# EVALUATION OF STIFFNESS MATCHING CONCEPTS FOR VEHICLE SAFETY IMPROVEMENT

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Paper Number 07-0112

## ABSTRACT

The concept of 'stiffness mismatch' between front structures of colliding vehicles has been viewed as one of the important factors in collision incompatibility in front-to-front crashes between vehicles of different size. Consequently, it has been hypothesized that 'better matching' of stiffness properties of the front structure of the colliding pair of vehicles may improve the safety of the occupants of the smaller vehicle in such crashes. However, since the front structures of automobiles are designed to meet the protection requirements for their occupants in various frontal impacts, any changes in these properties need to be evaluated for possible influence on all requirements of self-protection as well as of improved compatibility. This paper examines statistical data to estimate the portion of the vehicle front end that may be of significance in front-to-front collision compatibility. The structural properties of an LTV's front structure were modified to reduce the force and energy levels during the front four hundred millimeters of its crush in order to bring its stiffness properties closer to that of a representative midsized car in the US fleet. Detailed studies were conducted for this modified LTV utilizing finite-element based simulations of frontal NCAP test as well as of frontal impact with a passenger car in a field-representative test configuration. Results of these studies show that changing the structural properties of the LTV to be closer to that of the passenger car may have negative consequences for the protection of the LTV occupants. Alternative scenarios for achieving the proper balance in vehicles' structural properties to improve overall safety are proposed.

## INTRODUCTION

Collision compatibility between vehicles of dissimilar sizes has been the subject of research by several investigators [1-3] in recent years. Statistics for such crashes in the US show that impacts between the front of a large vehicle to the side of a smaller vehicle account for a large part of the societal harm in LTV-to-car crashes, followed in order of magnitude by that in front-to-front impacts between such vehicles. Several hypotheses have been presented in literature [4] regarding possible solutions for improving collision compatibility in front-to-front impacts and one of such proposals is that of 'stiffness matching' of the front structures of the colliding automobiles. But, since the front structure of an automobile is a nonlinear structure with speed- and time-dependent response characteristics, the definition of a 'vehicle stiffness' is not straightforward [5]. A recent proposal [6] of 'stiffness matching' has been to match the slope of a predefined initial portion of force-versus-displacement response of a vehicle (as measured in a US NCAP test of 35 mph impact into a rigid barrier) to a 'medium range' as a possible solution for improving compatibility in frontal impacts. Such a concept is examined in detail in this paper by modifying the front end structure of a larger vehicle and evaluating its self-protection as well as partner protection.

## CONCEPT OF STIFFNESS MATCHING FOR FRONT STRUCTURES

Front structures of automobiles are designed to meet many different functional and operational requirements. Protection of the occupants in case of a crash is one such requirement and therefore, one of the primary structural functions is to efficiently dissipate the impact energy in the available crush distance and thereby minimize the injury potential to the occupants. The degree of crash protection is usually evaluated in tests specified by regulations (e.g. FMVSS) as well as by various consumer information programs (e.g. NCAP, IIHS tests) which consist of impacts into a fixed barrier at specified speeds.

For such test conditions, the pre-impact kinetic energy of the vehicle ('impact energy') is proportional to its mass. The post-impact kinetic energy is zero (i.e., the vehicle comes to a stop). The impact energy is dissipated in deforming the vehicle (ignoring second order effects such as acoustic and thermal energies) and from mechanical principles, the mechanical work (which equals force times displacement) must equal the impact energy. Thus, the area under the force versus deformation curve for the vehicle must equal its impact energy which is proportional to the vehicle's mass.

To illustrate this, test results for several vehicles are shown in Figures 1 and 2 for US NCAP tests (frontal impact into a rigid barrier at 35 miles per hour). Figure 1 shows plots of measured forces on the barrier versus the vehicle displacement. Since the front end structure of each vehicle is usually optimized subject to the particular vehicle's constraints of that vehicle, no general observations regarding the vehicle properties can be made from such data alone.

