50% overlap for the mini car were carried out.

According to the current regulation in Japan, the crash velocity of a mini car into a rigid wall is 40 km/h. In this simulation the crash velocity is put at 50 km/h, similar to the crash regulation of other types of cars. In the simulation of the car-to-car frontal collision, the crash velocity of each car is 50 km/h. The influence of the stiffness of the mini car on the injury risks to the driver in crashes into a rigid wall or a large car are examined. The injury criteria of the driver from the simulations are compared with threshold levels (HIC 1000, chest acceleration 60 g, chest deflection 0.075 m, femur force 10 kN).

Effect of Restraint Systems - The effects of restraint systems, including a seat belt force limiter, pretensioner (4 kN, 0.15 m), energy absorbing (EA) steering system (4 kN, 0.15 m), knee bolster and their combination, on the injury risk of the driver in a mini car are examined. The stiffness of the mini car is 1000 kN/m, which is larger than that of current mini cars to reduce the intrusion into the passenger compartment in a crash. The results are compared with those when a basic restraint system (airbag and seat belt) is used. The injury risks to the driver in the mini car in crashes into a rigid wall or a large car are studied when each restraint system or its combination is used with the basic restraint system.

Additional Crush Space of Large Car - When a large car has additional crush space designed for colliding with a mini car, the injury risk to the driver in the mini car may decrease. Tarrière et al. [1994] proposed a maximum force level 200 kN of a heavy car for compatibility with small car. Thus, in the present study, the additional crush length (c) of 0 to 0.4 m with a force level of 200 kN is simulated (Figure 4.) without changing the front length of the large car.
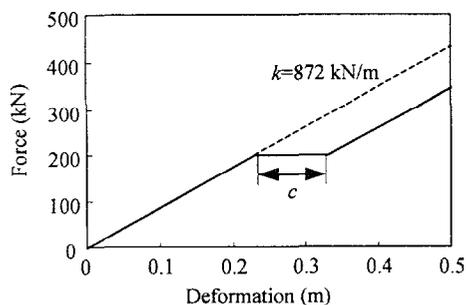
Car-Pedestrian Accidents

Accident Analysis - The compatibility in car-pedestrian accidents involves the mass, stiffness and geometry of the car. The car mass has little effect on a pedestrian injury because even the lightest car is much heavier than the pedestrian. The simulation demonstrated that the geometry of the car has a larger effect on the pedestrian injury than the stiffness [Ishikawa et al. 1991]. Thus, in order to clarify the influence of the geometry of the car, pedestrian accident data were examined in terms of car class since the cars have a similar geometry in the same car class.

Pedestrian accidents where the pedestrian was struck by the front of the vehicle were selected. To exclude the influence of impact speed of the vehicle, the accident data were used in which the velocity recognized to be dangerous was below 40 km/h. The velocity recognized to be dangerous is one of the items included among the accident data, which is defined as the velocity at the moment the driver perceives the danger of striking a pedestrian. It indicates the velocity before the driver brakes or steers to avoid the accident, and is compiled mainly from drivers' testimony. The distribution of the injuries according to the body region of the pedestrian were examined from accidents with fatal or severe injury to the pedestrian.

Simulation of Car-Pedestrian Accidents - Computer simulations using MADYMO were performed to examine the influence of vehicle geometry on the injury risk to the pedestrian (Figure 5.). Elderly people are frequently involved and injured in car-pedestrian accidents [Ishikawa et al. 1991]. Thus, the elder pedestrian model was made based on the average Japanese male aged 60 to 69, whose height and weight is 161.3 cm and 59 kg, respectively. The geometry, mass, moment of the inertia and center of the gravity of segments of this pedestrian model are generated by the GEBOD (Generator of Body Data). The joint characteristics and the stiffness of the ellipsoid of the pedestrian are based on the biomechanical data [Ishikawa et al. 1993; Yang 1998].
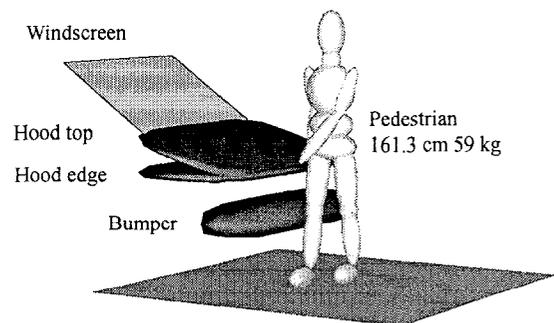

Figure 4. Additional crush space of a large car.

Figure 5. Pedestrian and vehicle model.

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Three vehicle models representing mini car, sedan B and 1BOX were made to evaluate the injury risk to the pedestrian for each car. In examining the influences of vehicle shape on the pedestrian struck by a car, the model was designed so that the same part of the vehicle would have the same force-deformation characteristics in three vehicles. The crash velocity of the car is 40 km/h.

In order to estimate the injury risk to the pedestrian, the injury parameters [i.e., the HIC, chest, pelvis and femur accelerations (3 ms)] of the pedestrian in crash were evaluated for three car models. The results of the simulation were compared with those of statistical analysis of pedestrian accidents.

RESULTS

Accident Analysis of Mini Car Crash

Distribution of Fatalities by Accident Type - From accident data in Japan, the distribution of fatalities was calculated. This distribution was examined by the number of fatalities internal and external to the subject car in various types of accidents. Figure 6 shows the number of fatalities in relation to the subject car per million registrations.
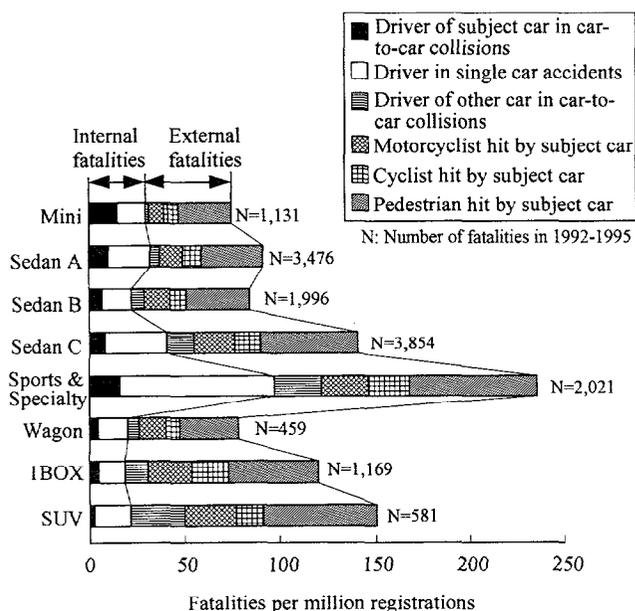

Figure 6. Internal and external fatalities of various subject cars for different types of accidents.

Sports & specialty, SUV, 1BOX and sedan C vehicles cause more external-type fatalities than any other type vehicles. SUV and sports & specialty car, in particular, cause the most fatalities in the other car in car-to-car collisions. Cyclists sustain more fatalities when struck by sports & specialty car and 1BOX vehicle, while more

pedestrians die from accidents involving sports & specialty car and SUV.

