

MASS TRANSIT BUS-VEHICLE COMPATIBILITY EVALUATIONS DURING FRONTAL AND REAR COLLISIONS.

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ABSTRACT

Mass transportation systems and specifically bus systems are a key element of the national transportation network. Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur. Therefore, crashworthiness research is a continuing effort. Using funding from the Federal Transit Administration, NIAR at Wichita State University is performing research to analyze and improve the crashworthiness of mass transit buses.

According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. An average of 11 bus occupants per year are killed in two vehicle crashes while 162 occupants per year of other vehicles are killed. For this period of time an average of 12,000 bus occupants per year are injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured.

Vehicle compatibility is an issue that needs to be addressed in order to reduce the number of fatalities and injuries to mass transit bus, and collision partner vehicle occupants. Crash incompatibility between vehicles has been attributed to three factors: mass, stiffness, and geometric incompatibilities. The objective of this research is to identify vehicle compatibility issues encountered during typical Mass Transit Bus collisions with sedans, light trucks, and heavy trucks through the use of numerical finite element simulations. The findings of this research can be used in the future by bus and vehicle manufacturers to improve crash compatibility.

INTRODUCTION

Mass transportation systems and specifically bus systems are a key element of the national transportation network. According to data from the Nation Transportation Statistics 2005 report [1]; transit bus usage, in terms of passenger-miles, averages 20.6 billion miles per year. From 1992-2002, transit motor bus ridership has increased 11% in terms of unlinked trips. From 1990-2002, the number of transit motor buses in the U.S. has increased 30%. Clearly, transit buses are an integral part of the national transportation system. Buses are one of the safest forms of

transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur.

According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. As shown in figure 1 and 2, an average of 11 bus occupants per year are killed in two vehicle crashes while 162 occupants per year of other vehicles are killed (102 occupants in passenger cars, 49 in light trucks, 9 in motorcycles, and 2 in large trucks).

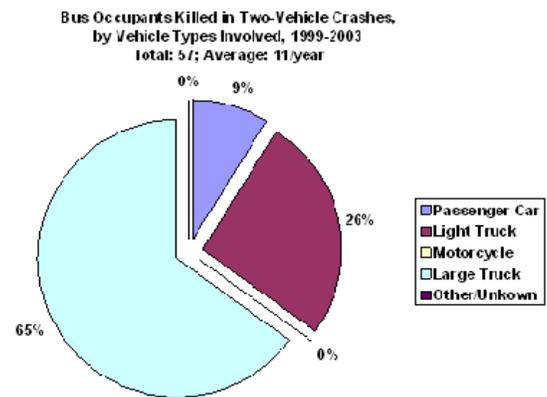


Figure 1. Bus Occupants Killed in Two-Vehicle Crashes, by Vehicle Types Involved.

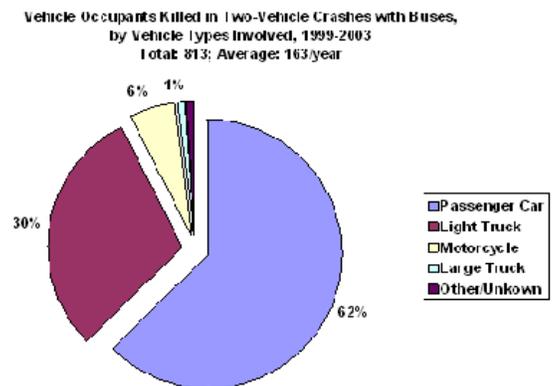


Figure 2. Vehicle Occupants Killed in Two-Vehicle Crashes with Buses, by Vehicle Types Involved.

An average of 12,000 bus occupants per year are injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured (6,000 in passenger cars and

2,800 in light trucks). Note that in the Traffic Safety Reports, buses are defined as “Large motor vehicles used to carry more than ten passengers, including school buses, inter-city buses, and transit buses”.

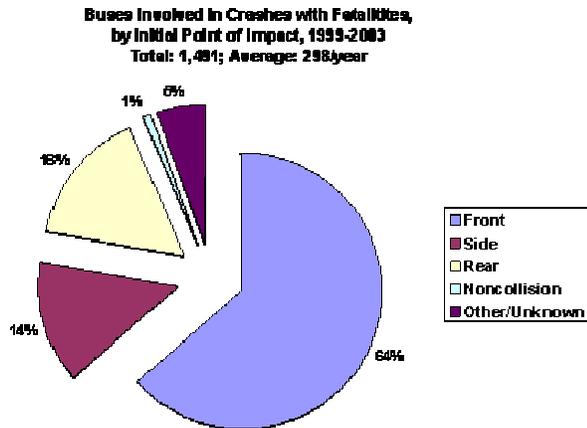


Figure 3. Buses Involved in Crashes with Fatalities, by Initial Point of Impact.

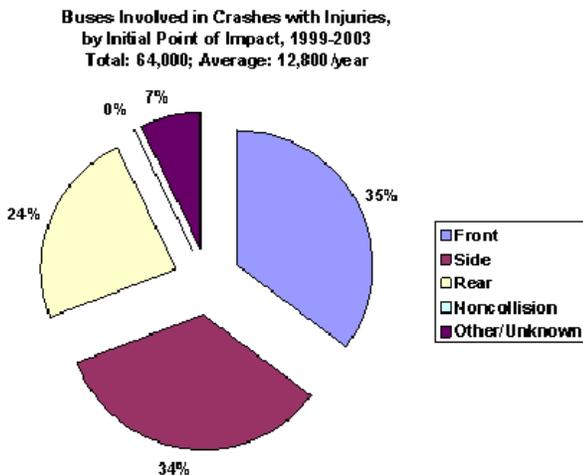


Figure 4. Buses Involved in Crashes with Injuries, by Initial Point of Impact.

According to the ‘Buses Involved in Fatal Accidents’ reports from 1999-2001, an average of 111 transit buses are involved in a fatal traffic accident each year. A total of 246 fatalities resulted from transit bus involvements from 1999-2000. Forty three percent of the fatalities were drivers of other vehicles, 37% were pedestrians, and 13% percent were passengers of other vehicles. The majority of transit bus fatalities occur during the work week, in urban environments, on dry roadway surfaces under normal weather conditions. Over half of fatal transit bus involvements occur on roadways with posted speed limits of 25-35 mph. Shorter, heavy-duty, low-floor transit buses account for the majority of fatal transit bus involvements.

