A COMPARATIVE ANALYSIS OF VEHICLE-TO-VEHICLE AND VEHICLE -TO-RIGID FIXED BARRIER FRONTAL IMPACTS

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ABSTRACT

The relationship between designing for both rigid fixed barrier (RFB) and vehicle-to-vehicle tests is a topical area of research. Specifically, vehicle-to-vehicle compatibility has been a topic of keen interest to many researchers, and the interplay between the two aspects of design is presently addressed.

In this paper, the studied vehicles for potential vehicle-to-vehicle impacts included: sport utility vehicles (SUVs), Pickups (PUs), and passenger cars. The SUV/PU-to-Car frontal impact tests were compared to those obtained from vehicle-to-rigid fixed barrier frontal impacts. Acceleration pulses at the B-pillar/rocker as well as dash and cabin intrusions were monitored and compared. Additionally, the energy distributions in SUV/PU-to-Car crash tests were compared to those of single vehicle-to-RFB tests.

It was concluded from the analysis that vehicle weight and front-end stiffness were not always the overriding factors dictating performance. Design alternatives that have positive impact on the distribution of energy on both vehicles involved in a crash were shown to provide improvement in vehicle compatibility. In the present work, it was also shown that good geometrical interaction in SUV/PU-to-Car impact was fundamental in providing self and partner risk-reducing potential. Moreover, the effect of geometry was shown to possibly mask the effects of mass and stiffness.

1. INTRODUCTION

Improvement in occupant risk-reducing potential and vehicle crashworthiness has traditionally been studied and addressed through a well-defined laboratory crash test procedures. Examples of such procedures include regulated full-frontal vehicle-to-rigid fixed barrier testing conducted by the National Highway Traffic Safety Administration (NHTSA) in the United States, Transport Canada in Canada, the Federal Office of Road Safety (FORS) in Australia, and the Ministry of Transport in Japan. Similar crash testing, but at a higher speed, is used in the New Car Assessment Program (NCAP) which serves to provide consumer safety information via a star ratings system (which represents various levels of attendant life-threatening combined head-chest injury potential).

Full-frontal rigid fixed barrier crash tests are used to evaluate the performance of restraint systems and safety devices. These devices may or may not provide the same level of risk-reducing potential to the occupants in SUV/PU-to-Car impacts as observed in real-world accidents [1]. This is mainly due to cabin intrusions caused by incompatibility between vehicles on the road, especially in the case of a SUV impact with a passenger vehicle. Serious injury and fatalities have been reported in conjunction with cabin intrusions [2]. Cabin and windshield intrusions observed in SUV/PU-to-Car crashes are generally not observed in controlled vehicle-to-rigid fixed barrier impacts. Therefore, a different structural design philosophy needs to be introduced in order to reduce injuries related to vehicle intrusions subject to the development of a front-end structure capable of dissipating crash energy in both vehicle-to-rigid fixed barrier and SUV/PU-to-Car impacts. Clearly, the distribution of stiffness and the force levels by which a vehicle's front-end components can absorb kinetic energy are important factors.

In most cases, vehicle development for front impact is concentrated on vehicle occupant protection without considering partner protection in SUV/PU-to-Car impact. Moreover, developments in frontal and side impact research are taking place with little interaction. For instance, improved occupant performance in frontal impact through higher stiffness of the front-end structure may have a trade off effect in side impact [3]. Therefore, it is very important to consider interactions between different crash configurations to ensure both self as well as partner protections.

The work described in this paper provides a comparative analysis of the vehicle structural performance obtained from vehicle-to-rigid fixed barrier and SUV/PU-to-Car impacts. A series of full-frontal SUV/PU-to-Car and vehicle-to-rigid fixed barrier crash tests, in conjunction with a series of full-scale finite element simulations were carried out in this study to support the comparative analysis. The comparative analysis in this paper was intended to provide a basis for possible future improvements, e.g., an upgrade to current test procedures, development of a complementary test to that specified in FMVSS 208, or a new design approach.