From the analysis of distributions of fatalities, it is found that the total number of fatalities of mini car is lowest, so this car type could be considered as most compatible vehicle. But this conclusion cannot be drawn because the mini cars are used for short-distance travel at a relatively low velocity [ITARDA 1996a] and also the frequency of driver internal fatalities in car-to-car collision is high. It is also necessary in the analysis of the compatibility to exclude the influence of factors which are not related to the car itself, such as driver behavior, car velocity and accident rate.

The number of fatalities in single car accidents involving sports & specialty cars is especially large, reflecting their higher crash velocity and accident rate compared to any other car classes. As a result, the number of fatalities involving sports & specialty cars is large for all types of accidents.

Compatibility in Car-to-Car Frontal Collision - Car mass is one of the most significant factors affecting driver injury in car-to-car collisions. It is well known that the fatality rate of the driver decreases with car mass. Evans [1993] found that the ratio of the injury rate in a lighter car to that in a heavier one may be expressed by the power ratio of the car mass of the heavier car to that of the lighter car. In the present study, the individual injury rate is expressed by average car mass ratio.

According to Joksch [1993], the injury rate R (%) can be expressed by delta-V (Δv) as:

$$R = |\Delta v / \alpha|^k \qquad (5.)$$

where α and k are parameters obtained by curve fitting. For many head-on collisions, delta-V is approximated for a central collision. Assuming the restitution coefficient is zero, the delta-V can be expressed using the average mass ratio as:

$$\Delta v_1 = \frac{m_2}{m_1 + m_2} v_c \qquad (6.)$$

where Δv_1 is the delta-V of car 1, v_c is a closing speed, and m_1 and m_2 is the mass of car 1 and 2, respectively. Substituting Eq. (6) for (5), the injury rate of driver 1, R_1, is given by

$$R_1 = \left| \frac{m_2}{m_1 + m_2} \frac{v_c}{\alpha} \right|^k = a \left(\frac{m_2}{m_1 + m_2} \right)^k \qquad (7.)$$

where $a = |v_c / \alpha|^k$. When Eq. (7) is applied to a real

accident, the probability of serious and fatal injury to the driver of car 1 can be calculated as shown in Figure 7. The parameters k and a are calculated for seat belt wearing and injury severity as shown in Table 2. Based on this method [Mizuno et al. 1997], the parameter k is obtained as 2.64 for belted drivers sustaining fatal and serious injury. This value is almost the same as the 2.62 shown by Evans [1994]. However, he calculated the injury ratio of belted car drivers in heavier cars to those in the lighter cars, and considered all directions of impact.
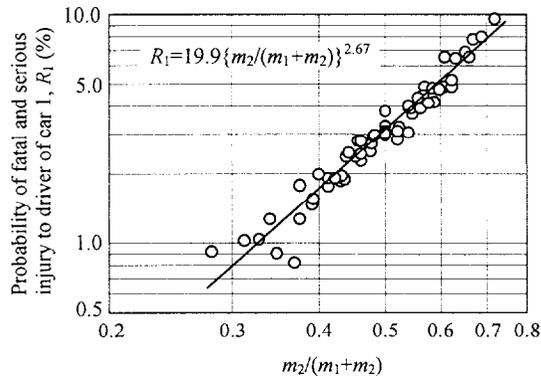

Figure 7. Average mass ratio and probability of driver injury in car 1 (Belted and unbelted driver).

Table 2.
Parameter k and a

Injury severity	Seat belt	k	a
Fatal and serious	Belted	2.64	13.9
	Unbelted	2.49	33.4
Fatal, serious, and minor	Belted	1.08	107.8
	Unbelted	0.955	123.5

The percentage of driver injuries in the subject car plus that in the other car corresponds to the driver fatalities per accident. From Eq. (7), we obtain

$$R_1 + R_2 = \frac{m_1^k + m_2^k}{(m_1 + m_2)^k} a .$$
(8.)

R_1+R_2 has a minimum as $2^{1-k} a$ ($k>1$) when $m_1 = m_2$. Thus, cars with equal masses are most compatible in a collision since the injuries per accident are minimal and the injury rate is equal for both cars.

The percentage of driver fatalities in the subject and other car is shown in Figure 8. As the mass of the subject car increases, the fatality rate of the driver in the subject car decreases; on the other hand, that of the driver in the other

car increases. The sum of the percentage of driver fatalities in the subject and the other car indicates the number of driver fatalities per accident where the subject cars are involved. When the car mass is 1150 kg, the number of fatalities per accident takes the minimum value, while the fatality rate of the subject car and that of the other car are almost the same. Then, the car with a mass of 1150 kg is considered most compatible in the current car population in Japan. The compatible car mass of 1150 kg is almost the same as the average mass of passenger cars in Japan, that is 1131 kg [Mizuno et al. 1997]. This is because there is a high possibility that the subject car with mass close to the average will crash into the other car with a small mass difference from the subject car.

When the mass of the subject car is in the range of 750 kg < m < 1350 kg, the number of fatalities per accident is small. However, when the subject car mass is less than 750 kg or greater than 1350 kg, the number of driver fatalities per accident increases. Thus, in order to decrease the total number of fatalities, it is necessary to design the lighter car so as to keep in mind the safety of the drivers in the subject cars, and to design the heavier car while keeping in mind the safety of the drivers in the other cars.
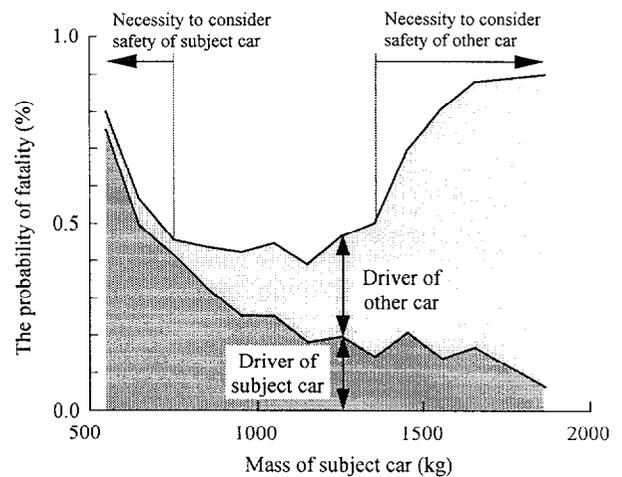

Figure 8. Car mass and the driver fatality of subject and other car in car-to-car frontal collisions.

Car classes have different mass, stiffness and geometry distributions. The effects of mass, stiffness and geometry are combined when the compatibility is analyzed by car class.

