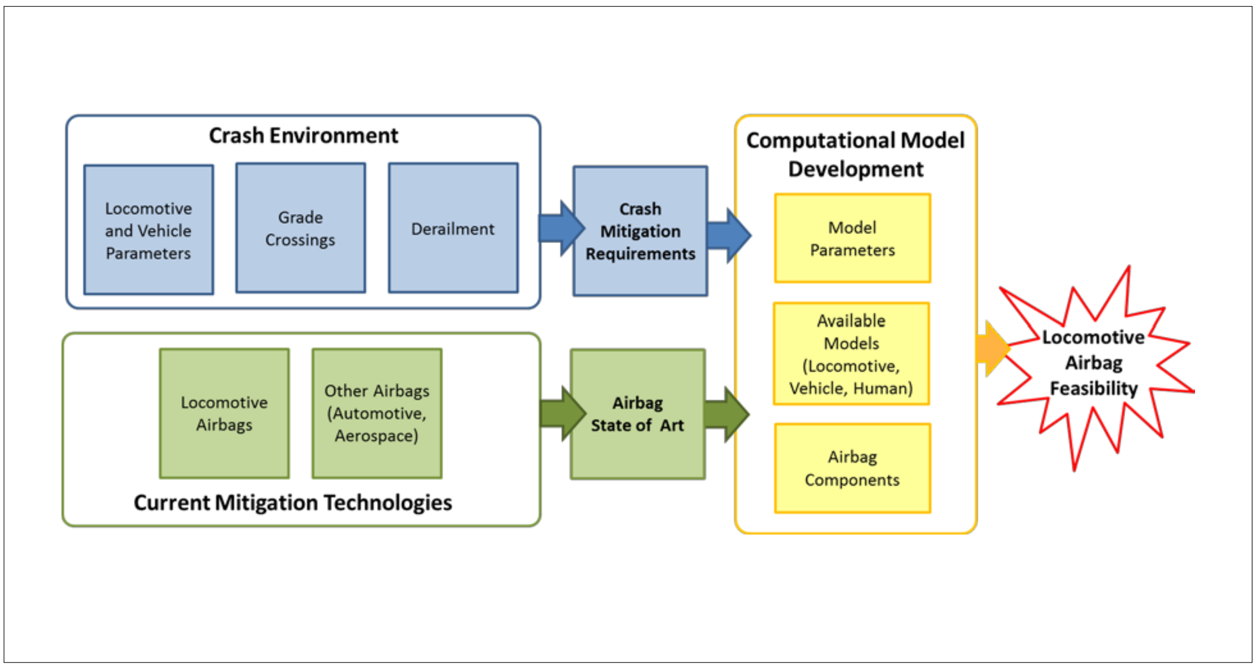
U.S. Department of Transportation

Federal Railroad Administration

The Use of Air Bags for Mitigating Grade Crossing and Trespass Accidents: Literature Review and Research Plan

Office of Research, Development,
and Technology
Washington, DC 20590



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This literature review will confirm prior work in the use of locomotive airbag technologies for vehicle or pedestrian collision mitigation, and to focus planned activities and tasks for this research. The state of the art in relevant technologies has been summarized to assess the feasibility of this technology and identify critical model challenges for supporting impact simulations. The literature review did not reveal any currently deployed locomotive airbag solutions. In patent literature, external airbag technology has been described for mitigation of crashes between railcars and motor vehicles, but no meaningful analysis of feasibility has been discussed in detail in scientific or professional literature. Therefore, it appears that although crash mitigation technology using airbags in front of locomotives has been conceptualized, it has not yet been rigorously engineered or implemented.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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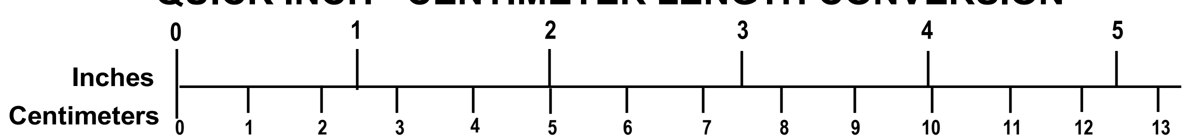

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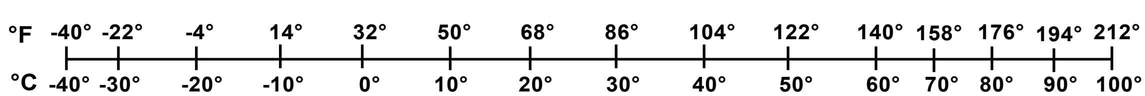

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Executive Summary

This literature review confirms prior work in the use of locomotive airbag technologies for vehicle or pedestrian collision mitigation, and to focus planned activities and tasks for this research. This report summarizes the state of the art in relevant technologies to assess the feasibility of this technology and identify critical model challenges for supporting impact simulations. The literature review did not reveal any currently deployed locomotive airbag solutions. In patent literature, external airbag technology has been described for crash mitigation between railcars and motor vehicles, but no meaningful analysis of feasibility has been discussed in detail in scientific or professional literature. Therefore, it appears that although crash mitigation technology using airbags in front of locomotives has been conceptualized, it has not yet been rigorously engineered or implemented.

Prior applications of airbag-based crash mitigation systems for large vehicles have been demonstrated. Deployed external airbags have been successfully used for impact mitigation in the Mars lander and proposed for impact mitigation in the Orion Space capsule, in helicopters, and in automobiles (e.g., front-to-side impact vehicle crashes and vehicle-pedestrian crashes). The sizing and the necessary components for these related applications are sufficient to mitigate automobile crashes; therefore, the research results in these applications show that an airbag-based solution for locomotive-automobile crash mitigation is likely to be viable.

A variety of computational tools exist to investigate the feasibility of locomotive airbags and identify the critical design requirements for such systems. Simulations would focus on the development of relevant airbag materials and parameters (e.g., size, material strength, location) and the overall kinematics between train and impacted vehicles or pedestrians that would reduce the risk of injury.

