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# A numerical study of occupant responses and injuries in vehicular crashes into roadside barriers based on finite element simulations

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ABSTRACT

Occupant responses and injuries are important considerations in the design and assessment of roadside safety devices such as barriers. Although incorporating occupant responses and injuries into the design of safety devices is highly recommended by the current safety regulations, there are limited studies that directly consider occupant responses and injuries. Crash test dummies are seldom equipped in the state-of-the-art crash testing of roadside barriers and thus occupant responses and injury risks are evaluated primarily based on vehicle responses. In the present work, occupant responses and injuries in automotive crash events were investigated by incorporating crash test dummies into the vehicle model that was used in the finite element (FE) simulations of roadside crashes. The FE models of a Ford F250 pickup truck and a Hybrid III 50th percentile crash test dummy were employed and a passive restraint system was developed in the FE model. The FE model was validated using existing experiments including a sled test and a full-frontal impact test. Simulations of the Ford F250 impacting a concrete barrier and a W-beam guardrail were conducted and the occupant responses were analyzed. Furthermore, occupant injuries were quantitatively estimated using occupant injury criteria based directly on dummy responses and compared to those based solely on vehicle responses. The correlations between vehicle responses and occupant injuries were studied.


## 1. Introduction

Traffic barriers are effective safety devices in preventing vehicles from crossing the median so as to avoid head-on collisions. Median barriers are especially effective in reducing the chances of small, light passenger vehicles crashing into large, heavy vehicles. In the current safety standard, the Manual for Assessing Safety Hardware (MASH) [1], the impact performances of a barrier system under vehicular impacts are assessed by "the risk of injury to the occupants of the impacting vehicle," "the structural adequacy of the safety feature" and "the post-impact behavior of the test vehicle" [1]. Although the occupants should not experience severe or fatal injuries, there is currently no crash dummy specified by MASH to be used in barrier crash testing to obtain occupant responses.

The ultimate goal of designing a median barrier system is to save life and minimize the injury to the occupant. It is of great significance to comprehend the mechanism of occupant injury in automotive crashes. To establish proper injury criteria for estimating the levels of injury severity, it is necessary to study the parameters that can be used to assess occupant responses such as accelerations, forces, stresses, and strains. Over the years, a number of injury criteria have been established to estimate the level of human injuries. Research on injuries of human bodies including the head, neck, thorax, abdomen, pelvis, and lower extremities has been conducted in the field of impact biomechanics in the last 60 years [2,3]. Since different parts of the body have different injury mechanisms, injury criteria for different body regions have been proposed for assessing the restraint system in automotive crashes [4,5]. For example, the head injury criteria (HIC) [6], which was based on the head translational accelerations, was adopted by the U.S. federal government in the Federal Motor Vehicle Safety Standards (FMVSS) No. 208 [7]. A certain HIC value corresponds to a certain probability of a skull fracture. Although injury criteria should be established for each type of injuries for different body parts, directly evaluation of injury criteria on human bodies in vehicular crashes is nearly impractical. There are two approaches to study occupant responses and injury criteria in vehicular crashes: the direct approach that employs a crash test dummy [8] and the indirect approach that utilizes the dynamic vehicle responses. For the direct approach, crash test dummies are instrumented to record data on its dynamic behavior in vehicle impact tests and injury levels can be determined using the measured quantities. With their good repeatability and controllability, crash test dummies are often used to help

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establish injury criteria for evaluating the effectiveness of occupant protection system in vehicle designs.

Full-scale crash testing [9,10] and computer simulation are the two most common approaches to evaluate the impact performances of barrier systems before their placements on highways. Since it is infeasible to test all possible crash scenarios using physical testing, computer simulations, such as those using finite element (FE) analysis, provide a supplemental way to study barrier impact performances and evolve new designs. Once reliable FE models such as vehicle and median barrier are established, different impact conditions could be studied. Over the past two decades, researchers at the National Crash Analysis Center (NCAC) have developed a number of FE models of various vehicles that could be used to study vehicular crashworthiness and roadside barrier crashes. These vehicles vary from small passenger cars to pickup trucks and are available in the public domain. To construct these FE models, reverse engineering technique was used [11,12] and the majority of the models were partially or fully validated using experimental data of full-frontal impacts. These models released by NCAC have been widely used in simulation studies of median barrier crashes and consistently modified and improved by various users. Besides a number of vehicle models, NCAC has also developed a number of roadside barrier FE models including a concrete barrier, W-beam guardrail and cable median barrier [13]. With the FE models of vehicle and roadside barrier systems, computer simulations can be conducted to evaluate the impact performances of the barriers [14–17].