2. OBJECTIVES

The main objective of this work was to provide a comparative summary of results obtained from the frontal rigid fixed barrier and SUV/PU-to-Car crash tests. Results for a reference (Target) vehicle, in terms of crash deceleration pulse at B-pillar/rocker, dash and cabin intrusions, lower tibia index, and crash energy measurements were used in the comparison. The secondary objective was to identify the effect of vehicle design imbalances in SUV/PU-to-Car impact on the toe-board intrusions and energy management in the reference vehicle. The final objective was to recommend design actions to manage the crash energy in SUV/PU-to-Car impacts without performance degradation in related single-vehicle rigid fixed barrier tests.

3. FULL-SCALE CRASH TEST MATRIX

Table 1 shows the selected vehicles and their associated weight used in both vehicle-to-rigid fixed barrier and SUV/PU-to-Car impacts. The reference vehicle used for rigid fixed barrier impact was selected to be the struck vehicle in SUV/PU-to-Car impact for structural performance evaluation. The reference vehicle was a four-door sedan representing an average mid-size passenger vehicle in the fleet.

Table 1.

Vehicle Description and Weight

Frontal Impact Test	Striking Vehicle	Bullet Vehicle Test Weight	Target Vehicle Test Weight
Unit		kg	kg
50 Kph Rigid Fixed Barrier	-	-	1775
57 Kph Rigid Fixed Barrier	-	-	1776
Vehicle-to-Vehicle	Sport Utility (SUV I)	2132	1863
Vehicle-to-Vehicle	Pickup (PU)	2127	1778
Vehicle-to-Vehicle	Sport Utility (SUV II)	2694	1777

Two sport utility vehicles and a Pickup, viz., SUV I, SUV II, and PU, with different mass, stiffness and geometry were selected for the striking vehicles in SUV/PU-to-Car impacts. For the remainder of the text, the striking vehicle is referred to as the bullet vehicle (B).

3.1 Vehicle-to-Rigid Fixed Barrier Impact Tests

Two RFB crash tests that presently exist in the vehicle design process include: (1) FMVSS 208 with belted mid-sized male, instrumented test dummies, and (2) The USA NCAP test involving belted mid-sized male, instrumented test dummies. The FMVSS 208 test is conducted at 48 kph while the USA NCAP is conducted a 57 kph.

Typical velocity changes, ΔVs, that the occupants undergo in FMVSS 208 and NCAP crash tests, are 48 kph and 57 kph, respectively (neglecting the rebound velocities). The restraint system is designed to handle such changes in velocity. Two rigid fixed barrier crash tests were conducted with the target vehicle at 50 kph and 57 kph. The kinetic energy of the vehicle impacting the rigid fixed barrier was mainly absorbed by the vehicle structural deformation and the restraint system. It should be noted that the height from the ground of the bumper and front rail has negligible effect on the vehicle structural performance and energy management during a rigid fixed barrier impact. However, it may have a significant effect in SUV/PU-to-Car impacts.

3.2 SUV/PU-to-Car Impact Tests

US cars and light trucks are designed to 57 kph rigid fixed barrier impact (NCAP) for belted occupants. Therefore, relatively low occupant response rates are expected in real-world collisions up to 57 kph fixed barrier equivalent velocities. In the test configuration shown in Figure 1, the target vehicle was initially at rest in all of the SUV/PU-to-Car tests carried out in this study. The bullet vehicle's velocity was selected based on the relative masses involved, i.e., the bullet vehicle impact velocity was mass-adjusted to result in a 57 kph barrier-equivalent velocity for the target vehicle. Lighter vehicles generally experience higher velocity changes, ΔVs, while heavier vehicles experience lower ΔVs in SUV/PU-to-Car impacts. The initial speed of the bullet vehicle ranged from 92.3 kph to 95 kph. The induced velocity changes in the target vehicle ranged from 50 kph - 57 kph. The velocity changes in both the bullet and target vehicles could be calculated either from the basic momentum conservation or from velocity time histories obtained from tests.

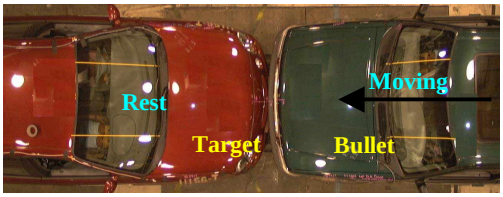


Figure 1. SUV/PU-to-Car test configuration.