Figure 9 shows the number of driver fatalities in the subject and other car per thousand accidents. For SUV and 1BOX, the total number of driver fatalities is large and the proportion of the fatalities in other cars is large, so SUV and 1BOX can be considered incompatible cars. On the other hand, for mini cars, the number of fatalities in the

subject car is the largest in all car classes. Therefore, mini cars cannot be said to be compatible in car-to-car frontal collisions. The wagon and sedan B are compatible cars in car-to-car frontal collision because the proportion of the number of fatalities in the subject to that in other cars is almost the same, and the total number of fatalities in the subject and other cars per accident is small. However, the number of registrations of the incompatible car types such as SUV and 1BOX is increasing, while that of sedan B, a compatible car type, is decreasing [Mizuno and Kajzer 1997].
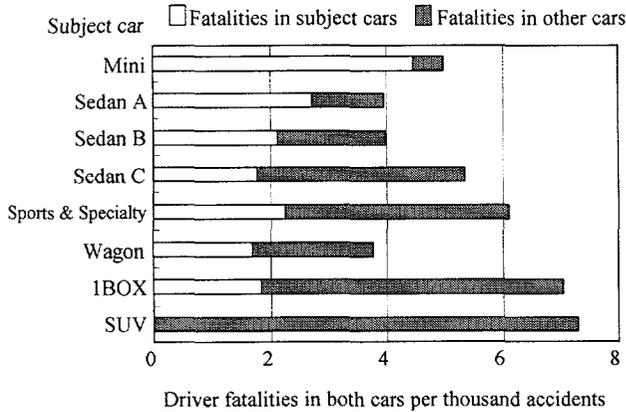
Figure 9. Car compatibility (N=531).

The aggressivity estimated by method 1 is shown in Figure 10. In this method, cars can be defined as aggressive when the aggressivity value is greater than one, because the number of fatalities in the other car is larger than in the subject car. Therefore based on Figure 10, the SUV, 1BOX, sedan C and sports & specialty can be described as aggressive. According to this analysis, the aggressivity ranking of the car itself is shown as:

Mini < Sedan A < Sedan B < Wagon
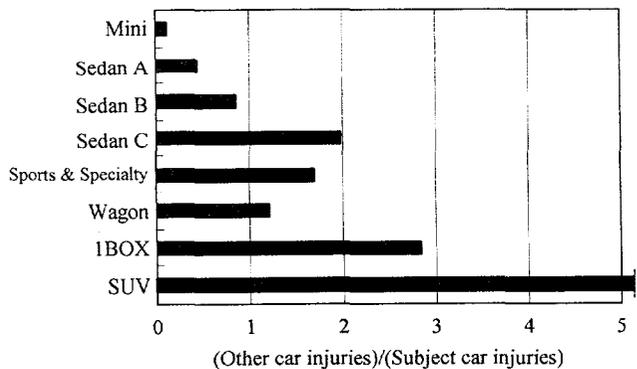< Sports & Specialty < Sedan C < 1BOX < SUV.

Figure 10. Car aggressivity calculated by method 1.

Computer Simulation of Mini Car Crash

Computer simulations of a crash of a mini car were performed in order to clarify the injury risk to the driver of mini car and to examine a compatible mini car.

Mini Car Crash into Rigid Wall - The crash of a mini car into a rigid wall at 50 km/h was analyzed in terms of different stiffness of the mini car (k). Figure 11 shows the variation of the acceleration, deformation of the car and the firewall intrusion with the stiffness of the mini car. The acceleration increases with the stiffness, while the deformation and the intrusion decrease. Thus when the stiffness increases, the driver is exposed to injury risk due to the high acceleration. On the other hand, when the stiffness decreases, the driver is exposed to injury risk due to the large intrusion.
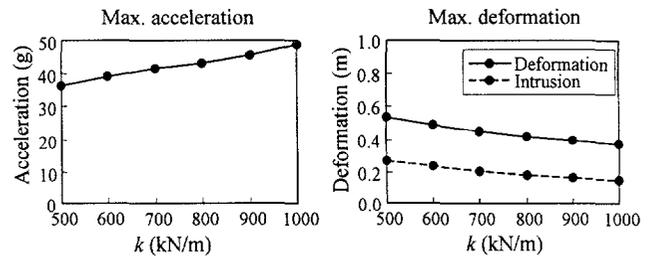
Figure 11. Maximum acceleration and deformation of mini car in crash into a rigid wall with varying stiffness of the mini car (k).

Figure 12 shows the driver behavior where the stiffness of the mini car (k) is 500 kN/m and 1000 kN/m, respectively. When the stiffness of the mini car is 500 kN/m, the intrusion is large but the acceleration of the car is small. As a result, the head and chest movement of the driver is less, but the foot rotation angle at 500 kN/m is greater than at 1000 kN/m.
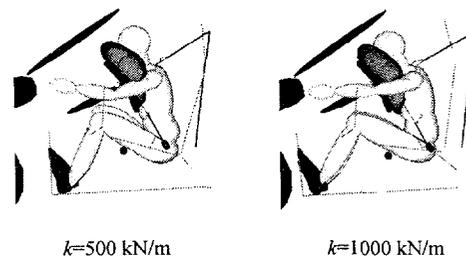
k=500 kN/m k=1000 kN/m

Figure 12. Kinematics of the driver in a mini car in a crash into a rigid wall (50 km/h).

Figure 13 shows the relation between the injury risk to the driver and the stiffness of the mini car (k). When k is lowest (500 kN/m), the HIC is 706, chest acceleration (3 ms) is 55.9 g and chest deflection is 0.042 m, all of which are less than the injury tolerance levels. The HIC and

chest acceleration increase consistently with the stiffness of the mini car. On the other hand, the chest deflection, femur force, tibia axial force and moment do not change so much with the stiffness of the mini car, and its level is less than the injury threshold. These results suggest that in a mini car crash into a rigid wall, the risk of injury to the driver decreases when the front stiffness is low.
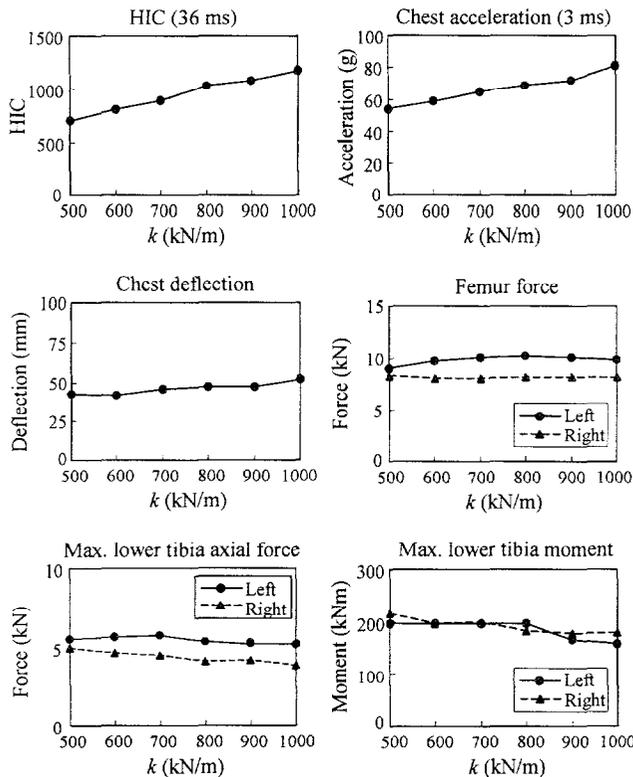

Figure 13. Driver injury risks in a crash into a rigid wall with varying stiffness of the mini car (k) (50 km/h).