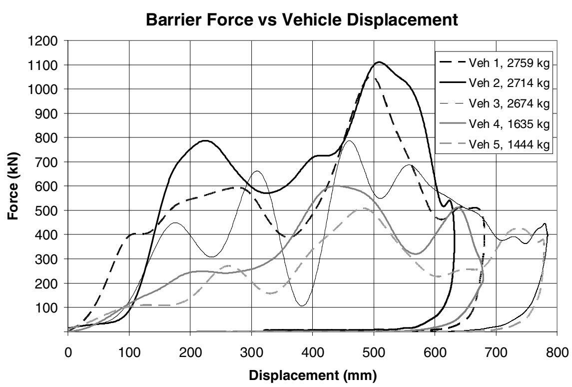


**Figure 1: Force and Deflection Measurements in Frontal Impact Tests**

Shown in figure 2 are calculated values of work (area under the force-deflection curve) for each vehicle.

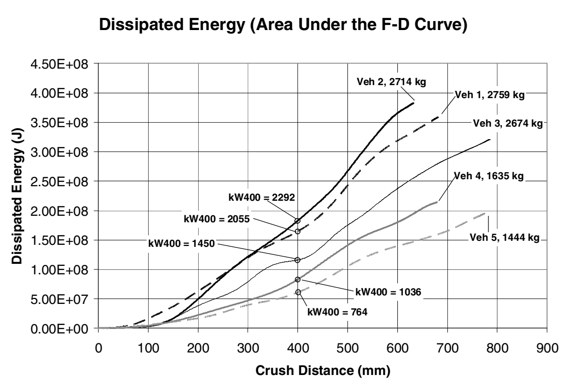


**Figure 2: Relationship of Vehicle Mass and Total Work in Frontal Impact Tests**

It is observed that, in accordance with the principles of mechanics, the area under each vehicle's curve (or the mechanical work) is proportional to the mass of that vehicle [7]. Thus, the total area under the barrier force versus vehicle displacement plot is a property of the vehicle, is proportional to the vehicle's mass (assuming a fixed impact speed) and cannot be changed unless vehicle mass is changed.

We will now evaluate the impact of altering a specific portion of the force-versus-displacement property of a given vehicle. Since an automobile's front structure is usually optimized for its multiple functional and operational requirements and constraints, it can be hypothesized that isolated changes to alter specific portions of its force versus displacement property will render the front structure suboptimal in overall protection in frontal impacts.

It can also be hypothesized that if changes were made to reduce force levels in specific parts of the front structure, the consequence is likely to be an increase in force levels in the rest of the structure such that the total area under the curve remains constant. This is illustrated in figure 3 for force-displacement responses of two vehicles in US NCAP tests at 35 mph. Vehicle 1 has a larger mass than vehicle 2. If the front end of (the heavier) vehicle 1 were modified to lower its force levels to be similar to that of (the lighter) vehicle 2 over a distance'd', the consequence

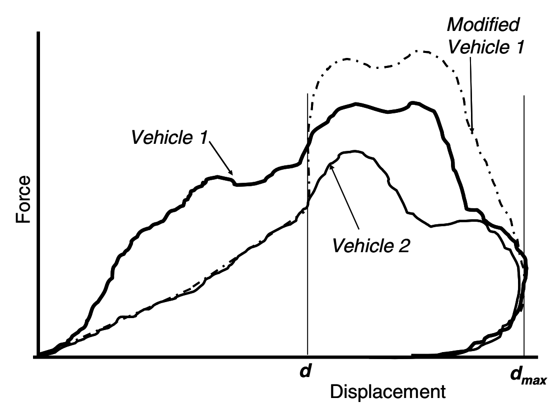


**Figure 3: Concept of Stiffness Matching Between Vehicles of Different Sizes**

will be that the structural force levels of vehicle 1 are higher for the rest of the crush (shown by dash lines) than that of the original vehicle 1.

This is an important consideration because concepts of 'stiffness matching' usually denote lowering the force levels in the earlier part of the crush of the heavier vehicle and as shown above, this is likely to cause higher force levels in the remaining portion of the front end of the heavier vehicle, so that the calculated work is the same in both cases.

The above reasoning is based on the assumption that available crush distance remains essentially unchanged as the vehicle's front end is altered for 'stiffness matching'. This is a valid assumption since the possibility of significantly increasing available crush space in a vehicle may not be feasible due to the following constraints:
- Increase in total crush distance by allowing higher values of $d_{max}$ may imply more intrusion into the passenger compartment of the vehicle ;
- Increase in available crush distance by adding more length to the front of the vehicle requires additional structure and will increase the mass of the heavier vehicle more (leading to higher values of impact energy).