Eighty two percent of two vehicle fatal transit bus involvements on the same trafficway, same direction resulted from a rear-end, bus struck. Eighty eight percent of two vehicle fatal transit bus involvements on the same trafficway, different direction resulted from a head-on collision in the buses’ lane

In mass transit bus-to-vehicle crashes, two vehicle safety viewpoints have to be addressed:

- Self-protection, the ability of a vehicle to protect its own occupants.
- Partner-protection, the ability of a vehicle to protect the occupants of the partner vehicle.

Therefore compatibility should be defined as the ability of a vehicle to provide self- and partner-protection in a manner that optimum overall safety is achieved. It is generally accepted that compatibility should take place without compromising self-protection.

Vehicle compatibility is an issue that needs to be addressed in order to reduce the number of fatalities and injuries to mass transit bus, and collision partner vehicle occupants. Crash incompatibility between vehicles can be attributed to three vehicle factors: mass, stiffness, and geometric incompatibilities. The effect of vehicle mass is relatively straightforward. However, the influence of stiffness and geometric compatibility require additional research.

The objective of this research is to identify vehicle compatibility issues encountered during typical Mass Transit Bus collisions with sedans, light trucks, and heavy trucks through the use of numerical finite element simulations. The findings of this research can be used in the future by bus and vehicle manufacturers to improve crash compatibility.

ANALYSIS METHODOLOGY

For two vehicles colliding the conservation of momentum is defined as;

$$M_1 \cdot V_{1i} + M_2 \cdot V_{2i} = M_1 \cdot V_{1f} + M_2 \cdot V_{2f}$$

the coefficient of restitution is defined as the ratio of velocities pre- and post-crash;

$$C_r = \frac{V_{2f} - V_{1f}}{V_{1i} - V_{2i}}$$

By solving the system of equations above, the residual velocities of a two vehicle collision upon impact are;

$$V_{1f} = \frac{[(C_r + 1) \cdot M_2 \cdot V_{2i}] + [V_{1i} \cdot [M_1 - (C_r \cdot M_2)]]}{M_1 + M_2}$$

$$V_{2f} = \frac{[(C_r + 1) \cdot M_1 \cdot V_{1i}] + [V_{2i} \cdot [M_2 - (C_r \cdot M_1)]]}{M_1 + M_2}$$

The energy dissipated by the vehicles structure upon impact is defined by the difference in kinetic energy pre and post-crash;

$$E_d = \frac{1}{2} \cdot (M_1 \cdot V_{1i}^2 + M_2 \cdot V_{2i}^2) - \frac{1}{2} \cdot (M_1 \cdot V_{1f}^2 + M_2 \cdot V_{2f}^2) \quad (\text{EQ 1})$$

by substituting the residual velocities in the equation above, the energy dissipation equation becomes;

$$E_d = \frac{1}{2} \cdot (M_1 \cdot V_{1i}^2 + M_2 \cdot V_{2i}^2) - \frac{1}{2} \cdot \left(M_1 \cdot \left[\frac{[(C_r + 1) \cdot M_2 \cdot V_{2i}] + [V_{1i} \cdot [M_1 - (C_r \cdot M_2)]]}{M_1 + M_2} \right]^2 + M_2 \cdot \left[\frac{[(C_r + 1) \cdot M_1 \cdot V_{1i}] + [V_{2i} \cdot [M_2 - (C_r \cdot M_1)]]}{M_1 + M_2} \right]^2 \right)$$

for Mass Transit Bus to Vehicle frontal collisions we can assume that the coefficient of restitution is approximately zero, hence the energy dissipation equation becomes;

$$E_d = -\frac{1}{2} \cdot M_1 \cdot M_2 \cdot \frac{V_{1i}^2 + V_{2i}^2 - 2 \cdot V_{2i} \cdot V_{1i}}{M_1 + M_2} \quad (\text{EQ 2})$$

The equation above (EQ 2) can be used to predict the amount of energy absorbed by both vehicles during impact, given that the masses and initial velocities are known. If initial and final velocities are known then equation 1 should be used.

Another method to find the total energy dissipated during impact can be calculated when the vehicle stiffness's and crush values are known;

$$E_d = \int_0^{X_{c1}} F(x)_1 \cdot dx_1 + \int_0^{X_{c2}} F(x)_2 \cdot dx_2 \quad (\text{EQ 3})$$

If we assume a linear behavior for the vehicle stiffness equation 3 becomes;

$$E_d = \frac{1}{2} \cdot K_1 \cdot X_{c1}^2 + \frac{1}{2} \cdot K_2 \cdot X_{c2}^2 \quad (\text{EQ 4})$$

In order to find the crush distance of the partner vehicle we can combine equations two and four into the following expression (EQ 5):

$$X_{c1} = \frac{1}{K_1} \cdot \left[-K_1 \frac{\left(\begin{aligned} & -M_1 \cdot M_2 \cdot V_{1i}^2 - M_1 \cdot M_2 \cdot V_{2i}^2 \\ & + 2 \cdot M_1 \cdot M_2 \cdot (-V_{1i}) \cdot V_{2i} \\ & + K_2 \cdot X_{c2}^2 \cdot M_1 + K_2 \cdot X_{c2}^2 \cdot M_2 \end{aligned} \right)}{M_1 + M_2} \right]^{\frac{1}{2}}$$

Where;

- C_r , Coefficient of Restitution
- E_d , Energy Dissipation
- F_b , Structural Force, Bus
- F_v , Structural Force, Partner Vehicle
- K_1 , Linear Stiffness, Partner Vehicle
- K_2 , Linear Stiffness, Bus
- M_1 , Mass, Partner Vehicle
- M_2 , Mass, Bus
- V_{1f} , Final Impact Velocity, Partner Vehicle
- V_{1i} , Initial Impact Velocity, Partner Vehicle
- V_{2f} , Final Impact Velocity, Bus
- V_{2i} , Initial Impact Velocity, Bus
- X_{c1} , Crush Distance, Partner Vehicle
- X_{c2} , Crush Distance, Bus

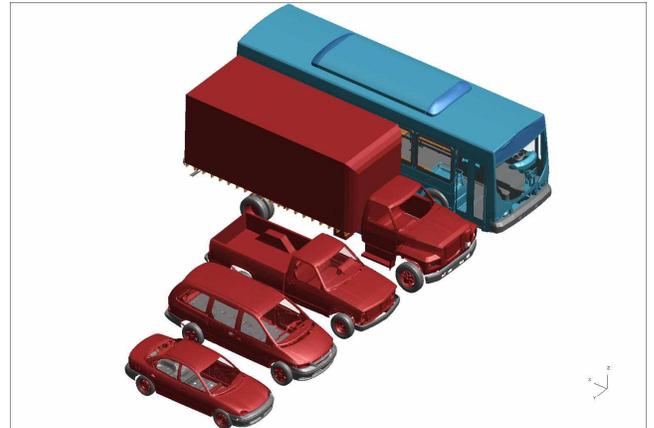


Figure 5. Finite Element Model Vehicles.