The following overall observations were generated from this review:

- Airbag-based mitigation of human injury risk in locomotive-road vehicle collisions has been conceptualized but not put into practical implementation.
- Existing airbag technologies that have been successfully employed in the automotive and aerospace industries may be adaptable for use in locomotive applications.
- While airbag technology can mitigate the initial collision, careful consideration of post-crash behavior must be included in the design and analysis of crash mitigation systems to prevent subsequent inertia-related damage to vehicles and their occupants.
- Computational models of locomotives, a range of occupant vehicle types (small vehicle, small truck, and large truck), and human kinematics are readily available for collision analysis.

1. Introduction

This literature review surveyed relevant background information from both the crash environment and current mitigation technologies to understand the state of the art and technical requirements for deployment of airbag-based crash mitigation systems for locomotives (Figure 1). The literature describing the locomotive crash environment focused on grade crossings and closely analogous situations, in order to assess the environment in which such a collision can be considered. Analyses of derailment in collisions with road-going or other vehicles were also reviewed since derailment in a collision is significantly more dangerous than a simple collision. The available mitigation technologies were reviewed next, including existing ideas for locomotive crash mitigation and analogous external airbag literature for automobiles, helicopters, and spacecraft. These findings will establish the crash mitigation requirements and the state of the art for airbags, which will focus attention on the computational impact simulation assessments of locomotive airbag feasibility.

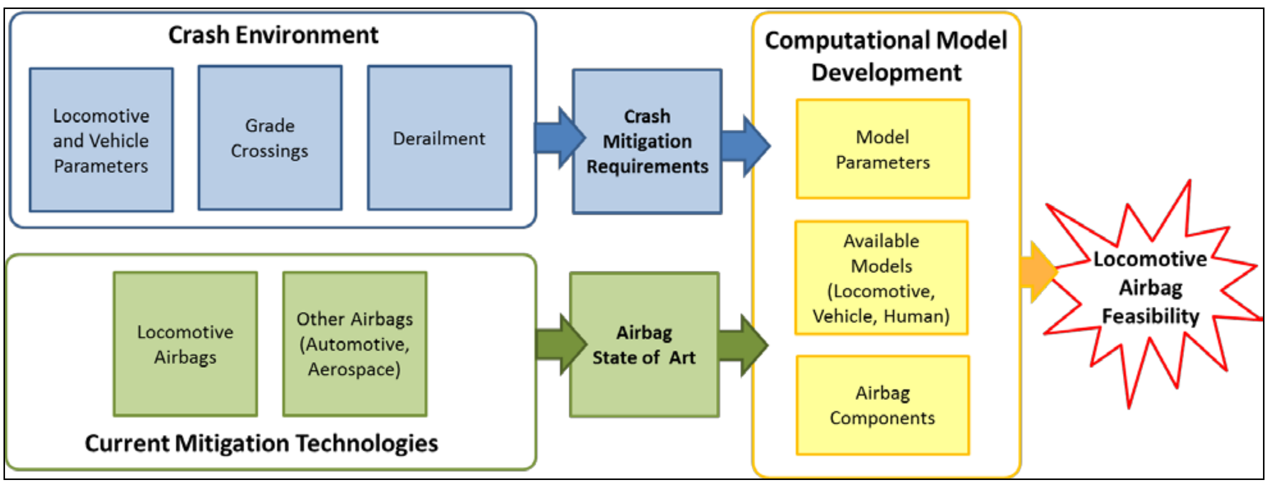

Figure 1. Background Components in Computational Modeling Efforts

2. Crash Environment

2.1 Locomotive and Struck Vehicle Parameters

The impacting vehicle in this project has been specified as a locomotive, but does not provide specifics for locomotive model or design. Therefore, as a relevant geometry, an LS-Dyna model of the SD70 MAC locomotive will be used. It is important to note that the resulting feasibility analysis of the airbag components (size, pressure, baffles, deployment methods) for crash mitigation will not be limited by the geometry of this specific locomotive, but should be applicable for a broad range of relevant locomotive models.

The struck vehicles have been selected in this project as a small car (roughly 2,500 lb), a mid-size pickup truck (roughly 5,000 lb), a tractor-trailer (roughly 15,000 lb), and a school bus (roughly 10,000 lb), as described in Section 5.2. LS-Dyna models for the passenger cars are available from the National Crash Analysis Center (NCAC), and the tractor-trailer model is available from the National Transportation Research Center. A model for a passenger bus is available from NCAC, and a school bus model has been developed by the Mercer Engineering Research center (MERC), although availability is not yet known (see below).

The approximate size and weight of vehicles anticipated for use in simulated crash impacts are shown in Table 1. Details of the vehicle geometries and available modeling tools are discussed in Section 5.2 of this report.

Table 1. Approximate Size and Weight Parameters of Locomotive and Struck Vehicles

Vehicle Type	Model	Weight (pounds)	Dimensions (feet) (length × width × height)
Locomotive	SD70 MAC	SD70 MAC	74 × 10 × 16
Small sar	Geo Metro	Geo Metro	13 × 5 × 5
Mid-sized pickup truck	Ford F-250	Ford F-250	19 × 7 × 7
Tractor trailer truck	NTRC Model	NTRC Model	TBD
School bus	MERC Model	MERC Model	35 × 8 × 7

2.2 Grade Crossing Collisions

Grade crossings represent the environment with the highest likelihood for occurrence of locomotive impacts with cars or pedestrians. Therefore, a survey of relevant literature studies was conducted to extract details of relevant crash scenarios, such as impact velocities, to provide context for subsequent literature studies of relevant technologies and to guide boundary conditions for future impact simulations.

Collisions at grade crossings involve the entire local environment. The high energy involved in a collision with a locomotive and its following railcars results in an extended crash event. The colliding train usually does not stop during the collision but proceeds until braking brings it to a stop. To develop a useful model for a grade crossing, and to understand the eventual resting point of the struck vehicles, the overall layout of the crossing must be specified. The dimensions of the grade crossing typically depend on the number of locomotive rails and the number of lanes on the crossing roadway. The specific location of a collision on the grade crossing is important, because the grade crossing has a finite width, and the rails on a road bed can have a significant effect on the path of a struck vehicle if the vehicle is pushed past the edge of the grade crossing. Grade crossing design has received substantial attention [1], including design factors that are meant to decrease the incidence of collisions with freight or passenger locomotives [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Specific discussion of derailments [13, 14, 15, 16, 17, 18, 19, 20], pedestrian accidents [21, 22, 23, 24], and vehicular accidents [25, 26, 27] are available. Discussions of European [28, 29, 30], Indian [31] Australian [32], and Japanese [33] experiences in prevention strategies are also available. Although many common aspects of grade crossing designs exist to minimize accidents, the experiences indicate that accidental collisions will occur at grade crossings.

