COMPATIBILITY STUDY IN FRONTAL COLLISIONS - MASS AND STIFFNESS RATIO

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ABSTRACT

Compatibility of vehicles of different mass and stiffens in head-on collisions is studied in this paper with the aid of an eight-degrees of freedom, two dimensional lumped-mass simulation model. The model takes into consideration mass and stiffness ratio as the main factors contributing to compatibility of the two colliding vehicles. Other factors like length of crumple zone, offset overlap and speed are also considered. Three injury risk criteria have been considered in this study; delta V or change in velocity of vehicle after impact, maximum acceleration sustained by the passenger compartment throughout impact, and length of deformation sustained by the car front. The most crucial compatibility parameter is the mass ratio for the delta V criterion. The second and third compatibility parameters are mass ratio and stiffness ratio for deformation length criterion. A longer crumple zone is proposed for heavier vehicles to provide the required protection for smaller vehicles involved in head-on collision. It was found that both mass and stiffness ratio have no aggressivity on the partner vehicle when maximum acceleration criterion is used at low impact speeds.

INTRODUCTION

The safety of car occupants does not only depend on the safe design of the car they ride, but depend also on the aggressivity of the design of the partner car involved in head-on collision. An aggressive design may provide good protection to the car in question and pause a threat to occupants of the other car involved in the collision. This raises the question of compatibility between vehicles where the level of protection of the occupants of a certain vehicle does not only depend on its crashworthiness performance, but on that of the other car too. The problem of compatibility is a problem of mass, structural and geometrical interaction between the two colliding vehicles.

The question of compatibility between vehicles involved in frontal collisions has been revitalised in Europe. Recent development has introduced the concept of the ultra small and light vehicle for economic and environmental reasons. This development coupled with alarming fatality rate of car-to-car accidents has brought the problem of compatibility - i.e. safety implication when large and small cars collide together - into the forefront. European statistics indicate those 60-65% of fatalities in truck accidents are car occupants. Some 4200 of them die every year in car-to-truck frontal collisions. Some 2900 die yearly in car-to-car frontal collisions.

Despite publication of numerous research programme on compatibility, conflicting claims are being made regarding various factors affecting compatibility and aggressivity of road vehicles. It is generally accepted that injury risk to the occupants is higher in lighter vehicle involved in head-on collision with larger one. This is considered so on the basis of the effect of mass ratio between the two colliding vehicles. Because mass is a surrogate measure for other factors like size, shape, length of crumple zone and stiffness too, the effects of these individual factors on compatibility are overshadowed by the effect of the mass[2].

It is envisaged that a comprehensive fast running simulation programme is required to achieve a thorough study involving all important factors affecting compatibility. This research focuses on the development of such a simulation programme, and to perform a thorough study and sensitivity analysis of main factors affecting compatibility of vehicle in head-on collisions. Mass and stiffness ratio are the main factors considered in this study. Other factors like length of crumple zone, offset overlap and speed are also considered. Geometric compatibility is not considered in this study. It is assumed that the two colliding structures geometrically interact with each other.

MATHEMATICAL MODEL

The objective of the model is to enable quick simulation of the crush process and allow at the same time independent variation of important parameters that might influence compatibility. The parameters to take into consideration are: mass, stiffness, crash overlap, engine mass and engine location. A two-dimensional lumped-mass model using two stage deformations is used in this study.

The full model include vehicle mass, engine mass and front assembly structure mass for each of the colliding cars. Two levels of plastic springs is assumed on both sides of the engine. The left and right longitudinal are replaced with plastic spring to simulate plastic deformation of the structure. Figure 1 shows all masses and stiffness elements for both cars.