Overview Vehicle Numerical Models Databases

Numerical models were used to conduct this compatibility study. The low floor mass transit bus model has been validated for frontal, rear, side and rollover impact conditions (for more detailed model information refer to reference 4). The Dodge Caravan and Neon finite element models have been validated for frontal and offset impact conditions (for more detailed model information see reference 5). Although there is no validation report available for the F800 and C2500 finite element models, these models were used to evaluate the mass transit bus performance. Table one provides an overview of the vehicles weight.

Accelerometers in the area of the lower B-pillar were selected for the analysis, see figure 6 for the location in the mass transit bus, and figure 7 for the location in the collision partner.

Table 1.
Vehicles mass overview

Vehicle	Mass (kg)	Mass Ratio
Bus	10360	1
F800	7792	0.75
Caravan	2043	0.19
C2500	1813	0.175
Neon	1333	0.13

Table 2.

Vehicle stiffness overview calculated from 30 mph rigid barrier tests

	Linear Stiffness	Mass	Maximum Disp.
Bus*	5176	10360	0.6
Neon**	708.7	1354	0.686
Caravan**	904.2	2003	0.757
	kN/m	Kg	m

* Based on simulation results. ** Based on NHTSA Tests [6].

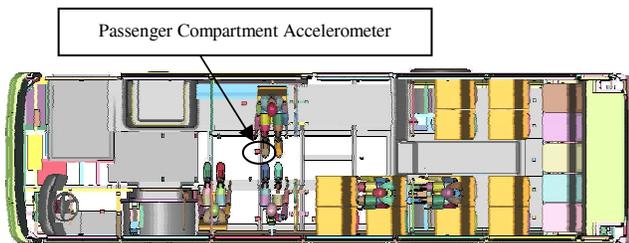


Figure 6. Transit Bus Accelerometer Location.

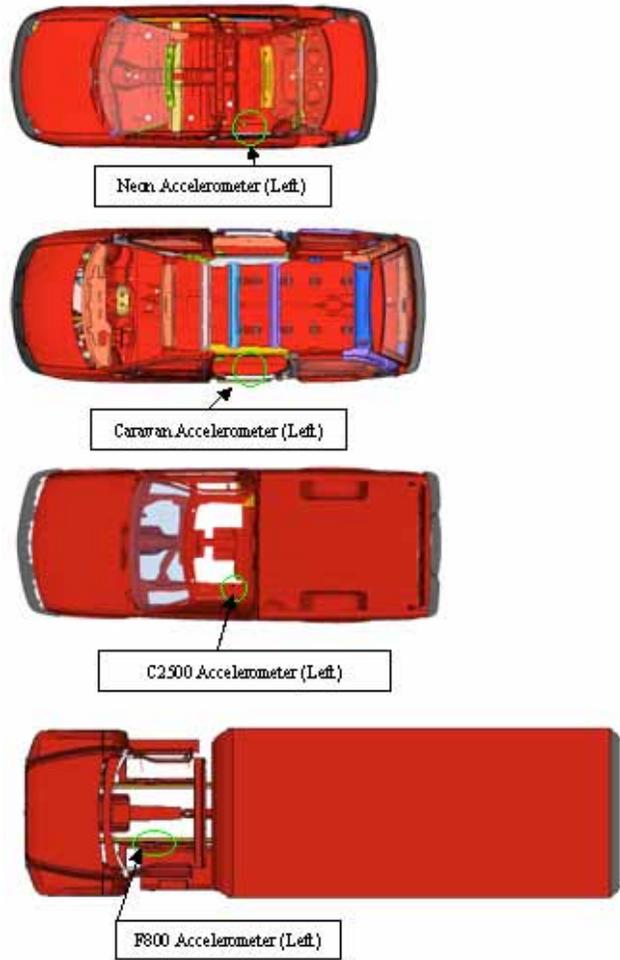


Figure 7. Collision Partner Accelerometer Locations.

SUMMARY SIMULATION RESULTS

Based on the data collected from typical mass transit bus accidents [7], the following frontal and rear impact conditions were analyzed

Table 3.

Summary impact conditions

Case	Impact Condition
1	Frontal: Bus - 30 mph (48.3 kph) : F800 – 30 mph
2	Frontal: Bus - 30 mph : Dodge Caravan - 30 mph
3	Frontal: Bus - 30 mph : Dodge Neon - 30 mph
4	Rear: Bus - 0 mph : Bus – 20 mph (32.2 kph)
5	Rear: Bus - 0 mph : Dodge Caravan - 20 mph
6	Rear: Bus - 0 mph : Dodge Neon - 20 mph
7	Rear: Bus - 0 mph : Chevy 2500 C - 20 mph