Table 2 shows the initial impact velocity, mass ratios, and velocity changes for all of the rigid fixed barrier and SUV/PU-to-Car crash tests conducted in this study.

Table 2.
Impact Speeds, Mass Ratios, and Velocity Changes

Frontal Impact Test	Initial Velocity		Mass Ratio	Velocity Change	
	Target	Bullet	Bullet/Target	Target	Bullet
Unit	kph	kph		kph	kph
Car-to-Rigid Fixed Barrier	50	-	-	49.6	-
Car-to-Rigid Fixed Barrier	56.7	-	-	56.7	-
SUV I-to-Car	0	94.9	1.14	50.6	44.2
PU-to-Car	0	101.6	1.20	55.3	46.3
SUV II-to-Car	0	92.2	1.52	55.5	36.6

Selection of bullet vehicles was based on providing different levels of mass, front-end stiffness, and bumper/rail heights. In SUV/PU-to-Car impacts, the effect of geometry can mask the effect of mass and stiffness, due to override or underride. Figure 2 shows the geometrical alignment, in terms of bumper heights, of the three bullet vehicles compared to the target vehicle. Table 3 provides bumper heights in (mm) for the bullet vehicles. These heights were measured from the center of the bumper of each bullet vehicle relative to the center of the bumper for the target vehicle. In other words, the reference point was the bumper center height of the target vehicle.

Table 3.

Relative Bumper Heights

Frontal Impact Test	Relative Bumper Height (mm)
Car-to-Rigid Fixed Barrier	-
Car-to-Rigid Fixed Barrier	-
SUV I-to-Car	94.0
PU-to-Car	116.8
SUV II-to-Car	12.7

SUV I-to-Car **PU-to-Car** **SUV II-to-Car**

Figure 2. Geometrical differences between bullet and target vehicles.

In all the SUV/PU-to-Car tests, both the bullet and target vehicles used a Hybrid III 50th percentile, male dummy in the driver mid position and a Hybrid III 5th percentile, female dummy in the passenger full forward position. All the dummies were belted and the airbags were active.

4. TEST RESULTS AND DISCUSSIONS

The safety performance of the restrained occupants as measured in rigid fixed barrier impact was dependent on several parameters, which included:

- The crash pulse and the design of the restrained system,
- The intrusions and the structural integrity of the vehicle cabin, and
- The energy management performance of the energy absorbing elements such as the front rail or frame.

It should be acknowledged that a passenger car whose structural design was specifically tailored to achieve high performance in a rigid fixed barrier impact might not necessarily perform as well in a SUV/PU-to-Car impact. That same passenger car might be subjected to both increased levels of intrusion and energy management in a SUV/PU-to-Car impact. The following sections provide the discussion and comparison of the target vehicle performance only, in terms of crash pulse, intrusions and crash energy management, between the rigid fixed barrier and SUV/PU-to-Car impacts.

4.1 Vehicle Deceleration Pulse Comparison

In vehicle crashworthiness, vehicle deceleration pulse, measured at B-Pillar/rocker, during a crash is generally considered to be an important characteristic of vehicle safety performance. However, the

characteristics of the time history of the crash pulse for the target vehicle at a certain ΔV may vary with the crash modes. In a target vehicle-to-rigid fixed barrier impact, the crash pulse depends only on the inherent front-end stiffness and structural design. While in SUV/PU-to-Car impact, it also depends on the structural stiffness, mass, and geometry of the bullet vehicle. Front-end design of a vehicle, which achieves better performance during a full-frontal crash into a rigid fixed barrier, can be less effective during SUV/PU-to-Car impact.

Figures 3 and 4 show the comparisons of the deceleration pulse of the target vehicle obtained from various rigid fixed barrier tests and SUV/PU-to-Car tests as listed in Table 1.