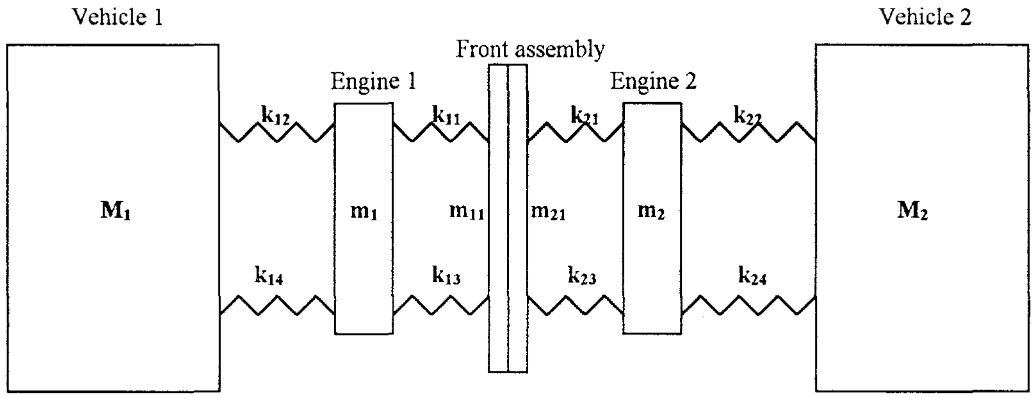

Figure 1 Schematic model of the crush system

The stiffness rates of the right and left hand sides are taken to be symmetrical for both cars. For each car, the two levels of 'spring' stiffness are increasing with deformation distance. Combining the primary stiffness k_{11}, k_{13}, k_{21}, k_{23} and the secondary stiffness k_{12}, k_{14}, k_{22}, k_{24}, the
overall force displacement characteristics for a 'standard specification' car (total mass 1500 kg) has primary stiffness and secondary stiffness. One input for the stiffness value for each car was used to determine both primary and secondary stiffness. The deformation displacement points were fixed. Although stiffness and mass distribution are symmetrical, an asymmetrical impact (overlap <1) produces asymmetrical loading and hence asymmetrical deformation for both cars. The front assembly parts, m_{11} & m_{21}, act as a rigid body of two masses stuck together, therefore providing a mechanism of load transfer from one longitudinal 'spring' to the other.

The primary part of the stiffness curve is a lower rate stiffness for the first 270 mm of deformation, followed by higher stiffness rate for the next 80 mm of deformation - before reaching the end of engine deformation zone at 350 mm. The secondary deformation zone starting at 350 mm is a constant deformation force (zero rate) for the rest of the deformation zone. The simulation solves 24 equations and 24 unknowns:

$\mathbf{X}, \theta, \mathbf{X_1}, \theta_1, \mathbf{X_2}, \theta_2, \mathbf{X_{15}}, \mathbf{X_{25}}$

$\mathbf{F_{11}}, \mathbf{F_{12}}, \mathbf{F_{13}}, \mathbf{F_{14}}, \mathbf{F_{21}}, \mathbf{F_{22}}, \mathbf{F_{23}}, \mathbf{F_{24}}$

$\mathbf{X_{11}}, \mathbf{X_{12}}, \mathbf{X_{13}}, \mathbf{X_{14}}, \mathbf{X_{21}}, \mathbf{X_{22}}, \mathbf{X_{23}}, \mathbf{X_{24}}$

Initial conditions for all masses, except for m_{11} and m_{21}, were assumed to be that of impact velocities of the vehicles. The central bumper assembly masses m_{11} & m_{21} were assumed to be in contact throughout the crush process and have a unified velocity and displacement. Its initial velocity is calculated using momentum equation of two masses colliding head-on with zero coefficient of restitution

CRASH SIMULATION

Various combination of mass ratio, stiffness ratio, impact speed ratio have simulated. Crash displacement, passenger compartment acceleration, 'spring ' forces have been plotted versus time to check and validate the simulation results. Standard data have been tried as well as comparison with other published work [(5), (13)] to validate the simulation. Typical simulation results of acceleration, displacement and force versus time are shown in figures 2 and 3 and 4. Figure 5 also shows acceleration versus displacement curve.

The simulation results show quasi equilibrium crash dynamics when ignoring effective mass of the structure. Only variation in stiffness is taken into consideration thus eliminating any high frequency oscillation from the results. The simulation data are that of 15 tons vehicle versus 1.5 tons both colliding at 30 mph speed 100% overlap.