Estimates of collision speed for freight train collisions are also available [34]. The range of 10 to 60 miles per hour (mph) spans nearly all the reported impact speeds in the reported collisions, and a relative peak is apparent at 20-30 mph.

Surveys of driver injuries due to grade crossing collisions are available [35, 36, 37, 38, 39]. They show that grade crossing accidents have been mitigated by good crossing design, but that collisions are a continuing issue. Older and female passengers tend to sustain more serious injuries in a grade crossing collision, and the likelihood of serious injury increases with the speed of the road-going vehicle. While grade crossing design can decrease the incidence of these collisions, their consequences are sufficiently dire to make mitigation technology relevant and important.

2.3 Derailment Analyses in Collisions

Derailment is the most dangerous result of a collision, given the mass of the locomotive and the trailing railcars. Analyses of derailment in general, and of derailment in collisions, exist in the literature [40, 41, 42, 43, 44, 45, 46] based on wheel-climbing dynamics. Derailment in collisions due to side loads on the railset has been addressed [47, 48] based on rail climbing. Other analyses of derailment in crash scenarios are based on the dynamics of the whole consist and the changes in side and vertical loads to be expected during a collision. These calculations are well-developed, and we used VI-Rail to perform them [49].

Derailment due to debris from a collision is a significant risk, because the hard steel components of an automobile (wheels, axles, springs, etc.) can become loose on the rails and disrupt the wheel-rail interaction of the leading wheelset. This is more likely when a struck vehicle is pushed along the rail bed ahead of the train. Butler [50] describes a collision mitigation system that is intended to lift colliding vehicles onto a flatbed, using a ramp, and then cushion the collision. If feasible, that technology would mitigate the risk of derailment by lifting the automobile off the railbed and away from the wheelsets; however, it seems expensive and cumbersome for day-to-day use.

2.4 Crash Mitigation Requirements Summary

The following list summarizes observations generated from this portion of the literature review:

- Effective crash mitigation efforts should target displacement of an impacted vehicle to the side of the railway, removing it from the path of the locomotive. This is because the mass of the locomotive and trailing rail cars is very large compared to that of the struck vehicle, and although the train may be applying brakes, the leading car will proceed across the grade crossing for a very substantial distance. This is different from most other crash mitigation scenarios, where the striking vehicle will stop in a short distance.

- Overall dimensions of the grade crossing and location of the impacted objects in the crossing will influence the post-crash impact mechanics and should be considered in analysis of mitigation strategies.
- Train derailment represents a "worst case" crash scenario, wherein the train can impact objects removed from the track, in addition to producing complex crash dynamics. Effective strategies to mitigate peripheral damage resulting from locomotive impacts should focus on maintaining the railcar on the rails.

3. Current Airbag/Deployable Crash Mitigation Technologies

External airbag deployment is a natural extension of crash mitigation using the now-standard internal airbags. Current thinking in automotive crash mitigation is that, between restraints and airbags, the space available within an automobile interior has been almost fully utilized for protection. Therefore, externally deployed mitigation systems (e.g., airbags or collapsible structures) are the most promising next technologies. Statically deployed structures (energy absorbers deployed on the rear of parked vehicles) have become common in highway repair work, as well. The following sections review the existing technologies that use external airbags in mitigating collisions.

3.1 Locomotive Impact Applications Using External Airbags

The literature search performed here did not reveal any currently employed external airbag technologies for improved safety during locomotive impacts with automobiles or pedestrians. Although our literature search showed no currently implemented locomotive airbags, concepts have been considered in the patent literature [51, 52, 53]. In these patents, the inventions are deployable energy absorbers mounted to the front of a locomotive, with several potential energy-absorbing technologies described, including airbags. These patents do provide a general discussion of the estimated airbag size and deployment methods. However, they do not often consider practical implications of the technology, such as visibility, clearance for couplers, or access to the locomotive front door. They also do not address the overall feasibility and cost-effectiveness of the system for grade crossing accidents. Additionally, continued literature searches of many professional scientific databases did not reveal an airbag-based crash mitigation technology for locomotives that has been analyzed quantitatively.

Although not a rigorous scientific study, the search did reveal one effort that explored a mitigation concept. The information was available only in an episode of a Discovery Channel show called “Smash Lab,” which “explored a type of airbag specifically designed for trains in hopes of lessening the impact of crashing into a car” [54]. The team showed a staged collision in which an automobile was impacted by a locomotive with a deployed airbag moving at 25 mph. The impact between the car and train was orthogonal, with impact centered on the vehicle midpoint. No meaningful engineering measurements were taken in this collision, so it is not possible to generalize this experience to a meaningful design. However, the video does show the effect of an automobile being pushed off the grade crossing onto the rail bed. In the video, the wheels of the impacted automobile become positioned outside the rails on the locomotive roadbed as it is pushed off the grade crossing ahead of the locomotive. The vehicle tires are blown, and the wheels of the vehicle slide along the exterior of the rails. This restricts the movement of the automobile, so that it is difficult to move the struck automobile off the roadbed in front of the locomotive. The occupants in an automobile being pushed along a rail by a locomotive are at a very high risk for injury and death due to crushing or shredding of the vehicle frame.

4. Computational Model Development

This section reviews the components that need to be modeled to simulate airbag technologies during a locomotive impact. The goal is to summarize the technology that can be brought to bear to model grade crossing collisions and to model the available technology that can mitigate injuries in the collisions.

4.1 Model Parameters

While externally deployed airbag concepts have not yet been realized for locomotive safety, alternative energy-absorbing and energy-managing devices have been used to mitigate damage in railroad collisions for many years [55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65]. An examination of the existing rail crash mitigation technologies will inform computational parameters, such as material models, of the planned impact simulations between locomotives and occupant vehicles. A series of specifications for rail crashworthiness have been developed [66, 67, 68], and several analyses of specific incidents and structures have been carried out [69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79]. The studies concentrate on the rail car deformation and on the specifics of rail passenger protection; as such, they show the state of the art in modeling, and they indicate the likelihood of deformation in a locomotive collision with an automobile.