The transition to serious injuries of the lower extremities (AIS 3 or more) appears when the intrusion exceeds 0.25 m [Morris et al. 1997]. As shown in Figure 11, the intrusion of the mini car firewall is less than 0.27 m in a crash into a rigid wall at 50 km/h. Therefore, in this type of crash configuration, the intrusion is a less important factor in determining the injury risk to the driver of a mini car, whereas the acceleration causes the majority of injuries.

Mini Car Crash into Large Car - Simulations of an offset frontal collision between mini and large cars were carried out. The overlap ratio of the mini car is 50% and that of the large car is 40%. Figure 14 shows the deformation of the car and intrusion of the firewall by the stiffness of the mini car (k). The acceleration level of the mini car in this type of crash is lower than in a crash into a rigid wall, whereas the car deformation and firewall intrusion of the mini car become large, especially when the

stiffness of the mini car is small. Thus, in this type of collision, the effects of the acceleration and intrusion are combined, and the risk to the driver of the mini car becomes high.

As can be seen in Figure 15, when the mini car is less stiff (k=500 kN/m), the steering column, instrument panel and toe pan intrude and hit the chest, knee and foot of the driver, respectively.
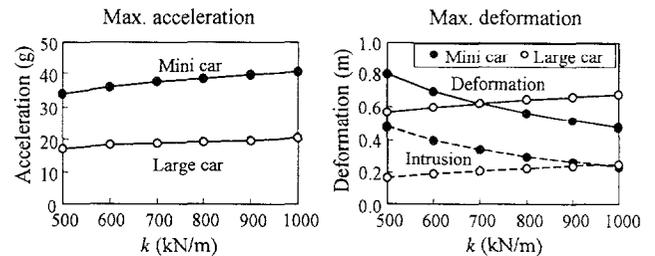

Figure 14. Maximum acceleration and deformation of mini and large cars in a car-to-car frontal collision with varying stiffness of the mini car (k).
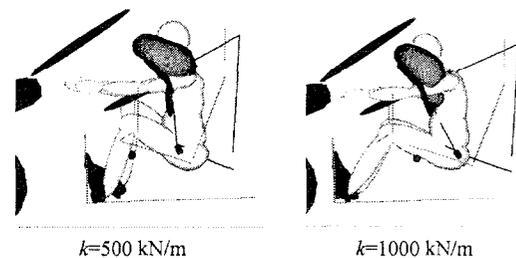

Figure 15. Kinematics of the driver in a mini car in a crash into a large car.

Figure 16 shows the variation of the injury risks to the drivers in mini and large cars with the stiffness of the mini car (k). When a comparison is made with Figure 13 and Figure 16, the HIC and chest acceleration of the driver in the mini car are lower in a crash with a large car than into a rigid wall, whereas the chest deflection, femur force, tibia force and tibia moment are higher. The chest deflection and tibia force are strongly affected by intrusion. Thus, in a crash of the mini car with a large car, the intrusion is an important factor in injuries. In addition, Figure 16 indicates that the injury risk of the driver in a mini car is higher than for the driver in a large car, irrespective of the stiffness of the mini car. This result corresponds to the findings from accident analysis that the injury risk to the driver in a mini car is high, while in a large car is low as shown in Figure 9.

When the stiffness of the mini car increases, there is a decrease in the risk to its driver as estimated on the basis of intrusion criteria such as chest deflection, maximum femur, tibia force and tibia moment. However, the HIC and chest acceleration of the driver in the mini car increase with the stiffness of the mini car because its acceleration becomes

high.

As the stiffness of the mini car increases, the risk of injury to the driver in a large car tends to become greater. When the stiffness of the mini car is high, the chest acceleration, chest deflection, femur and tibia forces of the driver in the large car increase because both acceleration and intrusion of the large car become high. Nevertheless, the risk of injury to the driver of the large car is less than that of the driver of the mini car, and even less than the tolerance level of the relevant injury criteria.
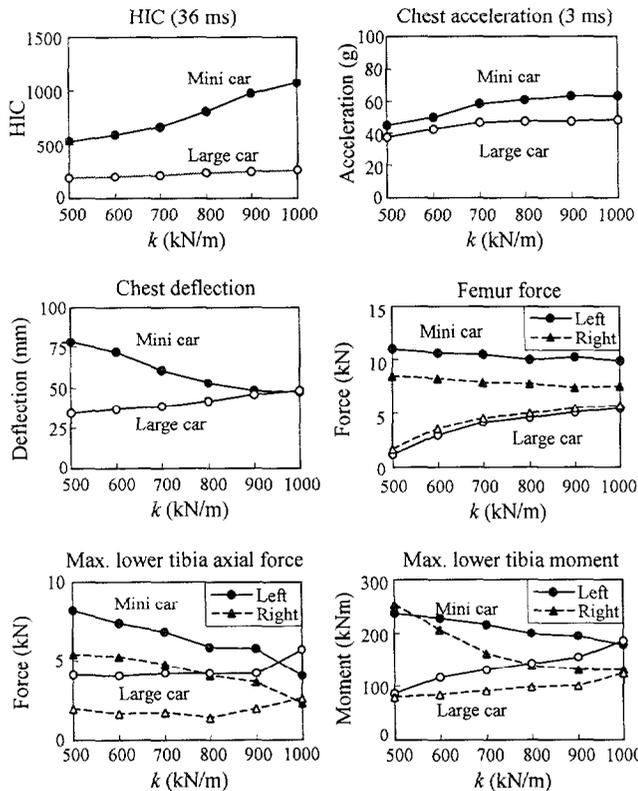

Figure 16. Driver injury risks in mini and large cars in a car-to-car frontal collision with varying stiffness of the mini car (k).

This analysis of collisions between mini and large cars demonstrates that the mini car should be stiff enough to prevent a large intrusion into the passenger compartment in a car-to-car frontal collision because greater intrusion means a higher risk of chest deflection and injury to the driver's lower extremities.

Effect of Restraint Systems - It is possible that the injury risk of the driver in mini car is reduced by the restraint system despite its high acceleration. In the current study, the stiffness of 1000 kN/m is applied for the mini car because the chest deflection, femur, tibia forces and tibia moment become low at this stiffness level as shown in Figure 16.

We evaluated the injury-reducing effect of the restraint systems (seat belt force limiter, energy absorbing

steering system, knee bolster and their combination) on the driver of the mini car, in comparison with the results when an airbag and seat belt are simulated as a basic restraint system.