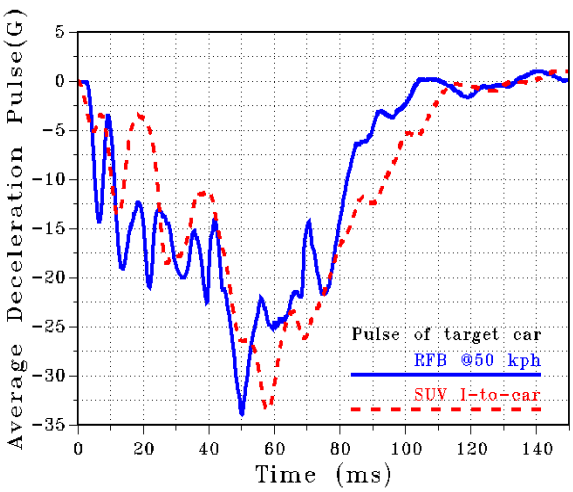


Figure 3. Comparison of crash pulse in a passenger car obtained from rigid fixed barrier and SUV I-to-Car impacts (50 kph velocity change).

In order to eliminate the effect of the velocity change, ΔV, on the deceleration pulse characteristics, the crash pulse of the target vehicle obtained from 50 kph rigid fixed barrier test was examined against that obtained from SUV I-to-target impact test which induced a 50 kph velocity change in the target vehicle. The crash pulse comparison of these two tests is shown in Figure 3. Similarly, the 56.7 kph crash pulse from the NCAP test was examined against those obtained from Pickup-to-target vehicle and SUV II-to-target vehicle impact tests that generated a 56.7 kph barrier equivalent velocity in the target vehicle. This comparison is shown in Figure 4.

As shown in Figures 3 and 4, and in the case of SUV/PU-to-Passenger car impacts, the target vehicle experienced a lower deceleration level early in the collision (up to 40 ms) and a higher deceleration later in the collision compared to that observed in rigid fixed barrier impact. This was due to the fact that in full-frontal rigid fixed barrier impact, at either 50 kph or 56.7 kph, the energy absorbing elements of the target vehicle's front-end fully engaged with the rigid fixed barrier at 40 ms. This leads to a progressive dissipation of the crash energy (kinetic energy) through a progressive and controlled deformation of the front-rails exhibited by the front-end stiffness of the target vehicle only. However, in SUV/PU-to-target vehicle impacts, the energy dissipation within the first 40 ms shared by the target vehicle was much less compared to that in rigid fixed barrier impact. The target vehicle front-end stiffness had little effect on the pulse outcome due to partial or minimum engagement with the bullet vehicle at 40 ms.

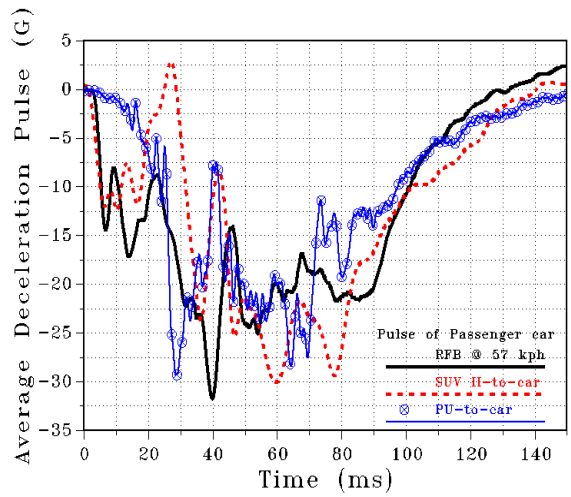


Figure 4. Comparison of crash pulse in a passenger car obtained from rigid fixed barrier and SUV II/PU-to-Car impacts (57 kph velocity changes).

In the case of the PU-to-target vehicle impact, as shown in Figure 4, there was a clear evidence that the Pickup overrode the target vehicle due to incompatible geometries (Table 3). This led to a very low level of the deceleration pulse early in the collision. The front-end stiffness effect of the target vehicle was almost negligible within the first 20–25 ms since there was no engagement of the front-end.

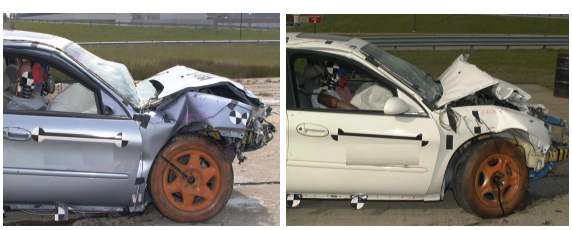
After 40 ms, the bullet vehicle was close to having full engagement with the target vehicle in all the three SUV/PU-to-Car impact tests. The deceleration pulses of the target vehicle appeared to be similar, but higher, compared to that in rigid fixed barrier impact. This was due to the lighter (target) vehicle experiencing a higher level of both velocity change and deceleration compared to the heavier (bullet) vehicle. In conclusion, the deceleration pulse of the target vehicle in SUV/PU-to-Car impacts

appeared to be similar to that in rigid fixed barrier impact in terms of peak amplitude and time to peak.