The rail crash mitigation analyses show that most road-traveling vehicles have much lower stiffness and strength than railroad cars. Therefore, in this project, as a first approximation, we consider the rail cars as rigid. Also, given the limited scope of this initial investigation, we concentrate on locomotive-led consists. Given the mass and construction of a locomotive, we consider the locomotive as rigid. Also, given the relative mass of a typical passenger or freight locomotive (over 150,000 lb) and the typical mass of a road-traveling vehicle (under 15,000 lb), we consider the velocity of the locomotive as constant during the collision. These operating assumptions will be revisited as necessary.

4.2 Available Locomotive and Vehicle Models for Crash Simulations

4.2.1 Locomotive

Because the goal of this research is a feasibility study, the degree of detail in the models that are available should be chosen to gain insights into specific issues, such as airbag size and shape, the reaction of the struck automobile, and the ability to move the struck vehicle off the track. As such, we will use a specific locomotive model as an impacting vehicle. A large-scale locomotive finite element model is available at JHU/APL. The model is based on a SD70-MAC freight locomotive (Figure 2). As discussed above, this computational model will be considered as rigid, with a constant velocity during the collision analyses.

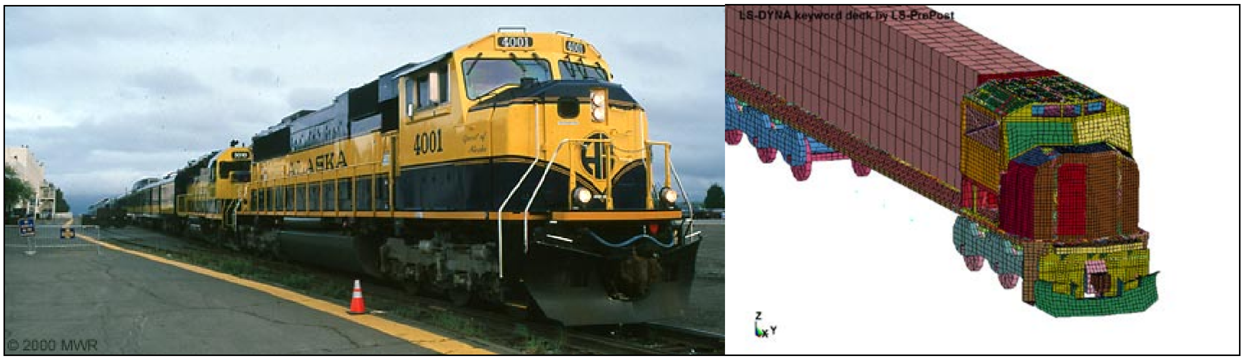

Figure 2. SD70-MAC Finite Element Model

4.2.2 Automobiles

An array of computational models for automobiles is available at the National Crash Analysis Center (NCAC) at George Washington University [80]. These models have been validated against collision testing in specific circumstances, and they are in LS-Dyna format. In this project, we will use the models as discussed in the SOW as targets in the collision analysis. The models are detailed enough to be useful for airbag contact, as will be discussed below. Two automobile models will be used for this project (Figure 3): a small passenger car (Geo Metro), and a mid-size pickup truck (Ford F-250).

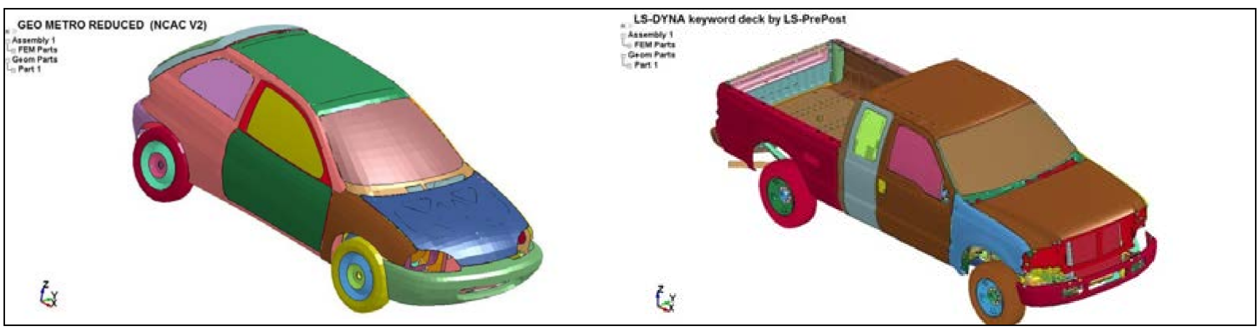

Figure 3. Geo Metro (left) and Ford F-250 (right) Finite Element Models from NCAC

4.2.3 Large Commercial Vehicles

Detailed models for a tractor-trailer (see Figure 4) have been developed under RITA Grant DTRT06G-0043 at the National Transportation Research Center (NTRC) [81]. These computational models, implemented in LS-Dyna, are based on three typical tractor designs and a 48-foot trailer. The models have been verified against experimental crash tests, as discussed on the web site of the National Transportation Research Center [82]. Similarly to the finite element models for vehicles, the geometric detail is well-suited for airbag contact analyses.