Frontal Impact Simulation Results

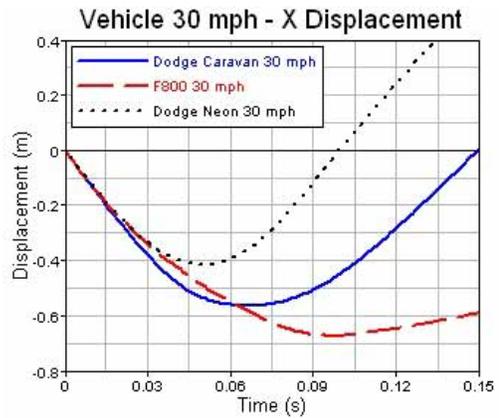
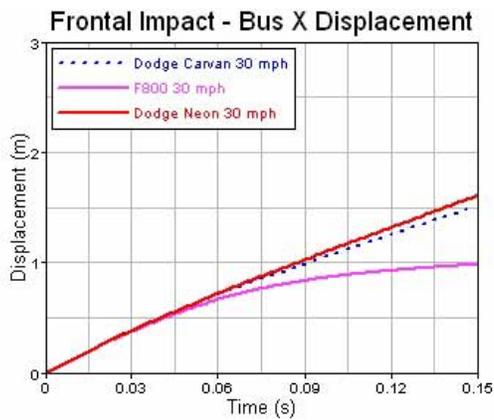
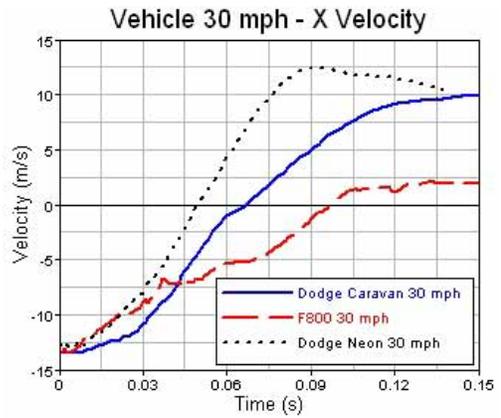
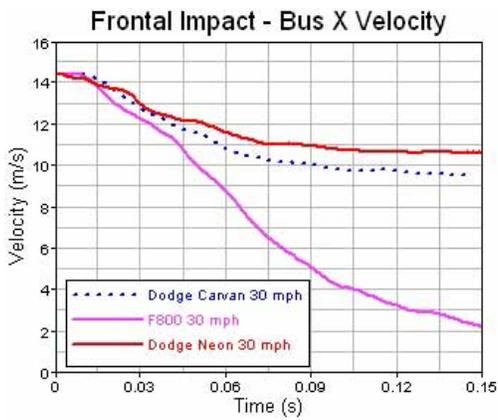
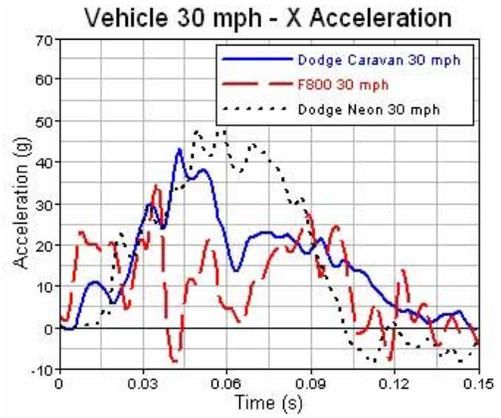
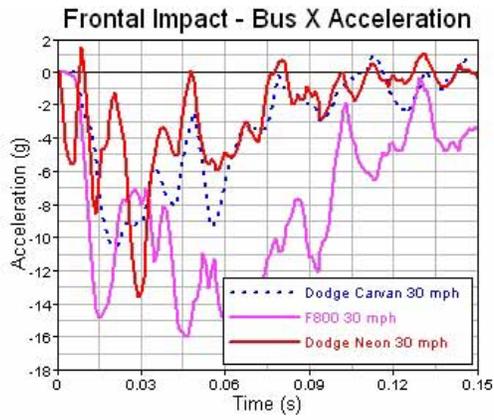


Figure 8. Mass Transit Bus Passenger Compartment Acceleration Velocity and Displacement.

Figure 9. Partner Vehicle B-Pillar Acceleration, Velocity and Displacement.

Rear Impact Simulation Results

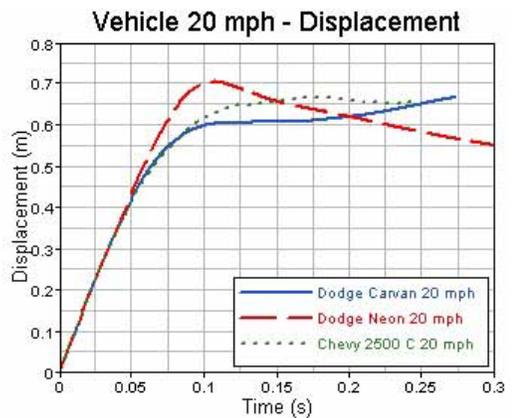
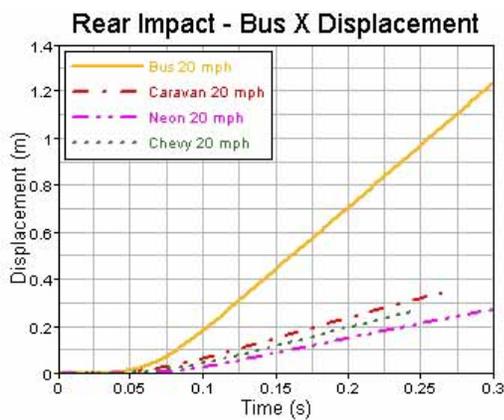
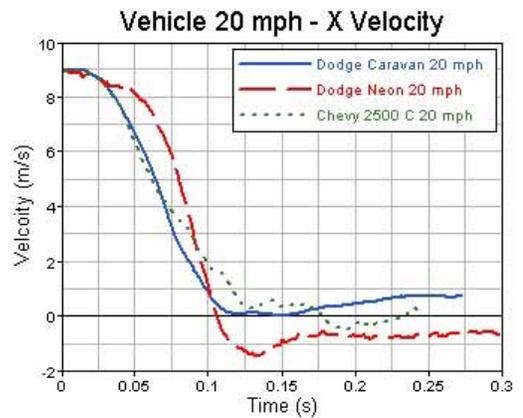
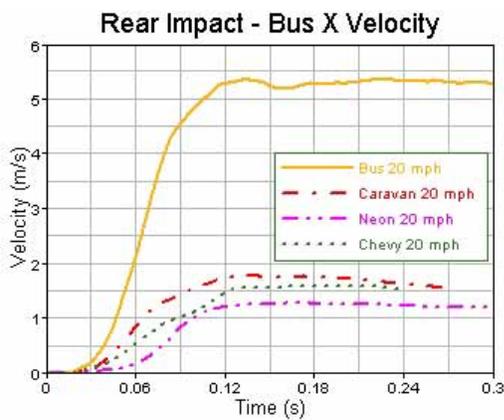
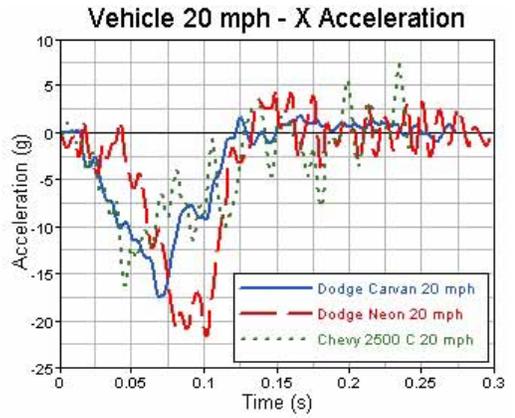
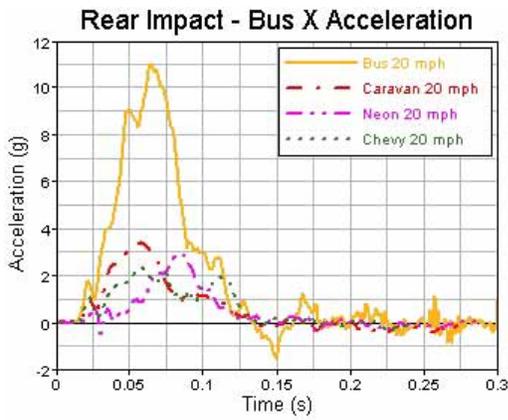


Figure 10. Mass Transit Bus Passenger Compartment Acceleration Velocity and Displacement.