4.2 Overall Deformation and Intrusion Comparison

For a full-frontal rigid fixed barrier impact, intrusions are of secondary importance compared to the crash pulse, which is generally considered to be an important factor in the occupant response outcome. However, both the crash pulse and intrusions are of comparable importance in occupant response outcome in SUV/PU-to-Car impact. A similar level of occupant risk-reducing potential in a target vehicle can be achieved in rigid fixed barrier and SUV/PU-to-target vehicle impacts, if the intrusions in the target vehicle are assumed the same. Post-crash static intrusion measurements in SUV/PU-to-target vehicle impacts indicated that cabin intrusions in the target vehicle were considerably greater than those measured in a target vehicle-to-rigid fixed barrier impact. Therefore, a SUV/PU-to-Car or similar impact test [4] might be a suitable test protocol to complement the full-frontal rigid fixed barrier impact test. This additional test will evaluate vehicle design to provide occupant protection and cabin structural integrity in single and multi-vehicle crashes.

(a) Rigid Fixed Barrier (b) SUV I-to-Car



(c) PU-to-Car (d) SUV II-to-Car

Figure 5. Overall, deformations in target vehicle in different crash configurations.

The resulting deformation of target vehicle's front structure for all frontal impact tests listed in Table 1 is shown in Figure 5. It was apparent that the collision type is an important factor governing front-end structural performance since it determined how the vehicle's front-end structures interacted. Figure 5 (a) shows a progressive deformation of the front-end structure when engaged with a rigid fixed barrier. However, Figure 5 (b, c and d) show that the front rail deformations were ineffectively used, and had noticeable deformation at the shotgun and hood areas. As a result, higher occupant compartment intrusions were observed due to the effect of mass, and possibly stiffness and geometrical differences.

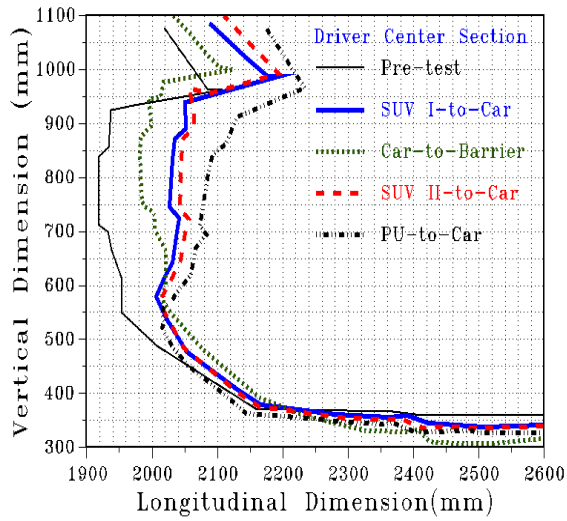


Figure 6. Comparison of dash intrusion profiles between rigid fixed barrier test and SUV/PU-to-Car tests.

Pre- and post-crash dimensional analyses on target vehicles were carried out to obtain intrusion profiles at the driver center section. The results are shown in Figure 6, where the intrusion profiles from the cowl top to the floor panel at this section are illustrated. As shown in Figure 2, there was considerable difference in the vertical heights of the significant front-end structures in the case of the PU-to-target vehicle impact. Table 3 also indicates a maximum of 117 mm difference in the vertical heights between the bumper center points of the Pickup and the target vehicle. The Pickup caused significantly more intrusion in the occupant compartment of the target vehicle compared to those caused by SUV I and SUV II in SUV/PU-to-Car frontal impact (see Figure 6). It was clear that there was little structural interaction due to geometrical differences that caused the Pickup to override on to the target vehicle. There was very little difference between the dash intrusion profiles caused by SUV I and SUV II impacts. However, this dash intrusion was significantly greater than that seen in related full-frontal rigid fixed barrier impacts.