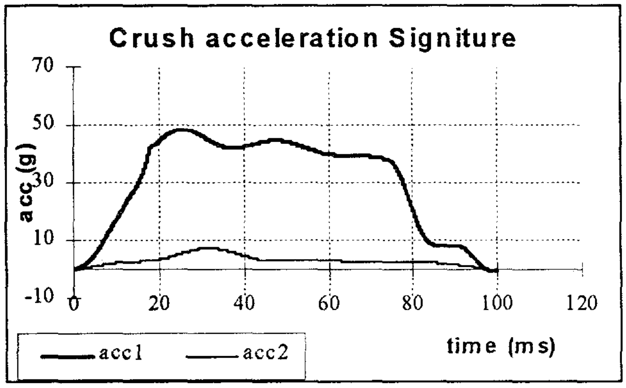

Figure 2 Crash acceleration signature

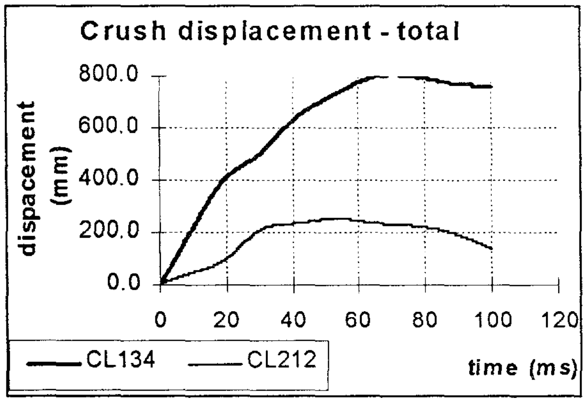

Figure 3 Crash deformation signature

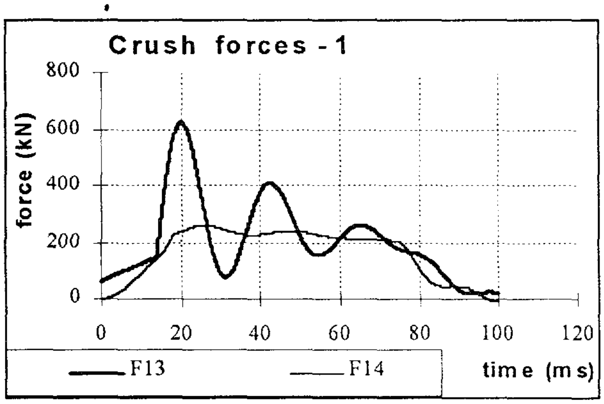

Figure 4 Primary and secondary forces

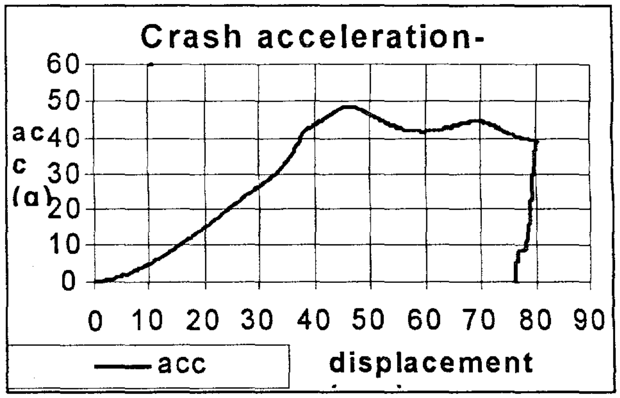

Figure 5 acceleration versus displacement

INJURY RISK CRITERIA

Various criteria have been used by different researchers ranging from the maximum or average acceleration of the passenger compartment, to the length of deformation attained during the crash. Other criterion involved occupants kinematics model by calculating acceleration and speed of various parts of the torso up to the time of the secondary impact between the occupant and car interior. The question of modelling the occupant's motion has been ruled out on the ground of the accuracy required. Three criteria have been identified as most relevant for this purpose;

i) Delta V change sustained by each vehicle at the end of the crash.
ii) Maximum acceleration sustained by the passenger compartment during the crash.
iii) Maximum length of deformation sustained by the frontal structure of the car.