## ANALYSIS OF STRUCTURAL CHANGES FOR STIFFNESS MATCHING

A detailed study was conducted for changes required to lower the frontal force levels (measured in a 35 mph front impact into a rigid barrier) of a light truck-based vehicle (LTV) in the first 400 mm of crush. One of the parameters used in this study is KW400 [6] which is defined as the stiffness of a hypothetical linear spring selected such that the work done by this spring over the first 400 mm of crush equals the energy dissipated by the vehicle in the same distance of crush in a 35 mph frontal impact into a rigid barrier (US NCAP test).

The LTV used for this study was approximately 2300 kilograms and its front end structure is modified so as to lower the value of KW400 for the LTV and bring it closer to that of a car (approximately 1650 kilograms). The consequence of such modification was evaluated by finite element simulation of the following impact conditions:
- LTV frontal impact into a rigid barrier at 35 mph;
- LTV impact into a compact size car with a $\Delta V$ of 35 mph in the car.

The first impact condition (LTV impact into a rigid barrier at 35 mph) is assumed for the purpose of this study to represent the self-protection of the LTV and the second case (LTV impact into a compact size car) is a measure of collision compatibility ('partner protection').

Shown in figure 4 is the front structure (shown without the engine) of a typical automobile and the complexity of such structures indicates that numerous changes need to be made in the geometric as well as in the material properties of multiple components to achieve the goal of lowering front 'stiffness'.

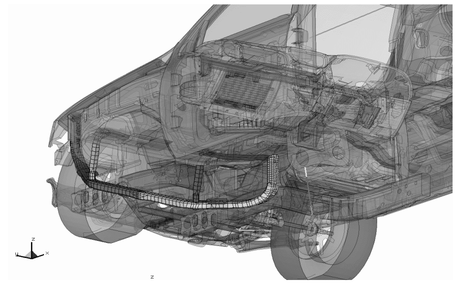

**Figure 4: Front End Structure of a Vehicle**

In this study, several iterations in LTV's structural design were necessary to achieve the above-mentioned goal of matching KW400. The effect of these iterations was to progressively lower the force levels in the front 400 mm of the vehicle. The total mass of the LTV changed only slightly during these iterations.

Results from the final iteration are shown in Figure 5 as barrier force-versus-vehicle displacement responses of the modified LTV structure, the baseline LTV and the car in 35 mph front barrier impacts. As expected from the discussion in figure 3 above, the effect of lowered forces in the first 400 mm of the crush space ('stiffness matching') is a significant increase in force levels in the rest of the vehicle structure. The implications of this on the protection of vehicle occupants are examined in the following sections.

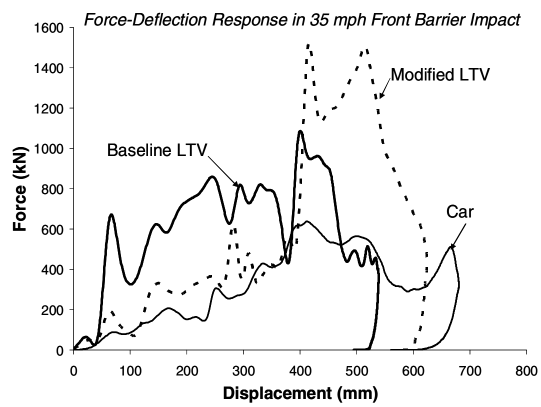


**Figure 5: Force Deflection Response of Base LTV and Modified LTV**

## EFFECT ON OCCUPANT PROTECTION IN RIGID BARRIER IMPACTS

Results from finite element simulation of vehicle front impact into a rigid barrier at 35 mph are presented below for the baseline LTV, the modified LTV and the car.

Figure 6 is a plot of vehicle velocity as a function of time ('deceleration plot') for each of the vehicles. It is observed that when the LTV is modified to reduce the force levels in earlier part of the crush, the effect in the barrier test is to reduce the slope in the earlier part of the deceleration plot and increase the slope in the later part.