Figures 7 and 8 show the effect of bumper height differences and mass ratio of the bullet to target

vehicles on the maximum dash intrusions in the target vehicle, respectively. These figures, as well as the results demonstrated in Figure 6, suggested that the effect of geometry in SUV/PU-to-Car impacts can reduce the effect of mass and stiffness.

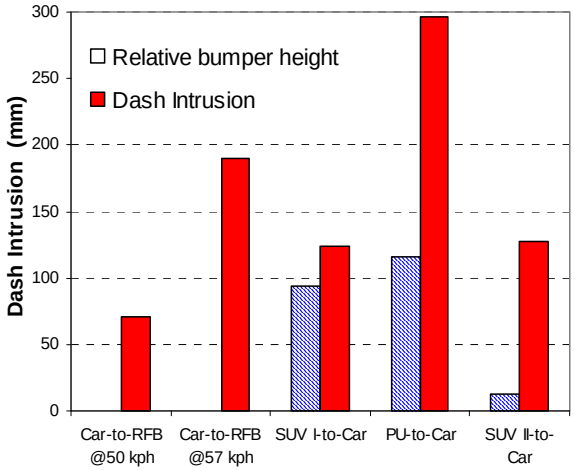


Figure 7. Effect of relative bumper height on dash intrusion in various crash tests.

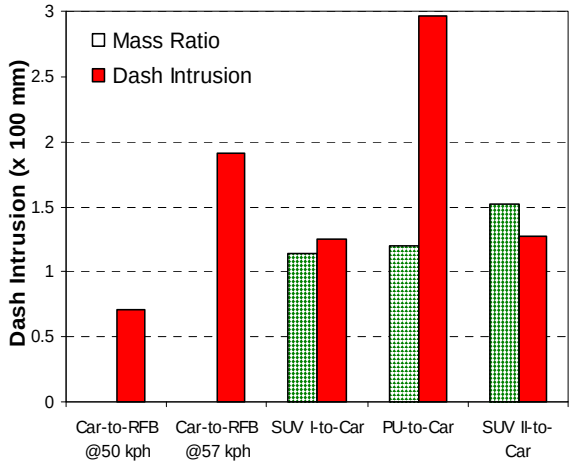


Figure 8. Effect of mass ratio on dash intrusion in various crash tests.

4.3 Lower Leg Tibia Index Comparison

Tibia Index is a function of axial force and bending moment measured by the lower Tibia load cell during crash tests. With a good, crashworthy front-end structural design for a target vehicle, occupants in full rigid fixed barrier impact have a much lower risk of potential lower leg injury than those in SUV/PU-to-target vehicle impact. The relatively high Tibia Index expected in SUV/PU-to-Car impacts was caused by higher intrusions.

Figure 9 shows the normalized values of the lower leg Tibia Index as a function of crash test configurations. It is shown that target vehicles with low intrusions, such as in vehicle-to-rigid fixed barrier, have lower Tibia Index. Since the maximum intrusions in SUV/PU-to-Car impact are associated with the Pickup overriding the target vehicle, this resulted in a very high Tibia Index of 1.8 exceeding the Injury Assessment Reference Values (IARV) of 1.0 [5]

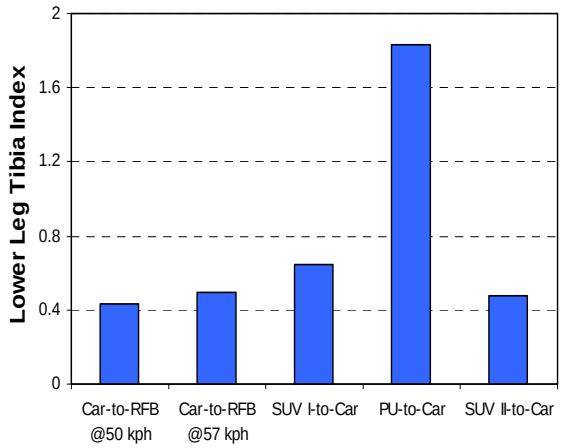


Figure 9. Lower leg Tibia Index comparison.