Figure 11. Partner Vehicle B-Pillar Acceleration, Velocity and Displacement.

GEOMETRIC COMPATIBILITY

Bus underbody clearance is defined in SAE J698 standard. This standard specifies the minimum clearance regardless of load up to the gross vehicle weight rating. As shown in figure 12 the approach angle shall be no less than 8 degrees, the departure angle shall be no less than 9 degrees, and the ground clearance shall be no less than 8.5 inches (216 mm) except within the axel zone and wheel area [8].

Bumpers shall provide impact protection for the front and rear of the bus with the top of the bumper being 26 ± 2 inches (660 ± 51 mm) above the ground. The front bumper system must comply with the following impact conditions defined in the Standard Bus Procurement Guidelines [8]:

- No part of the bus, including the bumper, shall be damaged as a result of a 5-mph (8 kph) impact of the bus at curb weight with a fixed, flat barrier perpendicular to the bus' longitudinal centerline.
- The bumper shall protect the bus from damage as a result of 6.5 mph (10.5 kph) impacts at any point by the Common Carriage with Contoured Impact Surface defined in FMVSS 301 loaded to 4,000 pounds (1814 kg) parallel to the longitudinal centerline of the bus and 5.5-mph (8.9 kph) impacts into the corners at a 30 degree angle to the longitudinal centerline of the bus.

The rear bumper system must comply with the following impact conditions defined in the Standard Bus Procurement Guidelines [8]:

- No part of the bus, including the bumper, shall be damaged as a result of a 2-mph (3.2 kph) impact with a fixed, flat barrier perpendicular to the longitudinal centerline of the bus.
- The rear bumper shall protect the bus, when impacted anywhere along its width by the Common Carriage with Contoured Impact Surface defined in Figure 2 of FMVSS 301 loaded to 4,000 pounds (1814 kg), at 4 mph (6.4 kph) parallel to, or up to a 30 degree angle to, the longitudinal centerline of the bus.
- The rear bumper shall be shaped to preclude unauthorized riders standing on the bumper.

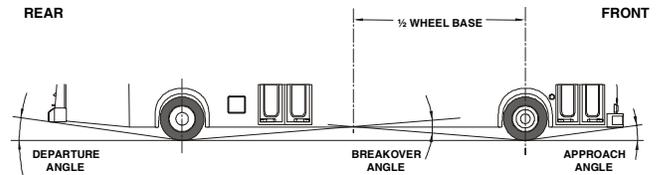


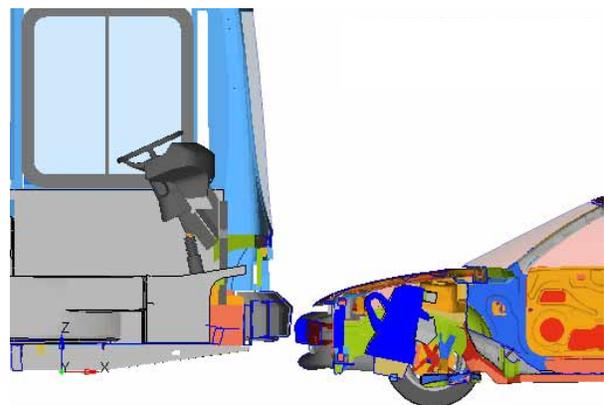
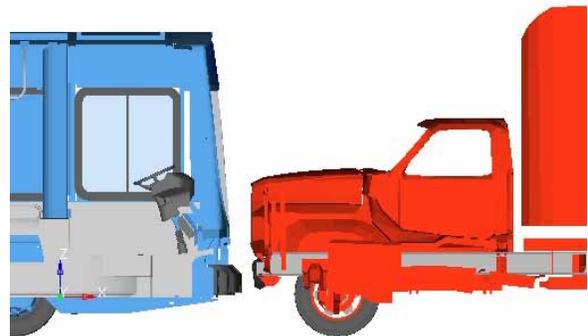
Figure 12. Transit Bus Diagram [8].

Frontal Impact 30 mph 100 % Overlap

According to data presented collected by the IHRA working group, typical frontal longitudinal member heights for sedans are in the range of 380/500 mm, and for SUV/Trucks in the range of 440/550 mm.

As shown in figures 13 through 16 the mass transit bus bumper system aligns with the frontal structural elements of the Dodge Neon and Caravan. There is a height mismatch between the bus and the F800; this could be prevented by increasing the height of the bus bumper or by equipping heavy trucks with under-ride devices.

Current Mass Transit Bus frontal bumper design standards provide the required data to design geometrically compatible frontal bumper systems with the majority of road vehicles.



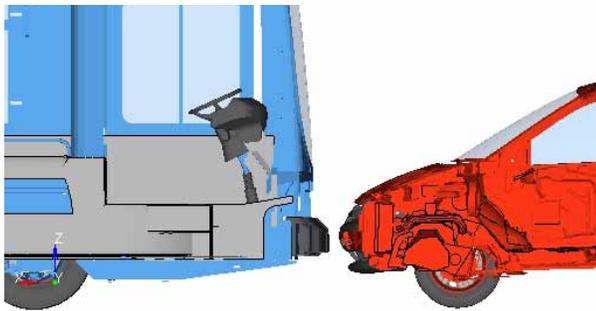
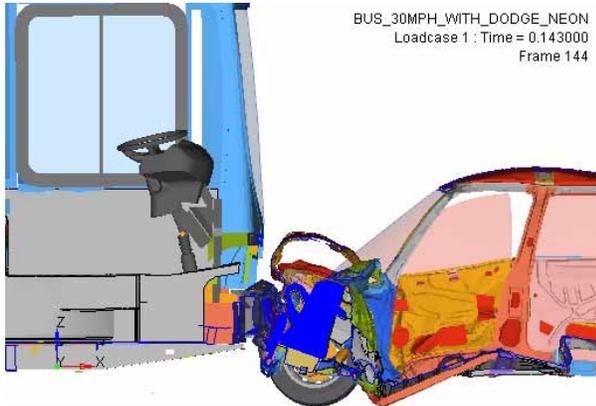


Figure 13. Frontal Impact Geometric Compatibility.