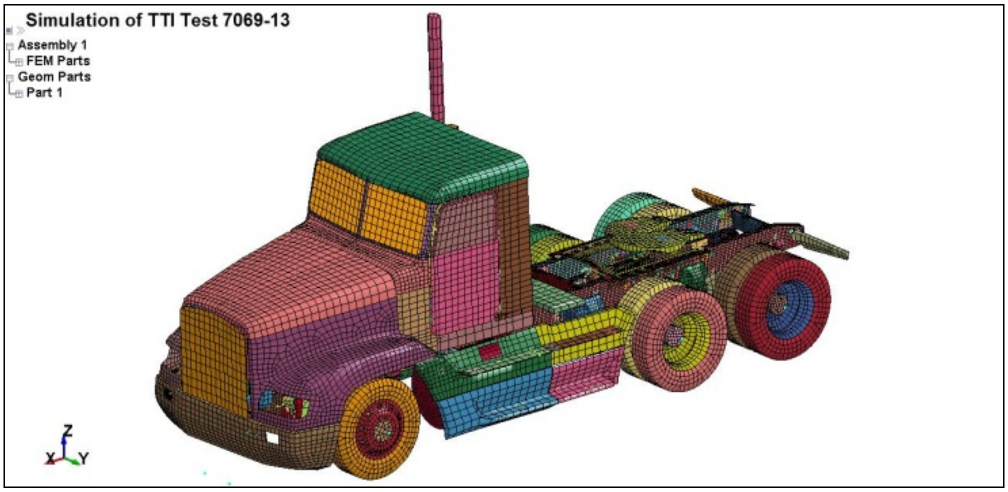

Figure 4. Finite Element Model of Tractor (Day Cab) from NTRC

4.2.4 School Bus

Computational models for school buses in collisions with tractor-trailers have been reported [83, 84], and detailed tests have been run to assess crashworthiness in these extreme situations. However, the wide variation in bus design complicates the collision analysis. The following school bus model (Figure 5) is detailed online from MERC [85], but its availability for use in the current project has not been confirmed.

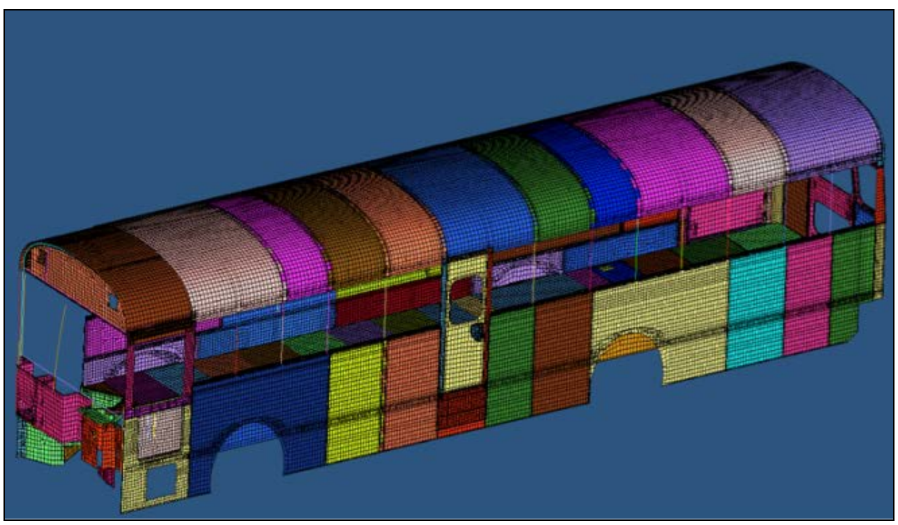

Figure 5. Finite Element Model of School Bus from MERC

4.2.5 Human Models (Pedestrians and Vehicle Occupants)

Computational models of pedestrians are available from several sources, with varying degrees of fidelity. In the existing work on pedestrian impacts with automobiles [86, 87, 88, 89, 90], the pedestrian models typically are based on a MADYMO simulation [91], or a finite element model of the Polar II dummy developed by Honda [92]. Livermore Software Technology Corporation (LSTC) supplies a standing Hybrid-III dummy model as well [93]. Because the dummy models are useful for evaluating overall trends, rather than specific injuries in individuals, they will be used to compare reactions to collision mitigation systems in a parametric fashion.

Standard LSTC Hybrid-III models will be used for evaluating the reactions of passengers in the struck vehicles to collisions in this project. The passenger dummies will be belted using standard techniques, and standard injury metrics will be compared, as in the automotive tests reviewed above [94].

4.2.6 VI-Rail Modeling Components

VI-Rail is a suite of tools that runs within the commercial dynamics code ADAMS [95]. A library of standard rail components is available, along with specific tools to model wheel-track dynamics. ADAMS is a validated commercial code for the dynamic analysis of structures and vehicles, and JHU/APL has an existing software license. VI-Rail will be added to the existing ADAMS capability to perform the analysis of derailment risk during grade-crossing collisions with airbag-based crash mitigation technologies. The decreased peak forces due to a mitigation system will be coupled with an increased time of contact, and the process necessary to deliver the struck vehicle to the side of the rail bed will generate lateral forces on the locomotive. By incorporating these features of the collision, the VI-Rail and ADAMS simulations will evaluate the risk for derailment.

4.2.7 Airbag Crash Mitigation Components

The LS-Dyna tools for airbag modeling are well developed and have been used in several applications [96]. Airbag models will be developed and implemented in simulated locomotive crashes for a variety of impact conditions in order to identify airbag size, stiffness, material characteristics, shapes, and position for optimized protection. In this project, we will use existing airbag technology with a number of modifications and some simplifications. The following assumptions will be made for airbag deployment in the locomotive applications:

- Simulations will model a fully deployed airbag for initial concept feasibility studies. This assumes that if a stopped vehicle is on a grade crossing, ample time will be available for the mitigating equipment to be fully deployed. Therefore, the technology for airbag inflation can be more robust than the technologies for many automotive-based airbag systems (compressed air, high-speed fans, etc.). This assumption may not hold for sudden vehicle crossings (e.g., a speeding vehicle attempting to cross in front of a moving train). However, the tradeoffs necessary for an automatic, high-speed deployment mechanism will be considered in later phases of this program.
- The deployed volume will be substantial, and the deployed shape will require an interior structure for the airbag, similar to inflatable structures used for recreation. Therefore the design of the filling process must consider the interior structure of the airbag.
- The load carried by the mitigation system will be substantial, compared to passenger airbags, but will be in the range of the loads carried in the analogous applications reviewed (see Table 1). This requires careful consideration of the strength of fabrics and joints in the design.

5. Conclusions

A review of existing airbag-based crash mitigation technology relevant to a locomotive collision with a road-going vehicle or pedestrian at a grade crossing has been completed. Airbag-based crash mitigation technology in these collisions has been conceptualized but not engineered to the point where a feasible design has been developed.