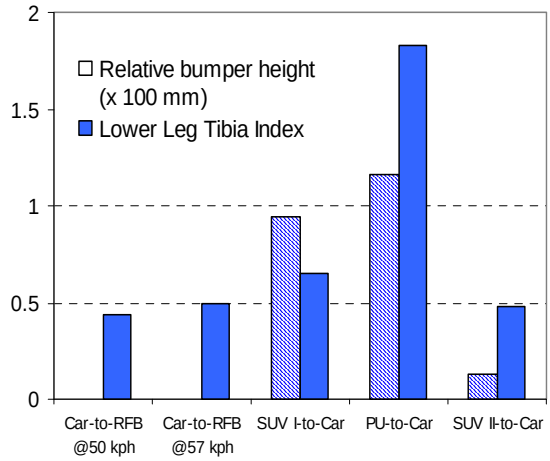


Figure 10. Relative bumper height effect on lower leg Tibia index.

4.4 Energy Absorption Comparison

Comparisons of crash energy management of a target vehicle involved in a single fixed barrier and multi-vehicle impacts can be an appropriate measure for examining good safety vehicle performance. In this section, energy absorbed by the target vehicle in a rigid fixed barrier test was compared to that from a SUV/PU-to-Car impact.

All vehicles consume the same amount of energy per unit weight when crashed against a rigid fixed barrier at any given speed (assuming negligible rebound speeds). However, uneven distribution of energy absorption is noticeable between the colliding vehicles in SUV/PU-to-Car crashes. The lighter and less stiff vehicle absorbs more of the impact energy while the heavier and stiffer vehicle deforms less and therefore absorbs less energy.

Various methods for calculating the energy absorbed by a vehicle when impacting a fixed barrier or another vehicle have been reported in previous studies [4]. Momentum and energy conservation equations do not provide details of how energy is shared between the two colliding vehicles, or how energy is absorbed by main components of the structure. Computer simulations were used to estimate the energy absorbed by each vehicle. Detailed finite element models of the target and bullet vehicles used in this study were developed. The models were fully validated at various speeds against a rigid fixed barrier and SUV/PU-to-Car tests (see Figure 11). Details of the models are beyond the scope of this paper.

Figure 11. Comparison of SUV-to-Car crash test (bottom) and related simulation (top).

Figure 12 shows the comparison between the energy absorption resulting from rigid fixed barrier and SUV/PU-to-Car impacts. The energy presented in this figure represented the internal energy absorbed by each vehicle as calculated in the finite element analyses. This figure clearly shows that the lighter (target) vehicle absorbed more energy than the heavier (bullet) vehicle in SUV/PU-to-Car impacts. It also indicated that the target vehicle absorbed more energy in SUV/PU-to-Car impacts (compared to that in rigid fixed barrier impact when similar levels of velocity changes were experienced). This was due to the deformation in the target vehicle resulting from the SUV/PU-to-Car impact.

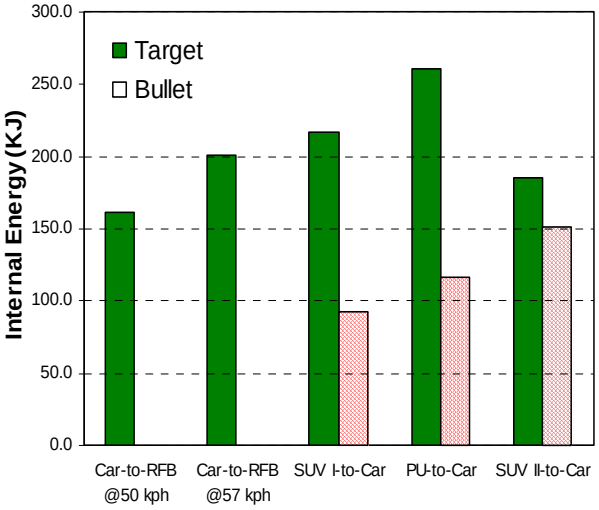


Figure 12. The comparison between the energy absorption.

To achieve good compatibility in SUV/PU-to-Car impacts, it is necessary for both vehicles to share the impact energy and to absorb a quantity of energy proportional to their own masses. In the following discussion, the energy absorbed by a target vehicle in a rigid fixed barrier impact at a certain speed was assumed to be equivalent to that absorbed by each of two identical target vehicles in a full overlap frontal SUV/PU-to-Car impact. It was also assumed to be true only when the closing speed between the two target vehicles was double that of the same target vehicle speed against a rigid fixed barrier. If the term " Energy Ratio" is defined as the ratio of the energy absorbed by the target vehicle to that of the bullet vehicle in SUV/PU-to-Car impact, then that Energy Ratio for the rigid fixed barrier impact will always be equal to one at any given speed.