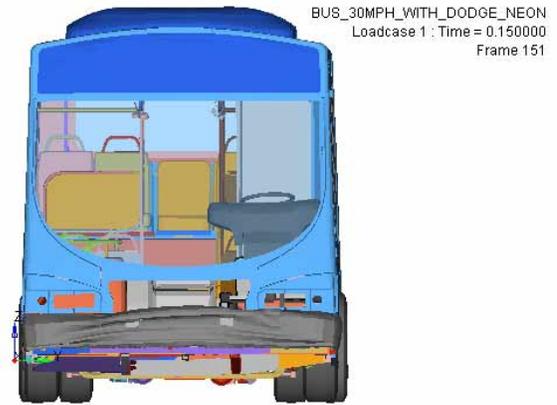
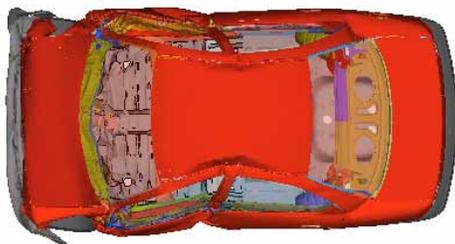


BUS_30MPH_WITH_DODGE_NEON
Loadcase 1 : Time = 0.143000
Frame 144

BUS_30MPH_WITH_DODGE_NEON
Loadcase 1 : Time = 0.150000
Frame 151

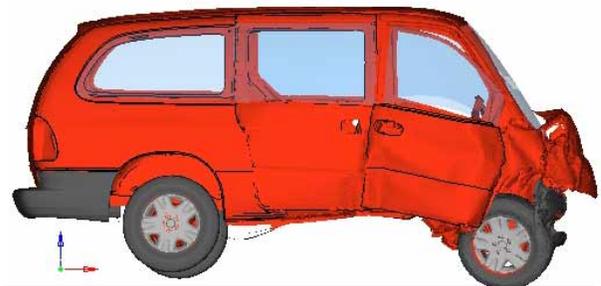
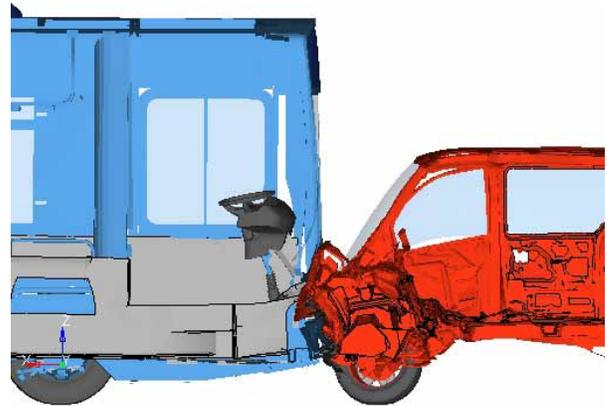


BUS_30MPH_WITH_DODGE_NEON
Loadcase 1 : Time = 0.150000
Frame 151



BUS_30MPH_WITH_DODGE_NEON
Loadcase 1 : Time = 0.150000
Frame 151

Figure 14. Neon-Transit Bus Interaction.



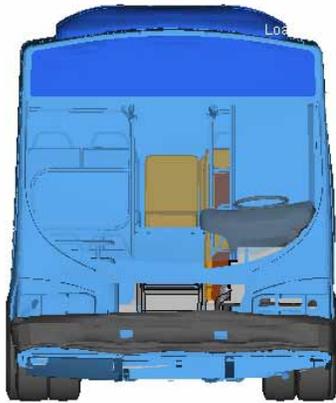


Figure15. Caravan-Transit Bus Interaction.

of the Dodge Caravan, C2500, and bullet mass transit bus. There is a height mismatch between the bus and the Dodge Neon; this could be prevented by lowering the height of the bus rear bumper system. Even though there is a height mismatch between the Neon and the transit bus the deceleration levels experience by the Dodge Neon are well below the 30 g deceleration threshold.

Current mass transit bus frontal bumper design standards provide the required data to design geometrically compatible bumper systems with the majority of road vehicles.

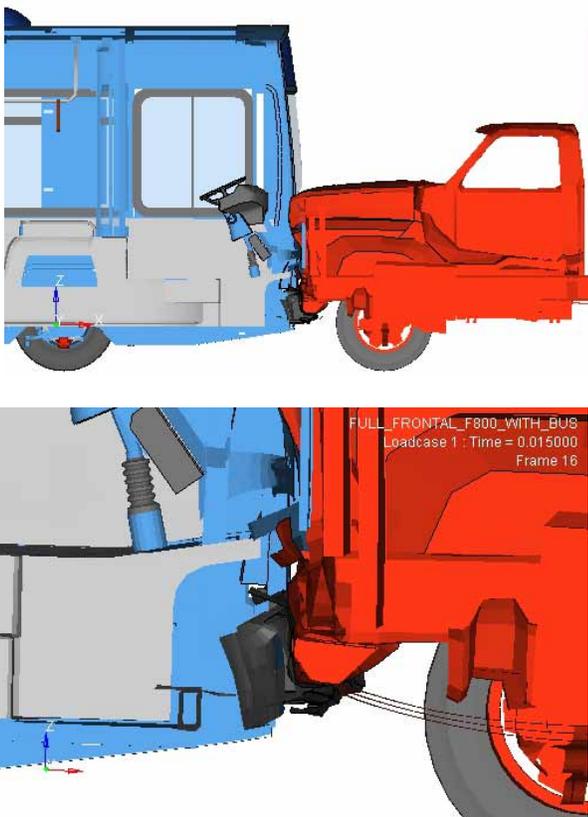


Figure16. F800 -Transit Bus Interaction.

Rear Impact 20 mph 100% Overlap

According to data obtained from “Mass Transit Crashworthiness Statistical Data Analysis” [7], the majority of rear impacts tend to occur at velocities below 30 mph (48.3 kph).

As shown in figures 17 through 19 the mass transit bus bumper system aligns with the frontal structural elements

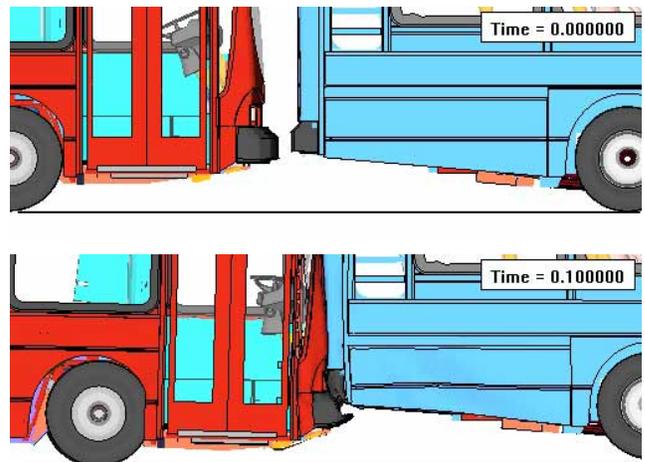


Figure 17. Bus 20 to Stationary Transit Bus.