The weightings of these criteria are believed to depend mainly on the closing collision velocity at the moment of impact. It can be said that the first criterion - delta V is more relevant at lower closing velocities than the other two criteria as acceleration and deformation length are not expected to attain critical levels. At intermediate closing velocities the second criterion - maximum acceleration becomes more relevant, whilst the third criterion - deformation length is relevant at high closing velocities only. What define the boundaries of these closing velocity categories depend on the combination of three design parameters: mass, stiffness and crumple zone. It is therefore considered that all these criteria are important to be considered and treated in the priority cited above.

Mass ratio compatibility

The first parameter investigated was mass ratio with regard to all three injury risk criteria. Figures 6, 7 and 8 show variation of injury criteria with mass ratio ranging from 0.5 to 10. Stiffness characteristics were assumed standard for both vehicles while offset overlap were taken to be 100%. Initial velocities for both vehicles were fixed at 13.33 m/s (30 mph). Vehicle 1 is the standard fixed characteristics vehicle while vehicle 2 is the varied characteristics one. Compatibility is measured on changes in injury criteria of the standard vehicle (no 1) due to variation in characteristics of the partner vehicle (no 2).

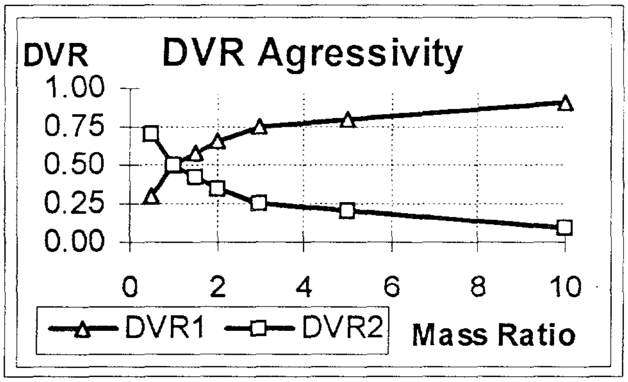

Figure 6 delta V ratio versus mass ratio

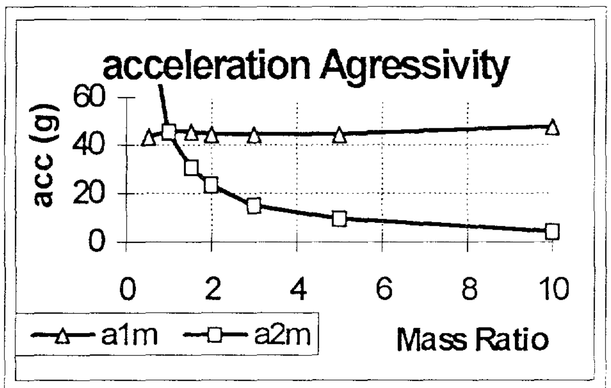

Figure 7 maximum acceleration versus mass ratio

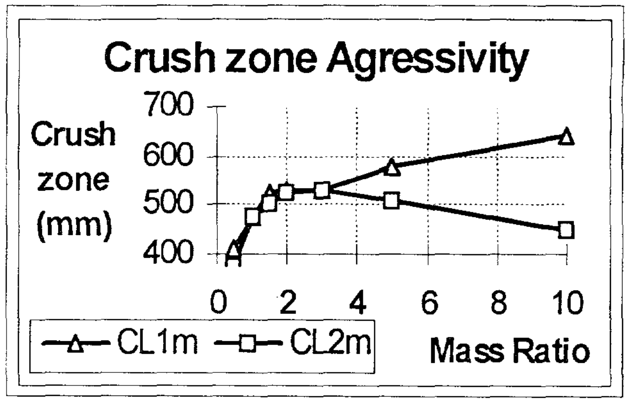

Figure 8 Deformation versus mass ratio

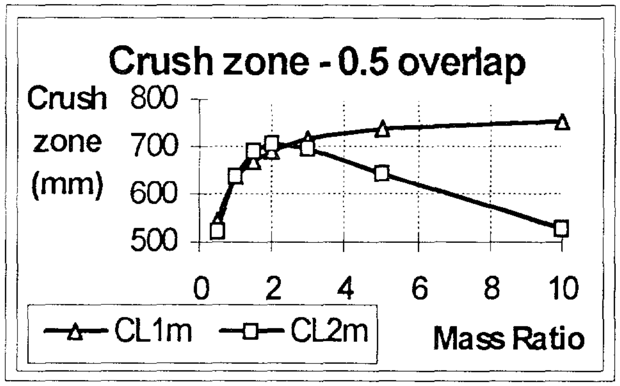

Figure 9 Deformation versus mass ratio

Figure 6 shows clear aggressivity of mass ratio for the delta V criterion. This is a direct implication of the momentum laws that result in the lower mass vehicle enduring higher velocity change. Figure 7 shows very low aggressivity for the acceleration criterion because stiffness of both vehicles is the same. The maximum crush force causing the deceleration of both vehicles is not changed, and therefore acceleration of the standard vehicle (no 1) does not change with variation of the partner vehicle's mass. The latter would experience smaller acceleration with increasing mass as the maximum force is fixed in all cases. For offset crashes of 50% overlap, the behaviours of delta V and acceleration criteria are almost the same as that of 100% overlap. However, acceleration levels in offset crashes are slightly lower due to concentration of load on one longitudinal.