Figure 17 and Figure 18 show the effect of restraint systems on the injury criteria of the driver of a mini car in crashes into a rigid wall and a large car, respectively. The
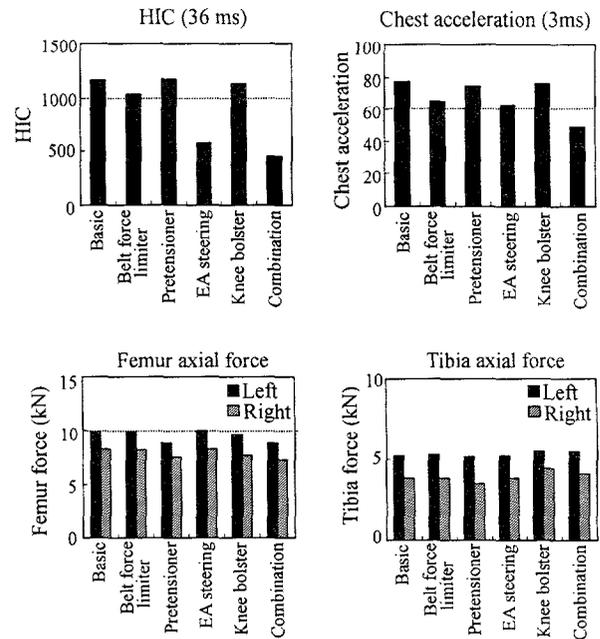

Figure 17. Effect of the restraint systems on the injury risks to the driver of the mini car in a crash into a rigid wall (k=1000 kN/m).
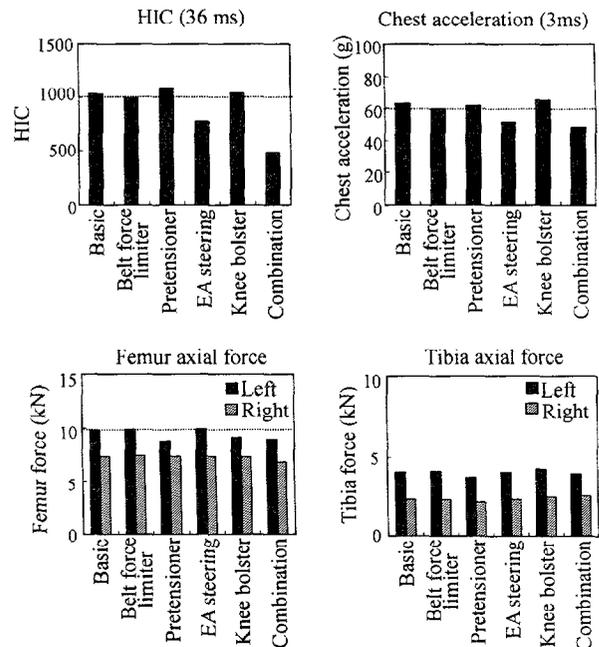

Figure 18. Effect of the restraint systems on the injury risks to the driver of the mini car in a collision with a large car (k=1000 kN/m).

injury-reducing effect of each restraint system for the driver of mini car differs between the two kinds of crashes. In the crash into the rigid wall, the seat belt force limiter effectively decreases chest acceleration and HIC by reduction of force transfer from the seat belt to the torso of the driver. Nevertheless, the force limiter has a small effect on the injury risks of the driver of the mini car in collision with a large car. In this type of crash, a large force is applied to the driver's chest by the steering wheel, not by the seat belt. Thus, the seat belt force limiter has a small effect on reduction of the chest acceleration in a collision with a large car.

The EA steering system is effective for both of the above-mentioned crashes. The movement of the steering column can decelerate the driver's head and chest by absorption of energy. The seat belt pretensioner reduces the femur force. The knee bolster also reduces the femur axial force, particularly in a crash with a large car. The restraint systems have little influence on the tibia force of the driver in a crash into a rigid wall or a collision with a large car. Thus, to reduce the tibia forces, the intrusion of the toe pan must be reduced.

When a mini car with high stiffness is equipped with restraint systems combining airbag, seat belt force limiter with pretensioner, EA steering system and knee bolster, the injury criteria levels for the driver are below the thresholds in either crashes into a rigid wall or a large car.

Additional Crush Space of Large Car - The additional crush space of the large car reduces the injury risk to the driver in the mini car due to reduction of acceleration and intrusion of the mini car in a collision. Figure 19 shows the chest acceleration, chest deflection, femur and tibia forces of drivers in the mini and large cars in terms of the length of additional crush space (c) of a large car (200 kN). The additional crush space reduces the chest acceleration and femur force of the driver in a mini car, when the stiffness of the mini car (k) is high. Particularly when k is small, the chest deflection and tibia force of the driver in the mini car decrease due to the small intrusion into the mini car, as the additional crush space of the large car increases. Therefore, the additional crush space of a large car has an injury-reducing effect on the driver of the mini car by reducing the acceleration and the intrusion of the mini car.

The chest acceleration of the driver in a large car decreases when the additional crush space of the large car is large due to the low acceleration of the large car. The chest deflection slightly increases by the additional crush space of the large car. The femur and tibia forces of the driver in the large car increase with the additional crash space of the large car, and have large values when the mini car is stiff. Thus, the analysis indicates that the additional crush space of the large car is effective in reducing injury risk to the

driver of the mini car. However, when the mini car is stiff, the risk to the driver in the large car, especially for injuries to lower extremities, becomes high.
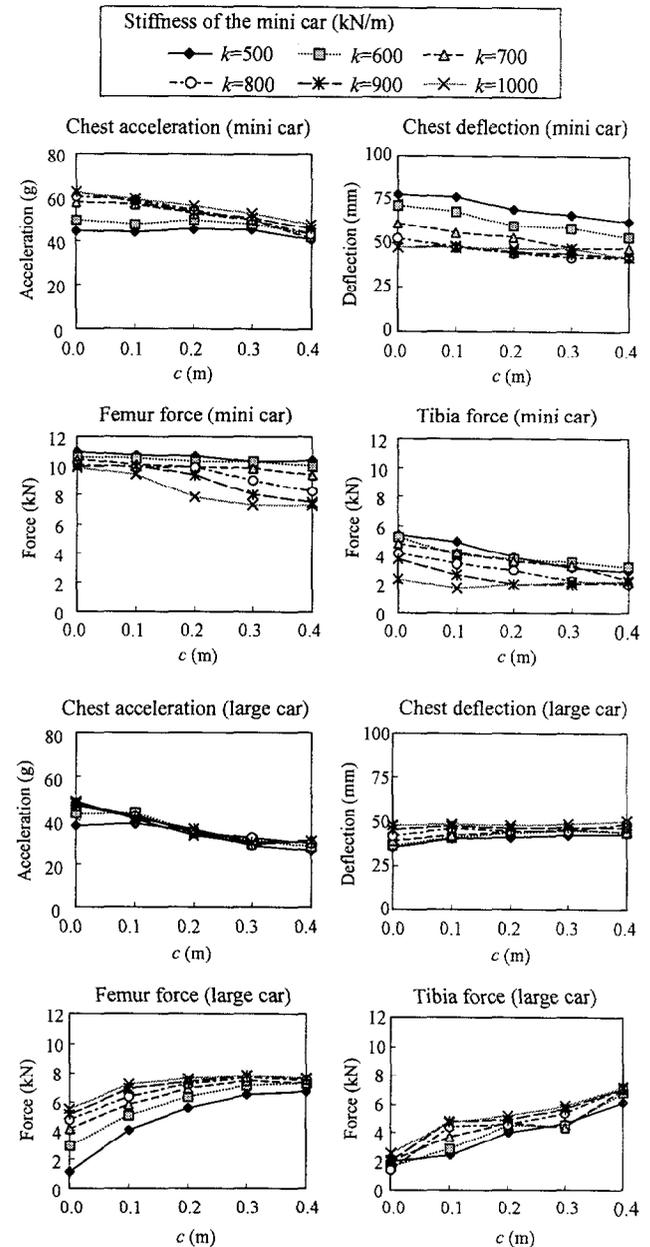

Figure 19. Driver injury risks in mini and large cars with the length of additional crush space (c) of the large car.