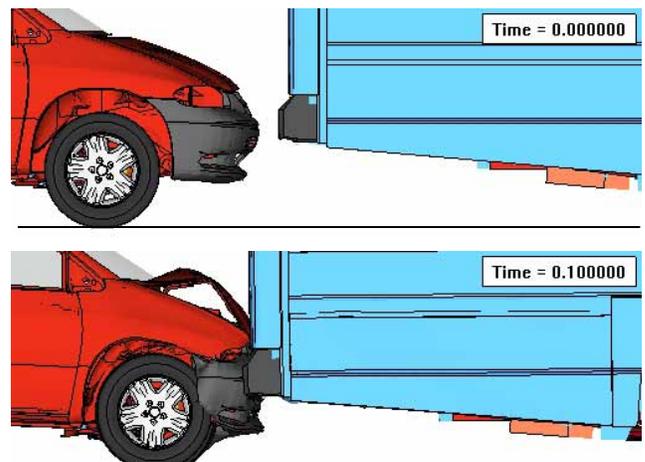


Figure 18. Caravan 20 mph to Stationary Transit Bus.

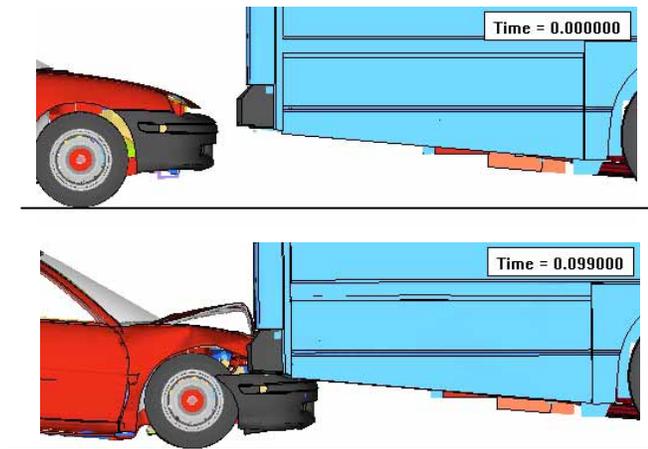


Figure 19. Neon 20 mph to Stationary Transit Bus.

MASS COMPATIBILITY

The conservation of momentum in a collision places smaller vehicles at a fundamental disadvantage when the collision partner is a heavier vehicle. As shown in table 1, there is a large difference in mass between the transit bus and the Dodge Neon/Caravan. Figure twenty illustrates the different range of energy absorbing specifications for the vehicles in this study versus the mass of the collision partner by using the equation derived in the previous section.

$$E_d = -\frac{1}{2} \cdot M_1 \cdot M_2 \cdot \frac{V_{1i}^2 + V_{2i}^2 - 2 \cdot V_{2i} \cdot V_{1i}}{M_1 + M_2}$$

Transit buses should be designed to absorb with its partner vehicle energy levels ranging from 424 kJ (impact with a small vehicle of mass 1333 kg) to 2000 kJ (impact with a large vehicle of mass 12000 kg). Compact vehicles such as the Dodge Neon will experience with its partner vehicle energy levels ranging from 239 kJ to 432 kJ (impact with a large vehicle of mass 12000 kg).

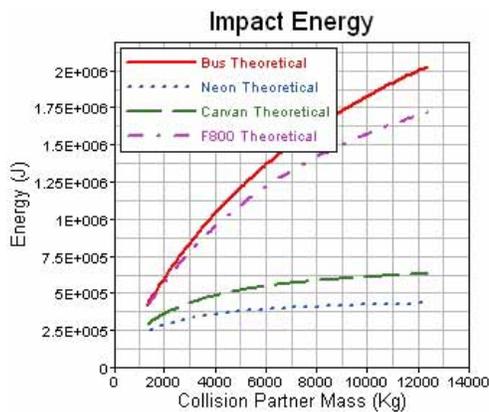


Figure 20. Crash Energy Dissipation vs. Collision Partner Mass for a 30 mph Frontal Collision.

The energy dissipated by the vehicles structure upon impact is defined by the difference in kinetic energy pre and post-crash. By applying the residual velocity values calculated with the finite element simulations (see figures 8 and 9) we can calculate the energy dissipation with the following equation;

$$E_d = \frac{1}{2} \cdot (M_1 \cdot V_{1i}^2 + M_2 \cdot V_{2i}^2) - \frac{1}{2} \cdot (M_1 \cdot V_{1f}^2 + M_2 \cdot V_{2f}^2)$$

The results of the Neon, Caravan, and F800 are plotted against the energy level prediction calculated with equation 2. Note that equation 2 can be used without prior knowledge of the residual velocities, see figure 21.

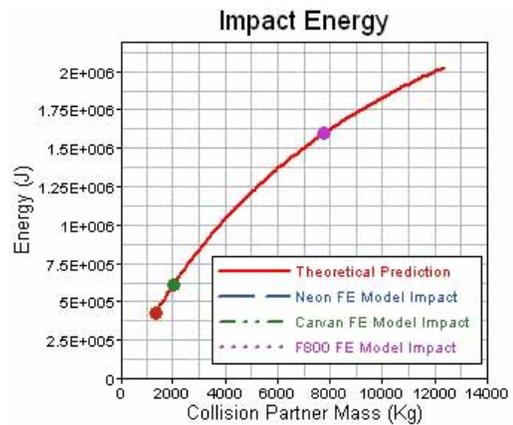


Figure 21. Crash Energy Dissipation Theoretical Prediction vs. Finite Element Model Results for a 30 mph Collision with a Transit Bus.

Other parameter influenced by mass is stiffness as shown in table 2. Variability in linear stiffness is directly proportional to the change in mass. For large mass differentials such as the Bus/Neon or Bus/Caravan the partner vehicle decelerates from impact velocity down to zero within the first 60 ms, afterwards it is accelerated to the residual velocity of the bus (See figures 22 and 23).