Aggressivity of the mass ratio for the deformation length criterion is clearly illustrated in Figure 8 with the increasing deformation length of the standard vehicle versus increasing mass ratio. The behaviour of the partner vehicle (no 2) is shown to increase first with the mass ratio up to a ratio of about 3, beyond which deformation length of the partner vehicle decreases with mass ratio. This behaviour of the partner vehicle is attributed to energy absorption which become less for the higher mass vehicle. Since the first 350 mm of deformation has lower crush force, higher deformation length is expected in this region. For offset crashes of 50% overlap, aggressivity of mass ratio for the deformation length criterion is demonstrated to be lower than 100% overlap. This is clearly demonstrated in Figure 9 where little change in deformation length of the standard vehicle (no 1) is shown versus increase in mass ratio. This behaviour in offset crashes is attributed to the existence of load transfer mechanism between the two longitudinal 'springs', transferring deformation from the highly loaded longitudinal to the less loaded longitudinal in the region when deformation reaches about 700 mm. This behaviour demonstrates how homogenous distribution of stiffness across car front contributes to Compatibility in head-on crashes.

Stiffness ratio compatibility

The second parameter investigated was stiffness ratio. Figures 10, 11, 12 and 13 show variation of injury criteria with stiffness ratio ranging from 0.5 to 6. The maximum ratio of 6 is dictated by the maximum possible rigid structure (equivalent maximum crush force of 1250 kN). Mass characteristics were assumed standard for both vehicles while offset overlap were taken to be 100%. Initial velocities for both vehicles were fixed at 13.33 m/s (30 mph). Vehicle 1 is the standard fixed characteristics vehicle, while vehicle 2 is the varied characteristics one. Compatibility is measured on changes in injury criteria of the standard vehicle (no 1) due to variation in characteristics of the partner vehicle (no 2).

Primary stiffness ratio k_{11}/k_{21}, k_{13}/k_{23}, and secondary stiffness k_{12}/k_{22}, k_{14}/k_{24} have been investigated separately. Very similar results were obtained for their effects on all three injury criteria. It was decided to lump the two stiffness ratios in one and vary both primary and secondary stiffness parameters at the same time and according to one common stiffness ratio input. Figure 10, 11 show the acceleration injury criterion versus stiffness ratio for 100% and 50% overlap respectively. For 100% overlap, Figure 10 shows that stiffness ratio has no acceleration aggressivity at all. This is the case because the maximum acceleration of the standard vehicle (no 1) stays constant at about 44 g regardless of the stiffness ratio. On the contrary higher stiffness of the partner vehicle increases acceleration injury risk of its own occupants as demonstrated in Figure 10. For 50% overlap, Figure 11 shows that stiffness ratio has some level of acceleration aggressivity, particularly for ratio less than 3. This is clearly evident from the fact that the maximum acceleration of the standard vehicle (no 1) in figure 11 increases from 25 g, at a ratio of 0.5 to 40 g at a ratio of 3.