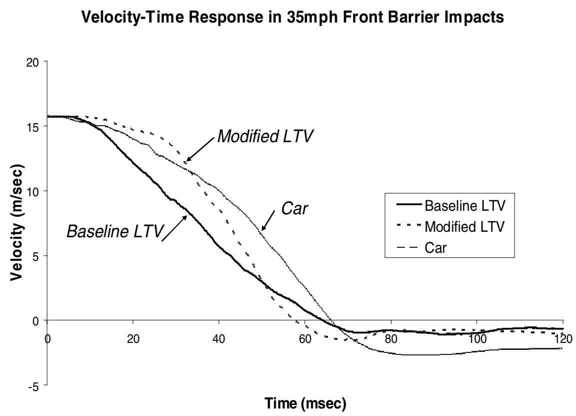


**Figure 6: Velocity-Time Response of Base LTV and Modified LTV in 35mph US NCAP Test**

One measure of this change is the 'effective deceleration' of the vehicle, defined as the slope of a linear approximation of a large portion of the deceleration plot. This is shown in figure 7 for the baseline LTV as well as for the modified LTV. The maximum effective deceleration in the baseline vehicle is approximately 30 g but this 'effective deceleration' increases to 54 g when the LTV is modified as mentioned above.

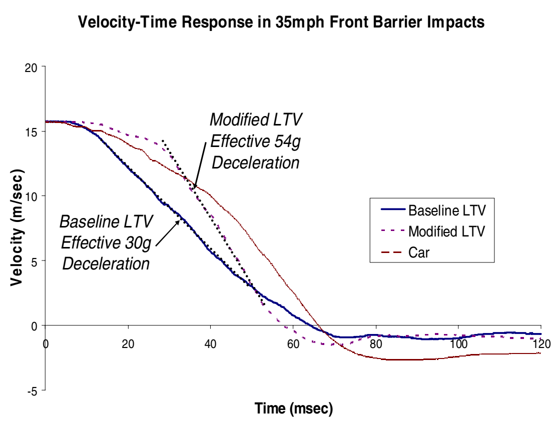


**Figure 7: Maximum Effective Deceleration in 35 MPH Front Barrier Test**

Figure 8 is a plot of the deceleration of the vehicles showing higher peak deceleration in the modified LTV (60 g) than in the baseline LTV (41 g).

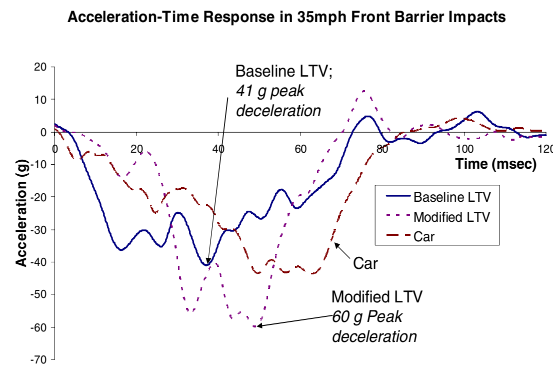


**Figure 8: Deceleration Response in 35 mph Front Barrier Test**

Similar conclusions are drawn from the calculated intrusions into the passenger compartment of the vehicles. As shown in figure 9, the calculated intrusions in the modified LTV (with lower KW400 value) are higher than those in the base LTV.

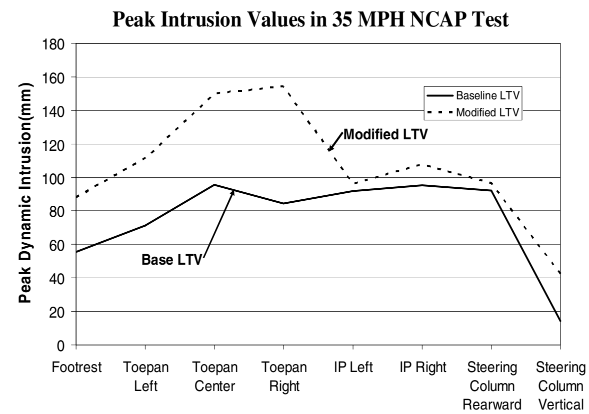


**Figure 9: Peak Intrusion Values in 35 MPH Front Barrier Test**

Further evaluation of the effect of these front structure changes in the LTV on the kinematics of the vehicle occupant was also obtained by finite element simulations. The driver was represented by a fiftieth percentile Hybrid III anthropomorphic test device, restrained by seatbelts and front airbag. The calculated decelerations of the head and the chest as obtained from the finite element model are shown in figure 10 and it is observed that these deceleration levels for driver ATD are higher in the modified LTV than in the base vehicle. The HIC (calculated from the head acceleration shown in Figure 10) for the driver ATD also increases from approximately 700 in the baseline LTV to about 1200 in the modified LTV.