Car-Pedestrian Accidents

Accident Analysis - In car-pedestrian accidents, the vehicle geometry affects the injury risk to the pedestrian. Figure 20 illustrates the distribution of pedestrian injuries per thousand accidents by body region, injury severity and
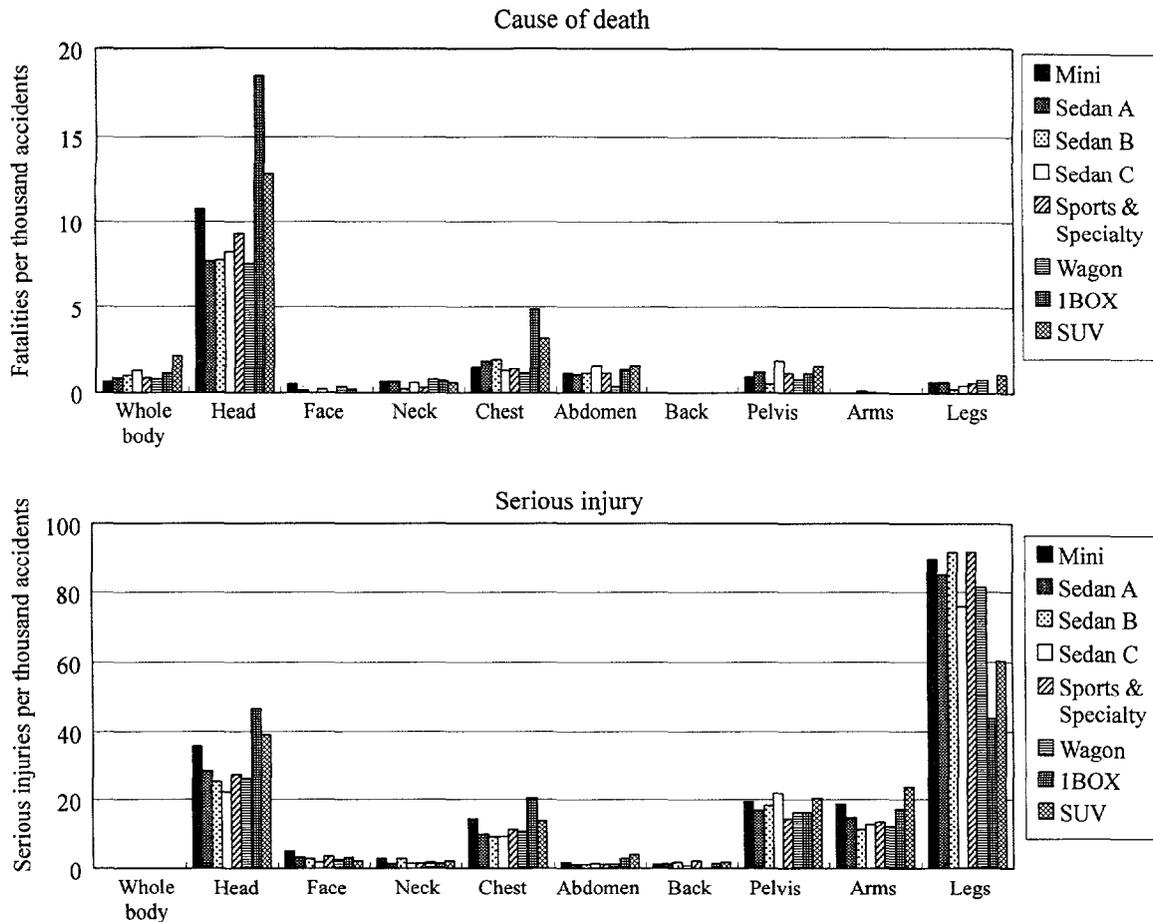
Cause of death

Serious injury

Figure 20. Distribution of pedestrian injuries per thousand accidents by body region, car shape and injury severity for the velocity recognized to be dangerous ≤ 40 km/h and pedestrian aged 13 or more (1994-1996).

car class. To exclude high-velocity collisions, especially between sports & specialty cars and a pedestrian, the velocity recognized to be dangerous was limited to 40 km/h or less.

The head is a dominant body region in fatalities for all car classes. The number of fatalities due to head and chest injuries is about two times larger for 1BOX than for bonnet-type cars (mini, sedan A, B, C, sports & specialty and wagon). In a serious injury, the number of head and chest injures which can be a cause of death is larger for 1BOX than for a bonnet-type car. Therefore, it is considered that the front shape of 1BOX is more aggressive for a pedestrian than that of a bonnet-type car. However, the shape of a bonnet-type car is aggressive in relation to pedestrian legs because the number of serious leg injuries is large in crashes with this type of car.

The risk of head injury to pedestrian when struck by a mini car is higher than for other bonnet-type cars. The SUV has a high aggressivity in relation to the head and chest of the pedestrian due to the height of the hood edge and bumper and the high stiffness of the vehicle body. As the

body front shape affects the distribution of pedestrian injuries, the modification of the shape of the car front can be effective to increase the compatibility between car and pedestrian.

Simulation of Car-Pedestrian Accidents - Computer simulations were carried out for crashes of mini car, sedan B and 1BOX with a pedestrian. Figure 21 shows the pedestrian kinematics when the head of the pedestrian contacts the vehicle body. The kinematics differs when the pedestrian is struck by vehicles with different front shapes.

When a pedestrian is struck by a mini car or sedan B, the bumper hits the leg and the hood edge hits the thigh, then the upper torso of pedestrian rotates toward the hood of the car. The pedestrian's head contacts the windscreen when hit by a mini car, and the cowl area when hit by sedan B. With a 1BOX vehicle, the whole body of the pedestrian is struck by the vehicle front almost at the same time. The chest contacts the upper part of the front panel, the head contacts the lower part of the windscreen, and then the whole pedestrian body is projected ahead of the vehicle. The pedestrian kinematics when struck by a vehicle is

influenced by the translational and rotational movement of the pedestrian. With a mini car and sedan B the rotational movement is dominant, while with a 1BOX the translational movement is dominant.
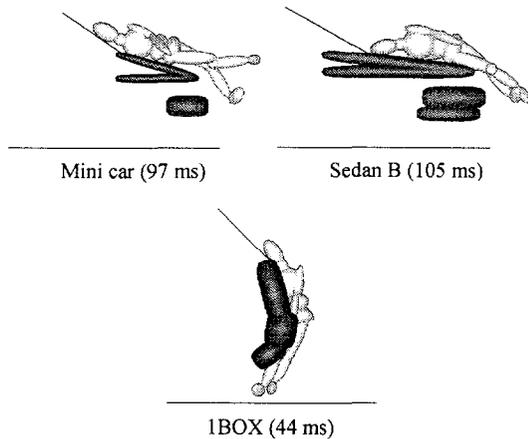

Mini car (97 ms)   Sedan B (105 ms)

1BOX (44 ms)

Figure 21. Pedestrian kinematics when the pedestrian head contacts the car body.