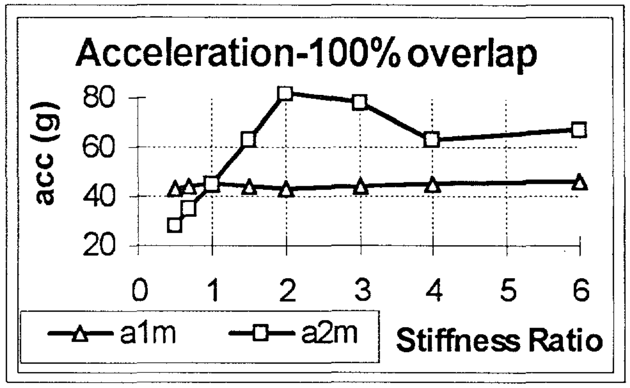

Figure 10 maximum acceleration versus stiffness ratio, 100% overlap

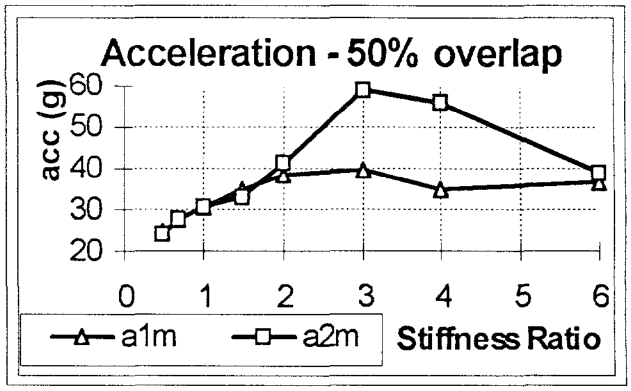

Figure 11 maximum acceleration versus stiffness ratio, 50% overlap

Stiffness ratio has no delta V aggressivity at all as far as the mass ratio remains constant. This is the case because the maximum delta V ratio (to closing velocity) of the standard vehicle (no 1) stays constant at about 0.5 regardless of the stiffness ratio. This behaviour is almost repeated for 50% overlap crashes. As for the deformation length criterion, Figure 12 (100% overlap) shows clear aggressivity of the stiffness ratio where the deformation length increases from 400 mm, at a ratio of 0.5, to 600 mm at a ratio of 6. Similar results are obtained for a 50% overlap crash.

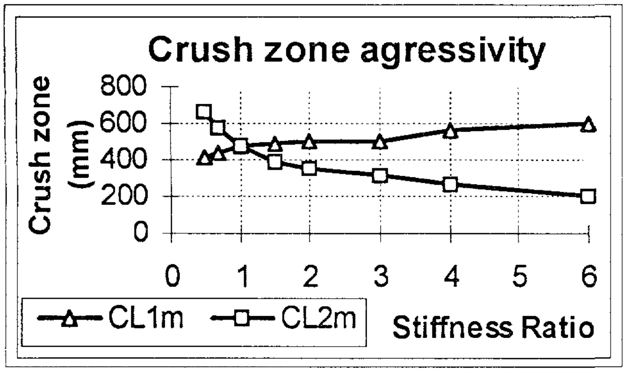

Figure 12 Deformation versus stiffness ratio

SUMMARY AND CONCLUSIONS

The aggressivity of mass ratio and stiffness ratio for three injury risk criteria is summarised in Table 1. Aggressivity
rating is given one of four scores; high, medium, low & none. Two scores are given for each category; 100% overlap and 50% overlap.

The most crucial compatibility parameter is the mass ratio for the delta V criterion. Nothing could be done about this incompatibility factor apart from geometric compatibility measures where structural interaction between the vehicles is prevented. The second and third compatibility parameters are mass ratio and stiffness ratio for deformation length criterion. These two compatibility factors could be made to compensate for each other. A slightly softer and longer crumple zone is required for heavier vehicles to achieve this compatibility. As far as acceleration injury criterion is concerned, both mass and stiffness ratio have no aggressivity on the partner vehicle. Acceleration is determined by the vehicle's own mass and stiffness.

	Delta V	Acceleration	Deformation length
Mass ratio	High	None	Medium
Stiffness ratio	None	None	Medium

Table 1 Summary of aggressivity 100% overlap

	Delta V	Acceleration	Deformation length
Mass ratio	High	None	Low
Stiffness ratio	None	Low	Medium

Table 2 Summary of aggressivity rating 50% overlap

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