It can therefore be summarized from the above results that force-reduction modifications to the

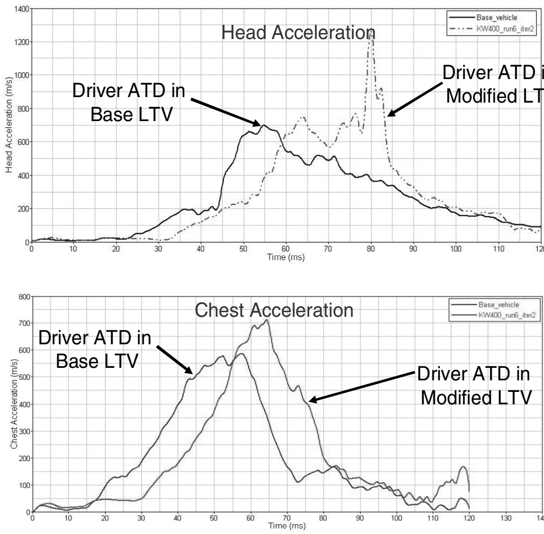


**Figure 10: Estimated ATD response in Baseline LTV and Modified LTV**

front structure of the LTV result in significant reduction in occupant protection in the 35 mph frontal crash. This is due to the modifications for stiffness matching reducing the front structure's ability to dissipate the crash energy.

## EFFECT ON OCCUPANT PROTECTION IN LTV-TO-CAR IMPACTS

The effect of stiffness matching on collision compatibility was also evaluated by simulating a frontal impact between the LTV and a passenger car of mass approximately 1650 kg. This was done by utilizing finite element models of both the LTV and the car in a full frontal collision with approximately

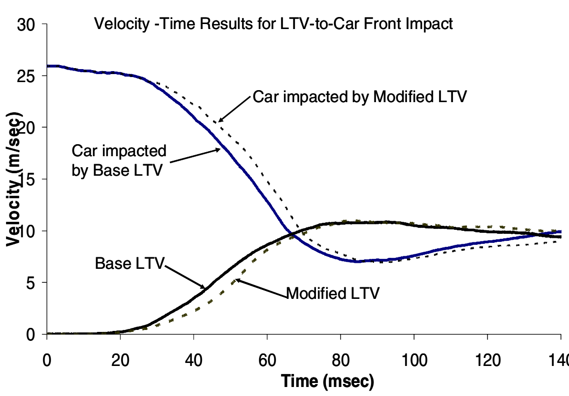


**Figure 11: Velocity versus Time Plot for LTV-to-Car Impacts**

35 mph change in velocity ('ΔV') in the struck car. This simulation was conducted for the baseline LTV as well for the modified LTV. The plot of vehicle velocities as functions of time is shown in Figure 11. The calculated responses in both the car and the LTVs are shown below.

Figure 12 is the plot of the deceleration in the vehicles. The result of modifying the front structure of the LTV to lower the force levels in the first 400 mm of its crush is observed to be insignificant in

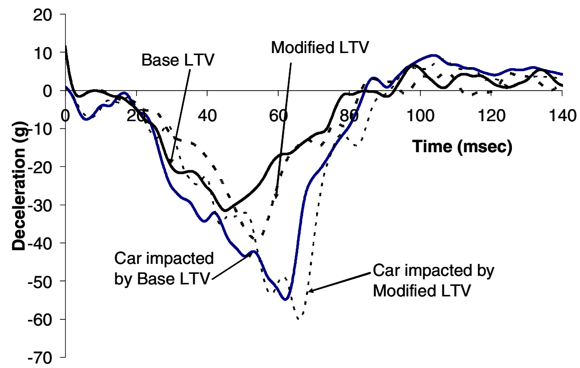


**Figure 12: Deceleration versus Time Plot for LTV-to-Car Impacts**

terms of the deceleration response of the vehicles because the small changes observed in the peak deceleration values are likely to be filtered by airbags and seatbelts and not likely to affect the response of the vehicle occupants.