HIC is affected by the head resultant velocity at impact as well as the stiffness of the vehicle body area where the head makes contact. The time history of the head resultant velocity varies with vehicle shape. Figure 22 shows the head resultant velocity in relation to the respective car class. As shown in this figure, when the pedestrian is struck by a 1BOX, the head resultant velocity decreases consistently. When struck by the mini car and the sedan B, the head resultant velocity increases gradually due to the rotation of the upper body of the pedestrian, decreases gradually, and then drops abruptly after the pedestrian's head contacts the car body. For a mini car, the head contacts the windscreen in such an early phase that the head resultant velocity at impact is high.

The injury risk to the pedestrian body region differs with the shape of the car impacting it. The injury parameters of the pedestrian are HIC, chest, pelvis and thigh accelerations (3 ms) as shown in Figure 23. The HIC is the highest for sedan B due to the high resultant velocity at impact and the high stiffness of the cowl area where the pedestrian head makes contact. When the pedestrian is struck by a mini car, the HIC is lower than sedan B due to low stiffness of the windscreen. The chest and pelvis accelerations are highest when struck by 1BOX compared with other cars. The thigh acceleration is higher for sedan B and mini car than 1BOX. The distribution of injury risk to the chest and leg by car class agrees with those of real-world accidents (Figure 20.). However, in real-world accidents, the injury risk to the pedestrian head is highest when struck by a 1BOX, followed by a mini car and a sedan B. This differs from the simulation results.
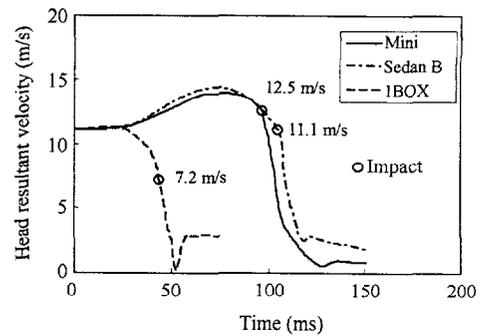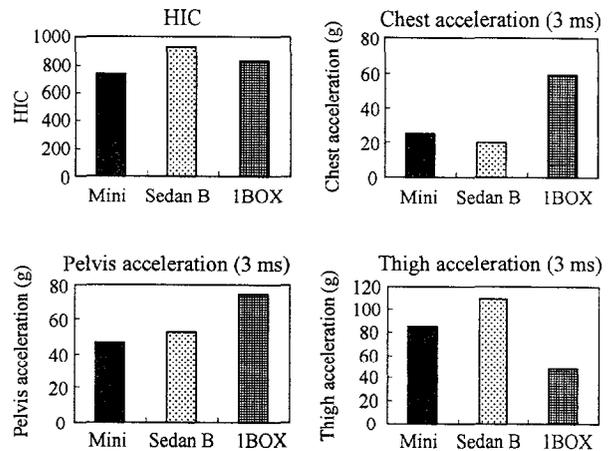

Figure 22. Head resultant velocity.

Figure 23. Injury risk to the pedestrian when struck by a car.

DISCUSSION

Mini Car Crash

The number of fatalities per registered mini car in real accidents is small, so the mini car may be considered compatible. However, in the method used in the present study, the injury risk to the driver in the mini car is underestimated since the accident rate and crash velocity of this type of car are low. When the injury risk to the driver is estimated by the probability of fatal injury, it is clear that the mini car is an incompatible car type because of the high fatality rate of the driver. Computer simulations of car-to-car frontal collisions also indicate that the injury risk to the driver in a mini car is far higher than in a large car.

This high injury risk to the driver of the mini car in a collision with a large car cannot be evaluated by the crash test into a rigid wall that is currently required by law. In a crash into a rigid wall, there is no influence of car mass on the injury risk to the driver and the influence of intrusion is small. However, in a collision with a large car, the driver of the mini car is at high risk of injury due to the high acceleration and large intrusion based on its small mass and size.

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Two methods are considered to reduce the injury risk to the driver of a mini car. The first is to stiffen the mini car. Since the acceleration of this car tends to be high, optimized restraint systems combining airbag, seat belt force limiter, pretensioner, EA steering system and knee bolster is necessary. The stiff front structure and special restraint systems of the mini car can directly reduce the injury risk of the driver. In this method, no modifications of the large car are necessary to reduce the injury risk to the driver in the mini car. However, the aggressivity of a stiff mini car should be considered not only in car-to-car frontal collision but also in other types of collisions, such as side and rear-end collisions. In a low-velocity crash in which the airbag should not deploy, the risk of minor injury to the driver in the stiff mini car may increase due to high acceleration.

The second method is to provide a large car with additional crush space designed for a crash with a mini car. It is possible that by reducing the acceleration and the intrusion of the mini car, the injury risk to the driver in the mini car would be reduced. Thus, in both cases, whether the mini car is less stiff or stiff, this additional crush space in a large car is effective to reduce the injury risk to the driver of the mini car. On the contrary, the additional crush space of the large car causes intrusion into the large car, so the injury risk to the driver of the large car, particularly to the lower extremities, increases, when the mini car is stiff.

Car-Pedestrian Accidents

The accident data obtained in the present investigation demonstrate that the pedestrian has a high risk of head injury when struck by a 1BOX or a mini car. In the simulation, when struck by a 1BOX and a mini car, the HIC of the pedestrian is not so high because the head contacts the windscreen. The average elderly pedestrian aged 60-69 was used for the model. In the real mini car-pedestrian accidents, the head may contact the stiff part of the car such as windscreen frame and cowl area when the stature of the pedestrian is shorter than average or the velocity of the mini car is less than 40 km/h. As the width of the mini car is small, there is a high risk of the pedestrian striking A pillar of the car, or to be thrown away from the hood to the ground. When struck by a 1BOX vehicle, the pedestrian will often sustain a head injury because of being thrown to the ground following impact.

The simulation results show that the HIC of the pedestrian is small when his or her head contacts the windscreen. The mini car should be safety-engineered by designing the vehicle configuration so that should it strikes a pedestrian any contact of the head will be with the windscreen, no matter how large or small the pedestrian and for a wide range of impact velocity.