The review of technologies from other crash applications (e.g. automotive, aerospace) indicated that an airbag-based crash mitigation system for locomotives at grade crossings is likely to succeed. The goals of such a system are more complex than those of most automotive crash mitigation systems, because the striking vehicle (i.e., the locomotive) will not stop during the collision but will proceed for a significant distance after the collision. The mitigation system must therefore address the process of moving the struck vehicle or pedestrian to the side of the railway in order to be effective.

The next step in the project is to perform computational simulations of locomotive impacts, to investigate feasibility further and to identify design requirements for deployed airbag systems. While there are a number of existing modeling components that could be used in the achievement of this goal, there are also several key technical issues that will require specific expertise:

- **Airbag modeling to estimate proper sizing:** An inflated airbag will compress under load, according to a predictable process in which the bag changes shape, and the baffles, vents, or permeable sections designed into the airbag modify the force-time-deflection characteristics. The design of the airbag will be developed to deliver the struck vehicle or pedestrian to the side of the railway without collapsing the airbag or causing excessive speed for the vehicle or pedestrian.
- **Versatility of the mitigation system:** The goal of the mitigation system is to decrease the potential for injury to pedestrians, occupants of small vehicles, and occupants of large vehicles. Given the large variation of struck objects, a collision mitigation system should be adaptable, either by command from the train crew or through automated sensing during the collision.
- **Mechanisms to exit struck vehicles or pedestrians to the side of the railbed:** As mentioned above, the train will brake to a stop during a collision, but the locomotive will proceed a substantial distance past the grade crossing after striking the object in the grade crossing. A specific and reliable mechanism to propel a vehicle or pedestrian to the side of the tracks is key to effective mitigation
- **Control of the struck vehicle or pedestrian:** Upon exit from the roadbed, the struck pedestrian or vehicle will be at significant risk for injury, given the exit velocity from the railbed. The trajectory of the struck vehicle or pedestrian should be controlled to decrease injury risk (possibly by minimizing velocity).

Abbreviations and Acronyms

LSTC	Livermore Software Technology Corporation
MERC	Mercer Engineering Research Center
mph	miles per hour
NCAC	National Crash Analysis Center
NTRC	National Transportation Research Center

References

1. Ogden, B.D., Railroad-highway grade crossing handbook. 2007.
2. Weart, W., Grade crossing safety: Freight and passenger railroads take a multi-pronged approach, in Progressive Railroading. 2013, Trade Press Media Group.
3. Yeh, M., T. Raslear, and J. Multer, Understanding Driver Behavior at Grade Crossings through Signal Detection Theory. 2013.
4. Ngamdung, T. and M. daSilva, Driver Behavior Analysis at Highway-Rail Grade Crossings using Field Operational Test Data—Light Vehicles. 2013.
5. Choros, J., et al., San Joaquin, California, High-Speed Rail Grade Crossing Data Acquisition Characteristics, Methodology, and Risk Assessment. 2006.
6. Cleghorn, D., Improving pedestrian and motorist safety along light rail alignments. Vol. 137. 2009: Transportation Research Board.
7. Davey, J.D., et al., Train drivers' ratings of perceived risk associated with illegal behaviours at level-crossings. Journal of Occupational Health and Safety, Australia and New Zealand, 2007. 23(5): p. 445-450.
8. Khoudour, L., Feltz, Philippe, Bertrand, Dominique, Ghazel, Mohamed, Heddebaut, Marc, Collart-Dutilleul, Simon. Ruichek, Yassine, Flancquart, Amaury. PANsafer Project: Towards a safer level crossing. in 11th World Level Crossing Symposium. 2010. Tokyo.
9. Silla, A., How To Prevent Railway Suicides And Fatalities Related To Trespassing Accidents? 2012.
10. Spicer, T. Consolidating 29 Coronial Investigations From 15 Rlx Crashes 2002–2009 In Victoria, Australia, Into 4 Coronial Inquests. in Level Crossing 2012. 2012. London.
11. Takahashi, T. Lessons Learned from the Collision at the Daikonbara Level Crossing on the Iiyama Line and Preventive Measures. in International Railway Safety Conference. 2012. London.
12. Jain, S.a.K.A. Level Crossing Scenario Of Indian Railways. in International Railway Safety Conference. 2012. London.
13. Chadwick, S.G., M.R. Saat, and C.P. Barkan. Analysis of Factors Affecting Train Derailments at Highway-Rail Grade Crossings. in Transportation Research Board 91st Annual Meeting. 2012.
14. Jeong, D., et al. Equations of Motion for Train Derailment Dynamics. in Proceedings of the 2007 ASME Rail Transportation Division Fall Technical Conference. 2007.
15. Oh, J.S.K.a.H.S., Study of Influence of Wheel Unloading on Derailment Coefficient of Rolling Stock. Trans. Korean Soc. Mech. Eng. A, 2013. 37(2): p. 177-185.
16. Koo, J.S. and S.Y. Choi, Theoretical development of a simplified wheelset model to evaluate collision-induced derailments of rolling stock. Journal of Sound and Vibration, 2012. 331(13): p. 3172-3198.
17. Wang, W. and G.-x. Li, Development of high-speed railway vehicle derailment simulation–Part I: A new wheel/rail contact method using the vehicle/rail coupled model. Engineering Failure Analysis, 2012. 24: p. 77-92.
18. Xia, C., et al., Dynamic analysis of a coupled high-speed train and bridge system subjected to collision load. Journal of sound and vibration, 2012. 331(10): p. 2334-2347.
19. Cherchas, D., Determination of Railway Wheel Climb Probability Based on the Derailment Coefficient. Journal of the Franklin Institute, 1981. 312.1: p. 31-40.
20. Liu, X., M.R. Saat, and C.P. Barkan, Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record: Journal of the Transportation Research Board, 2012. 2289(1): p. 154-163.
21. Cleghorn, D., Improving pedestrian and motorist safety along light rail alignments. Vol. 137. 2009: Transportation Research Board.