The effect of modification in the front structure of the LTV is observed in Figure 13 which shows the calculated intrusion levels in the car when impacted by the baseline LTV and by the modified LTV. The reduction in force levels in front part of the LTV is shown to lead to reduced intrusions of the instrument panel and the steering column and slightly increased intrusions in the toe pan area.

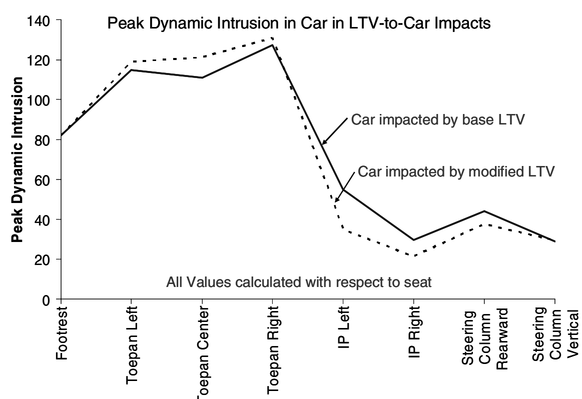


**Figure 13: Peak Intrusion Values in Car in LTV-to-Car Impacts**

## CONCLUSIONS

The effect of modifying front structure of a heavier vehicle (an LTV in this case) has been examined for its self-protection (protection of its driver in 35 mph front crash against rigid barrier) as well as for collision compatibility (protection of driver of a smaller vehicle in front-to-front crash). The front structure of the LTV was modified to reduce its force levels in the first 400 mm of crush and thus to bring its 'stiffness' (KW400) to be closer to that of the lighter mass car.

The effect of such modifications is observed to be a significant increase in the modified LTV's deceleration levels as well as in the peak intrusion value in passenger compartment and in the calculated ATD response in the LTV in frontal impacts against a rigid barrier. All of these are indicative of reduced self-protection in the modified LTV. For the case of the car driver when the car is impacted by the modified LTV, it is observed that the modified LTV is likely to reduce the peak intrusions inside the car at the instrument panel and the steering column and increase these values in the toe pan area.

Thus, this study for a specific LTV and a specific passenger car shows that reducing force levels in front part of LTV structure may have benefits in compatibility but has significant reduction in self-protection. Further studies are needed to assess the effects for the national fleet and determine if such measures have any possibility of improving the safety of automobile occupants. However, a preliminary assessment of the fraction of LTV-to-car crashes where the above changes in LTV design may be beneficial may be made from the 1999-2005 NASS data (Figure 14) for front crashes.

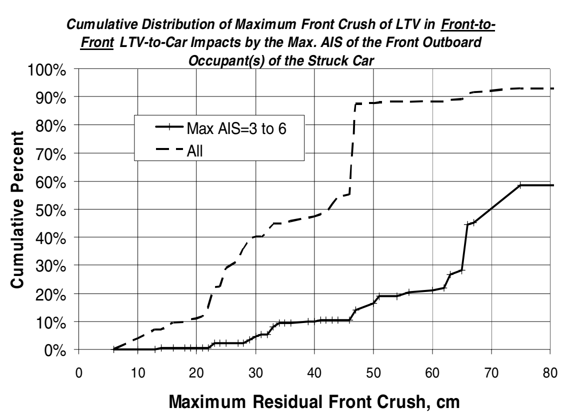


**Figure 14: NASS Data on Maximum Residual Crush of LTV in LTV-to-Car Crashes**

Figure 14 shows that 400 mm crush of the LTV corresponds to approximately 10% probability of injury levels of 3 to 6 in the struck car. It can therefore be hypothesized that softening the first 400 mm of the LTV front structure will affect only 10% of crashes.

As a recommendation, it is necessary that any proposed changes in automobile structures for 'stiffness matching' be evaluated for impact on protection of occupant in all types of crashes in the national automotive fleet before any decision is made regarding implementation.


## ACKNOWLEDGEMENT

We are grateful to Mr. Sairam Peddi for his help and guidance during this study.


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