CONCLUSIONS

Mini car compatibility issues were discussed for car-to-car frontal collisions and car-pedestrian accidents using traffic accident data in Japan and computer simulations.

The results of the accident analysis for car-to-car frontal collisions are as follows.
1. A car with mass of 1150 kg is considered most compatible among the current car population in Japan. This compatible car mass coincides with the average mass of cars in Japan.
2. The SUV and mini car are the least compatible car types, with high and low aggressivity in relation to other cars, respectively.
3. Sedan B and wagon type cars are considered compatible. The proportion of the number of fatalities in the subject cars to that in other cars is almost the same, and the total fatalities in the subject and other cars are few.

Simulations of the safety of the driver in a mini car were performed using MADYMO for crashes into a rigid wall and into a large car. The following conclusions were obtained:
4. The crash test of a mini car into a rigid wall is insufficient to assure safety in a crash into a large car. This is because in a crash into a rigid wall the acceleration greatly influences the risk of injury to the driver of a mini car, whereas in a crash with a large car the effect of intrusion as well as acceleration is large.
5. The combination of the restraint systems in conjunction with high stiffness of the mini car provides good protection for the driver in either crashes into a rigid wall or a large car.
6. When a large car has additional crush space, it is effective for reduction of the injury risk to the driver in the mini car. However, if the mini car is stiff, the driver of the large car risks chest and leg injury due to the intrusion into the large car.

The accident analysis and simulation of pedestrian accidents were carried out. It is concluded that:
7. Incompatibility of the car geometry with a pedestrian has a large effect on the distribution of pedestrian injuries. Accident data show high injury risk to the pedestrian when struck by a mini car. These data could not be reproduced by computer simulation where a pedestrian is impacted only by the car without considering the head impact with the ground.

REFERENCES

Appel, H., Ni, J., and Deter, T., "Grenzen der Passive Sichrheit von leichten Fahrzeugen". VID Berichite NR. 1134. 1994. pp. 235-238.

Appel, H., "Compatibility Guideline for Passive Safety, for Active Safety and Even for the Total Transportation System". FISITA1996. 1996.

Buzeman D. G., "Car-to-Car and Single Car Crash Compatibility: Individual Effects of Mass, Structure, Stiffness and Geometry". Thesis for the Degree of Licentiate of Engineering, ISBN 91-7197-536-5, Chalmers University of Technology, 1997.

Evans, L., "Driver Fatalities Versus Car Mass Using a New Exposure Approach". Accident Analysis & Prevention. Volume 16. 1984. pp. 19-36.

Evans, L. and Frick, M. C., "Mass Ratio and Relative Driver Fatality Risk in Two-Vehicle Crashes". Accident Analysis & Prevention. Volume 25. 1993. pp. 213-224.

Evans, L., "Driver Injury and Fatality Risk in Two-Car Crashes Versus Mass Ratio Inferred Using Newtonian Mechanics". Accident Analysis & Prevention. Volume 26. No. 5. 1994, pp. 609-616.

Frei, P., Kaeser, R., Hafner, R., Schmid, M., Dragon, A., Wingeier, L., Muser, M. H., Niedere, P. F., Waltz, F. H., "Crashworthiness and Compatibility of Low Mass Vehicles in Collisions". SAE Paper 970122. 1997.

Hollowell, W. T., Gabler, H. C., "NHTSA's Vehicle Aggressivity and Compatibility Program". 15th ESV 1996.

IRF, "World Road Statistics". Geneva. International Road Federation. 1995.

Ishikawa, H., Yamazaki, K., Ono, K., Sasaki, A., "Current Situation of Pedestrian Accidents and Research into Pedestrian Protection in Japan". 13th ESV. 1991.

Ishikawa, H., "Kinematics of Automobile Collision — Analytical Formulas for One-Dimensional Impact". Journal of JARI. Volume 12. 1990. pp. 25-32 (in Japanese).

Ishikawa, H., Kajzer, J., Schroeder, G., "Computer Simulation of Impact Response of the Human Body in Car-Pedestrian Accidents". SAE Paper 933129, 1993.

Ishikawa, H., Digges K., Ennis, J., "Restitution Coefficients and Delta-V in Offset Frontal Collisions". Proceedings of JSAE Autumn Convention. 1995 (in Japanese).

ITARDA, "The Relation between Traffic Accidents, Driver and Vehicle", Research Report 1996a (in Japanese).

ITARDA "Report of Accident Investigation and Analysis in 1996". 1996b (in Japanese).

Joksh, H. C., "Velocity Change and Fatality Risk in a Crash – A Rule of Thumb". Accident Analysis & Prevention Volume 25. 1993. pp. 103-104.

Kaeser, R., Walz F. H., and Brunner, A., "Collision Safety of a Hard Shell Low Mass Vehicle". IRCOBI 1992.

Kaeser, R., Muser, M., Spiess, O., Frei, P., Guenat J., M., and Wingeier, L., "Passive Safety Potential of Low Mass Vehicles". IRCOBI 1995.

Matsumoto, H., Sakaida, M., Kurimoto, K., "A Parametric Evaluation of Vehicle Crash Performance". SAE Paper 900465. 1990.

Maurer, D., Thompson, G., M., Muller, R., Graffe, M., Weyersberg, A, "Safety Concepts for Very Small Vehicles, Example: Opel MAXX". 15th ESV. 1996.

Mizuno, K., Umeda, T., Yonezawa, H., "The Relationship Between Car Size and Occupant Injury in Traffic Accidents in Japan". SAE Paper 970123, 1997.

Mizuno, K., Kajzer, J., "The Compatibility Problems in Collisions Analyzed Using Accident Data". Proceedings of JSAE Spring Convention. 1997.

Morris, A., Thomas, P., Taylor A. M., Wallace, W. A., "Mechanisms of Fractures in Ankle and Hind-Foot Injuries to Front Seat Car Occupants". SAE Paper 973328. 1997.

NHTSA, "Report on International Harmonized Research Agenda", Proceedings of 15th ESV. 1996.

Sakurai, T. and Aoki, T., "On the Safety Body Structure of Finite Element Method Analysis". 12th ESV. 1989.

Tarrière, C., "Accident Research and Experimental Data Useful for an Understanding of the Influence of Car Structural Incompatibility on the Risk of Accident Data". 14th ESV. 1994.

Tarrière, "Compatibility Issues and Vulnerable Uses". Crashworthiness of Transportation Systems: Structural Impact and Occupant Protection. Kluwer Academic Publishers. 1997. pp. 139-170.

Ventre, P., "Homogeneous Safety Amid Heterogeneous Car Population". 3rd ESV. 1972.

Ventre, P., "Proposal for Test Evaluation of Compatibility Between Very Different Passenger Cars". 4th ESV. 1973.

Waltz, F., H., Kaeser R., and Nieder, P., "Occupant and Exterior Safety of Low Mass Cars (LMC)". IRCOBI 1991.

Yang, J., "Injury Biomechanics in Car-Pedestrian Collisions". Doctoral thesis. ISBN 91-7197-527-6. Chalmers University of Technology. Göteborg. 1997.