22. Davey, J.D., et al., Train drivers' ratings of perceived risk associated with illegal behaviours at level-crossings. Journal of Occupational Health and Safety, Australia and New Zealand, 2007. 23(5): p. 445-450.
23. Silla, A., How To Prevent Railway Suicides And Fatalities Related To Trespassing Accidents? 2012.
24. Spicer, T. Consolidating 29 Coronial Investigations From 15 Rlx Crashes 2002–2009 In Victoria, Australia, Into 4 Coronial Inquests. in Level Crossing 2012. 2012. London.
25. Yeh, M., T. Raslear, and J. Multer, Understanding Driver Behavior at Grade Crossings through Signal Detection Theory. 2013.
26. Ngamdung, T. and M. daSilva, Driver Behavior Analysis at Highway-Rail Grade Crossings using Field Operational Test Data—Light Vehicles. 2013.
27. Hao, W.a.D., Janice. Motor Vehicle Driver Injury Severity Study at Highway-rail Grade Crossings in the United States. in Transportation Research Board 2013. 2013. Washington, DC.
28. Silla, A., How To Prevent Railway Suicides And Fatalities Related To Trespassing Accidents? 2012.
29. Evans, A.W., Fatal train accidents on Europe's railways: 1980–2009. Accident Analysis & Prevention, 2011. 43(1): p. 391-401.
30. Evans, A.W., Fatal accidents at railway level crossings in Great Britain 1946–2009. Accident Analysis & Prevention, 2011. 43(5): p. 1837-1845.
31. Jain, S.a.K.A. Level Crossing Scenario Of Indian Railways. in International Railway Safety Conference. 2012. London.
32. Davey, J.D., et al., Train drivers' ratings of perceived risk associated with illegal behaviours at level-crossings. Journal of Occupational Health and Safety, Australia and New Zealand, 2007. 23(5): p. 445-450.
33. Takahashi, T. Lessons Learned from the Collision at the Daikonbara Level Crossing on the Iiyama Line and Preventive Measures. in International Railway Safety Conference. 2012. London.
34. Davies, P. and F. Lees, Impact speed of heavy goods vehicles. Journal of Hazardous Materials, 1991. 26(2): p. 213-217.
35. Hao, W.a.D., Janice. Motor Vehicle Driver Injury Severity Study at Highway-rail Grade Crossings in the United States. in Transportation Research Board 2013. 2013. Washington, DC.
36. Evans, A.W., Fatal train accidents on Europe's railways: 1980–2009. Accident Analysis & Prevention, 2011. 43(1): p. 391-401.
37. Evans, A.W., Fatal accidents at railway level crossings in Great Britain 1946–2009. Accident Analysis & Prevention, 2011. 43(5): p. 1837-1845.
38. Eluru, N., et al., A latent class modeling approach for identifying vehicle driver injury severity factors at highway-railway crossings. Accident Analysis & Prevention, 2012. 47: p. 119-127.
39. Raub, R.A., Examination of highway-rail grade crossing collisions over 10 years in seven Midwestern states. ITE Journal, 2006. 76(4): p. 16-26.
40. Cherchas, D., Prediction of the probability of rail vehicle derailment during grade crossing collisions. ASME Journal of Dynamic Systems, Measurements and Control, 1982. 104(2).
41. Jeong, D., et al. Equations of Motion for Train Derailment Dynamics. in Proceedings of the 2007 ASME Rail Transportation Division Fall Technical Conference. 2007.
42. Oh, J.S.K.a.H.S., Study of Influence of Wheel Unloading on Derailment Coefficient of Rolling Stock. Trans. Korean Soc. Mech. Eng. A, 2013. 37(2): p. 177-185.
43. Koo, J.S. and S.Y. Choi, Theoretical development of a simplified wheelset model to evaluate collision-induced derailments of rolling stock. Journal of Sound and Vibration, 2012. 331(13): p. 3172-3198.
44. Wang, W. and G.-x. Li, Development of high-speed railway vehicle derailment simulation–Part I: A new wheel/rail contact method using the vehicle/rail coupled model. Engineering Failure Analysis, 2012. 24: p. 77-92.
45. Wang, W. and G.-x. Li, Development of high-speed railway vehicle derailment simulation–Part II: Exploring the derailment mechanism. Engineering Failure Analysis, 2012. 24: p. 93-111.

46. Liu, X., M.R. Saat, and C.P. Barkan, Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record: Journal of the Transportation Research Board, 2012. 2289(1): p. 154-163.
47. Chadwick, S.G., M.R. Saat, and C.P. Barkan. Analysis of Factors Affecting Train Derailments at Highway-Rail Grade Crossings. in Transportation Research Board 91st Annual Meeting. 2012.
48. Cherchas, D., Prediction of the probability of rail vehicle derailment during grade crossing collisions. ASME Journal of Dynamic Systems, Measurements and Control, 1982. 104(2).
49. Vi-Grade.com. VI-Rail data sheet. 2013.
50. Butler, P.A., Train collision system. 2001, Google Patents.
51. Moses, L.L., Protective crash barrier for locomotives and highway construction vehicles. 2004, Google Patents.
52. Payne, T.S. and J.M. Payne, Collision attenuator. 2003, Google Patents.
53. Payne, T.S. and J.M. Payne, Collision attenuating system. 2005, Google Patents.
54. DiscoveryEducation, Smash Lab: Train Crash, in Smash Lab, D. Channel, Editor. 2008, Discovery Education.
55. Martinez, E., Development of a detailed nonlinear finite element analysis model of colliding trains research results F.R.A. U.S. Department of Transportation, Editor. 2005.
56. Raiti, S., Front carriage of a train equipped with a front structure that absorbs energy in case of collision. 2012, EP Patent 1,930,226.
57. Ansaldobreda, Train equipped with interfaces that absorb energy between the carriage in case of collision. 2006: European.
58. Jacobsen, K., P. Llana, and D. Tyrell. Collision Scenarios for Assessing Crashworthiness of Passenger Rail Equipment. 2010. ASME.
59. Llana, P., Stringfellow, Richard, and Mayville, Ronald Finite Element Analysis And Full-Scale Testing Of Locomotive Crashworthy Components. in ASME/IEEE Joint Rail Conference JRC2013. 2013. Knoxville, TN, USA.
60. Jacobsen, K., K. Severson, and B. Perlman. Effectiveness of alternative rail passenger equipment crashworthiness strategies. in Rail Conference, 2006. Proceedings of the 2006 IEEE/ASME Joint. 2006. IEEE.
61. Kirkpatrick, S.W. and R.A. MacNeill. Development of a computer model for prediction of collision response of a railroad passenger car. in Railroad Conference, 2002 ASME/IEEE Joint. 2002. IEEE.
62. Severson, K., D. Tyrell, and A.B. Perlman, Analysis of collision safety associated with conventional and crash energy management cars mixed within a consist. American Society of Mechanical Engineers, Paper No. IMECE2003-44122, 2003.
63. Ujita, Y., K. Funatsu, and Y. Suzuki, Crashworthiness Investigation of Railway Carriages. Quarterly Report of RTRI, 2003. 44(1): p. 28-33.
64. Jacobsen, K.M., Collision Dynamics Modeling of Crash Energy Management Passenger Rail Equipment. 2008: ProQuest.
65. Martinez, E., Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment. 2007.
66. Llana, P., Structural Crashworthiness Standards Comparison: Grade-Crossing Collision Scenarios. Texas, USA, 2009. 3: p. 119-128.
67. Tyrell, D., et al. Overview of a crash energy management specification for passenger rail equipment. in Rail Conference, 2006. Proceedings of the 2006 IEEE/ASME Joint. 2006. IEEE.
68. Carolan, M., et al., Technical Criteria and Procedures for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service. 2011.
69. Parent, D., et al. Crashworthiness Analysis of the January 26, 2005 Glendale, California Rail Collision. in ASME/ASCE/IEEE 2011 Joint Rail Conference (JRC2011). 2011.
70. Parent, D., D. Tyrell, and A.B. Perlman, Crashworthiness analysis of the Placentia, CA rail collision. International Journal of Crashworthiness, 2004. 9(5): p. 527-534.