Figures 13 and 14 present the effect of geometry and mass on the energy management of the target vehicle in SUV/PU-to-Car impact. It was evident that the geometry effect dominated the effect of mass. The relatively high Energy Ratio resulted from the SUV and PU impact to the target vehicle was mainly due to high difference in bumper height compared to that of the target vehicle. This was due to the SUV/PU override that caused deformation and higher energy absorption by the target vehicle. Conversely, the Energy Ratio resulting from the heaviest SUV II impacting the target vehicle was close to one which

also confirmed that the alignment of energy absorbing elements and bumper heights in SUV/PU-to-Car impact was a very important design element that helped ensure the aforementioned characteristics of good compatibility were achieved. Also, it was observable that the effect of geometry can reduce the effect of mass in a SUV/PU-to-Car impact.

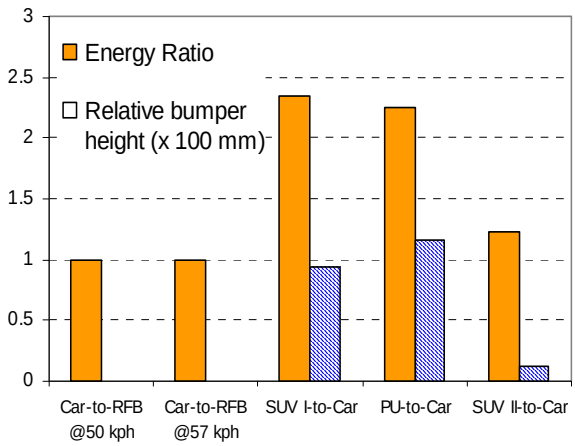


Figure 13. Variation of internal energy ratio with relative bumper height.

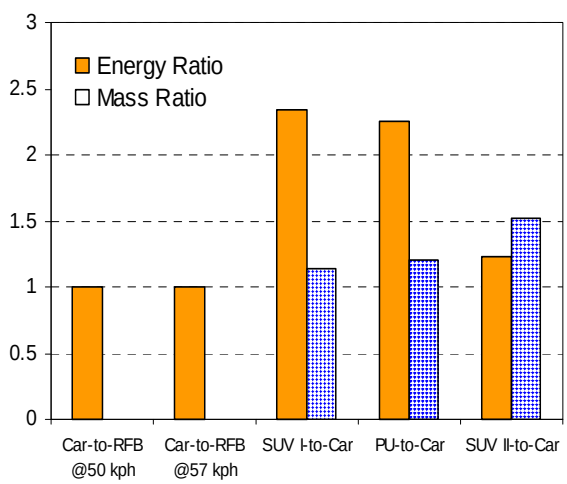


Figure 14. Variation of internal energy ratio with vehicle mass ratio.

6. CONCLUSIONS

- Vehicles that achieve good safety performance in rigid fixed barrier impacts may not necessarily achieve the same level of performance in SUV/PU-to-Car impacts.
- Crash pulse is generally considered to be an important factor for the occupant response outcome in a rigid fixed barrier impact. It was observed that similar crash pulses existed (after 40 ms into the crash events) for both the rigid fixed barrier tests and target passenger car in the studied SUV/PU-to-Car collisions.
- Significant deformation and dash intrusions were observed in the target vehicles in SUV/PU-to-Car impacts compared to that in rigid fixed barrier impacts.
- Higher intrusion-related Tibia Indices were observed in the studied SUV/PU-to-Car impacts
- The energy absorbed by target vehicles in the studied SUV/PU-to-Car impacts was higher than that resulting from rigid fixed barrier impacts.
- A SUV/PU-to-Car or an equivalent test to complement the current rigid fixed barrier test was proposed to help further assess vehicle structural performance.
- In the studied frontal SUV/PU-to-Car impacts, it was shown that good geometrical interaction and alignment of the energy absorbing elements were fundamental to crash compatibility.

7. ACKNOWLEDGEMENTS

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