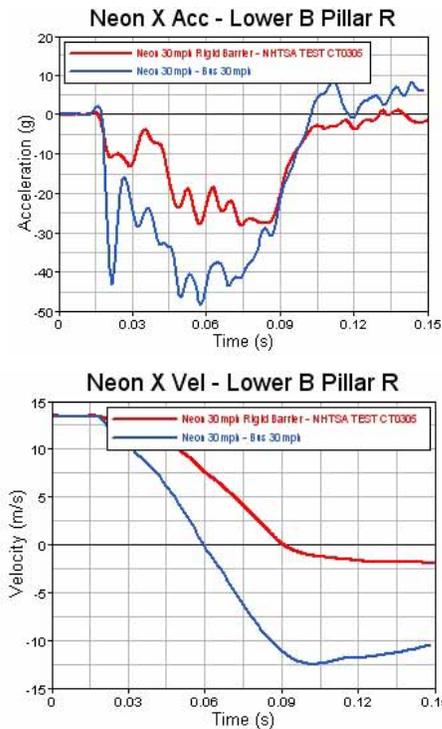


Figure 22. Dodge Neon Acceleration and Velocity at Lower B-Pillar Accelerometer Location, Comparison 30 mph Bus Impact vs. Rigid Barrier 30 mph NHTSA Test.

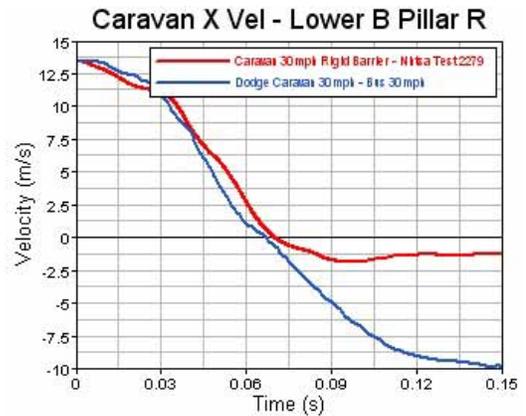
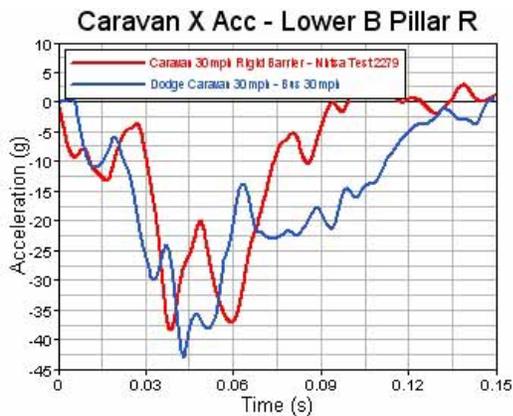


Figure 23. Dodge Caravan Acceleration and Velocity at Lower B-Pillar Accelerometer Location, Comparison 30 mph Bus Impact vs. Rigid Barrier 30 mph NHTSA Test.

STRUCTURAL STIFFNESS COMPATIBILITY

In the frontal collisions analyzed in this study, the vehicle with the lower stiffness (i.e. Caravan, and Neon) absorbs the bulk of the crash energy. For example in the 30 mph impact between the transit bus and the Dodge Caravan; the bus structure absorbs 108 kJ (18 %) while the Dodge Caravan structure absorbs 505 kJ (82 %). This results in large deformations of the partner vehicles as shown in figure 14, 15, 24, and 25. These large deformations in the partner vehicle can increase the injury potential for their drivers, and passengers.

In order to improve vehicle compatibility both vehicles need to dissipate equal levels of energy. Since mass is a fixed parameter, improvement can only be achieved by increasing the bus crush distance under load.

Due to the current transit bus design constraints, it may be difficult to increase the vehicle deformation to the desired levels without implementing variable stiffness active bumper systems triggered by pre crash sensors.

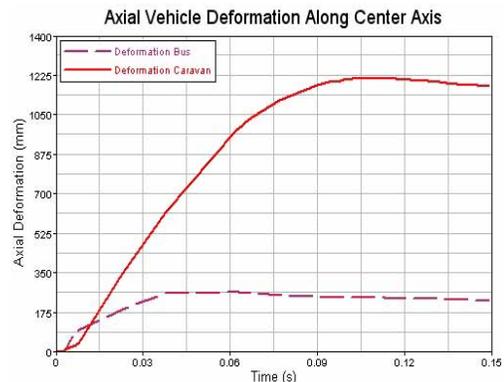


Figure 24. Mass Transit Bus and Caravan Change in Length, FE Simulation Results.

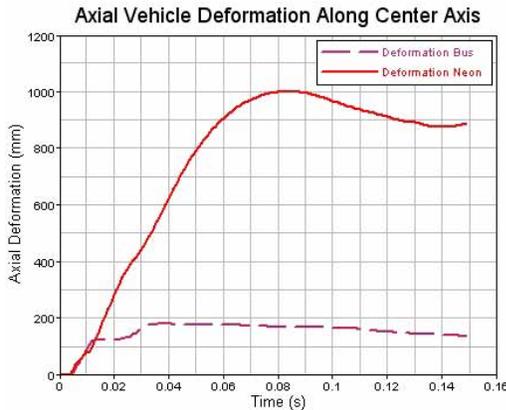


Figure 25. Mass Transit Bus and Neon Change in Length, FE Simulation Results.

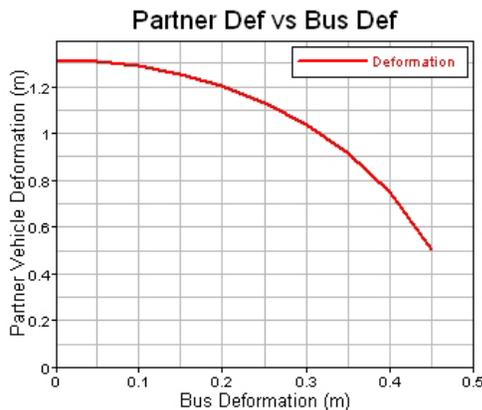


Figure 26. Calculated Increase in Bus Deformation vs. Decrease Dodge Caravan Deformation.

CONCLUSION

Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur.

The results of this study show that current transit bus bumper geometry design guidelines [8] generate bumper designs that are compatible from a geometric point of view with most vehicles on the road today. The only issue may be insufficient height to improve its compatibility with larger trucks; in fact according to the Traffic Safety Facts statistics from 1999 to 2003 most of the occupant fatalities occur when the bus impacts a large truck (see figure 1).

In order to improve vehicle compatibility both vehicles need to dissipate equal levels of energy. Since mass is a fixed parameter, improvement can only be achieved by increasing the bus deformation under load. Due to the current transit bus design constraints, it may be difficult to increase the bus structural deformation to the desired levels

without implementing variable stiffness active bumper systems triggered by pre crash sensors.

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