71. Tyrell, D., E. Martinez, and T. Wierzbicki, Crashworthiness studies of locomotive wide nose short hood designs. ASME Applied Mechanics Division-Publications-AMD, 1999. 237: p. 319-334.
72. Jacobsen, K., K. Severson, and B. Perlman. Effectiveness of alternative rail passenger equipment crashworthiness strategies. in Rail Conference, 2006. Proceedings of the 2006 IEEE/ASME Joint. 2006. IEEE.
73. Tyrell, D.C., et al. Evaluation of cab car crashworthiness design modifications. in Railroad Conference, 1997., Proceedings of the 1997 IEEE/ASME Joint. 1997. IEEE.
74. Tyrell, D.a.P., Benjamin, Evaluation of rail passenger equipment crashworthiness strategies. Transportation Research Record: Journal of the Transportation Research Board, 2003. 1825(1): p. 8-14.
75. Tyrell, D., et al. Locomotive crashworthiness design modifications study. in Railroad Conference, 1999. Proceedings of the 1999 ASME/IEEE Joint. 1999. IEEE.
76. Tyrell, D.C., Rail passenger equipment accidents and the evaluation of crashworthiness strategies. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2002. 216(2): p. 131-147.
77. Priante, M., D. Tyrell, and B. Periman. The influence of train type, car weight, and train length on passenger train crashworthiness. in Rail Conference, 2005. Proceedings of the 2005 ASME/IEEE Joint. 2005. IEEE.
78. Llana, P. and D. Tyrell. Preliminary Reconstruction of the November 30, 2007 Chicago, Il Rail Collision. in ASME/ASCE/IEEE 2011 Joint Rail Conference (JRC2011). 2011.
79. Sun, Y.Q., et al., Modelling and analysis of the crush zone of a typical Australian passenger train [Published online 7 February 2012]. 2012.
80. NCAC. National Crash Analysis Center at George Washington University (NCAC). 2013 [cited 2013 October 17, 2013]; Available from: http://www.ncac.gwu.edu/.
81. Plaxico, C., et al., U08: Enhanced Finite Element Analysis Crash Model of Tractor-Trailers (Phase B). 2009.
82. NTRCI, N.T.R.C. National Transportation Research Center (NTRCI). 2013; Available from: www.ntrci.org.
83. Panneer, G.R., School Bus Crashworthiness. 1998, West Virginia University.
84. NHTSA, N.H.T.S.A., TRC test report: VRTC Test number 990525. 1995.
85. MERC. Mercer Engineering Research Center (MERC). 2013 [cited 2013; Available from: http://www.merc-mercer.org/index.html#AppliedMechanics.
86. Bovenkerk, J., et al. New modular assessment methods for pedestrian protection in the event of head impacts in the windscreen area. in Proceedings Of The 21st (Esv) International Technical Conference On The Enhanced Safety Of Vehicles, Held June 2009, Stuttgart, Germany. 2009.
87. Anderson, R.W.G., et al. Pedestrian reconstruction using multibody MADYMO simulation and the Polar-II dummy: a comparison of head kinematics. in Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France. 2007.
88. Untaroiu, C., et al. Pedestrian kinematics investigation with finite element dummy model based on anthropometry scaling method. in Proc. 20th Int. Technical Conf. Enhanced Safety of Vehicle. 2007.
89. Fredriksson, R., J. Shin, and C.D. Untaroiu, Potential of pedestrian protection systems—a parameter study using finite element models of pedestrian dummy and generic passenger vehicles. Traffic injury prevention, 2011. 12(4): p. 398-411.
90. Secretariat, Pedestrian CAE Models & Codes Technical Bulletin, in European New Car Assessment Programme. 2012.
91. Anderson, R.W.G., et al. Pedestrian reconstruction using multibody MADYMO simulation and the Polar-II dummy: a comparison of head kinematics. in Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France. 2007.
92. Untaroiu, C., et al. Pedestrian kinematics investigation with finite element dummy model based on anthropometry scaling method. in Proc. 20th Int. Technical Conf. Enhanced Safety of Vehicle. 2007.
93. LSTC, L.S.T.C. LSTC Dummy Models Overview. 2011 [cited 2013 October 17, 2013]; Available from: http://www.lstc.com/products/models/dummies.
94. Barbat, S., X. Li, and P. Prasad. Bumper and grille airbags concept for improved vehicle compatibility in side impact: Phase I. in 23rd International Technical Conference on the Enhanced Safety of Vehicles.

95. Vi-Grade.com. VI-Rail data sheet. 2013.
96. Tutt, B., C. Sandy, and J. Corliss. Status of the development of an airbag landing system for the Orion crew module. in 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Seattle, Washington. 2009.