Although examining the vehicle responses and barrier performances is helpful to assess occupant safety in a crash, the occupant responses should be directly examined. This is because, as pointed out in MASH [1], the relationship between occupant risk and vehicle dynamics during interaction with roadside barriers is very difficult to be quantified. For example, a safe vehicle response may indicate a potentially satisfactory occupant safety but not a guarantee. To this end, incorporating a crash test dummy in the crash testing of barrier systems serves as a means to directly evaluate occupant safety. Crash test dummies are full-scale anthropomorphic test devices that are used by the automotive industry for decades to simulate human bodies and instrumented to record data of dynamic responses in vehicular impact testing. Incorporating a crash test dummy in the crash testing of roadside barriers is ideal but difficult due to the high cost, level of instrumentation, and required expertise. As a result, using crash test dummy is encouraged but not required in the current safety standard, MASH. Nevertheless, there is no obvious impedance to incorporating a dummy model, such as those used in vehicle crashworthiness design in automobile industry [18–20], in the crash simulations of roadside barriers.

The first technique to develop FE models of occupants in crashes was aimed at crash test dummies rather than the real human beings; this strategy was referred as “crash test dummy based modeling” [21–30]. In developing FE models of crash test dummies, the whole dummy was disassembled into a number of units such as head, neck, shoulders, thorax, lumbar spine, pelvis, and lower and upper extremities. Each of these units is composed of a few small components. These individual components with reasonable meshes and material properties are assembled into the corresponding larger unit. At the unit level various testing was done to ensure consistency between FE simulation results and test data [21]. Finally the FE model of the entire dummy was validated in a sled testing configuration. A second approach in developing the FE models of crash test dummies adopted a design strategy directly based on accurate and detailed representations of human bodies. These models resembled a real human body in geometry and structures and naturally incorporated the effects of body size, posture, and muscular activity. For example, Gayzik et al. [31] used three techniques namely the computed tomography, magnetic resonance imaging (MRI) and upright MRI to scan the geometry of a human body and construct an FE model. The disadvantage of this approach is that human bodies are generally too complicated to be modeled accurately and thus models based directly on human bodies have not been widely used as dummy based models.

The need to incorporate occupant injuries into the design and evaluation of roadside barriers requires in-depth understanding of occupant responses in roadside crashes. In this study, the occupant responses and injuries during roadside barrier crashes were evaluated based on crash dummy responses using FE simulations. The major research objectives of this study were to: (1) incorporate a crash test dummy model with a vehicular model in crash simulations of roadside barriers; (2) validate the integrated dummy and vehicle model using existing data of crash tests; and (3) investigate dummy responses in crash simulations and study the correlation of occupant based on dummy responses and those based on vehicle responses. In Section 2, the FE model of a 2006 Ford F250 pickup truck with airbag, steering wheel and column, dashboard, and seatbelt is presented and a Hybrid III 50th percentile human dummy model is incorporated into the vehicle model. This integrated model is validated in Section 3 based on test data of a sled test and a full-frontal impact. Occupant injury criteria based on human responses and vehicle responses are discussed in Sections 4 and 5, respectively. An analysis of occupant injuries in roadside crashes into a concrete barrier and a W-beam guardrail is presented in Sections 6 and 7. Finally, the correlation between vehicle responses and occupant injuries are discussed.

## 2. An integrated finite element model

### 2.1. Ford F250 pickup truck

The FE model of a 2006 Ford F250 pickup truck developed at NCAC [32] was chosen as the base model in this research. This vehicle model had 738,165 nodes, 698,501 shell elements, 2353 beam elements, and 25,905 solid elements as shown in Fig. 1a. The mass of the vehicle was approximated 2500 kg, which met the TL-3 requirement of a 2270P test vehicle (pickup truck) specified by MASH. This vehicle model was validated by NCAC using a full-frontal impact test, and exhibited numerical instability in barrier crash simulations. To use it in the current work, this model was revised by eliminating initial penetrations and redefining contact between parts wherever necessary to improve its numerical stability and simulation accuracy.

In the NCAC model, the steering (excluding steering wheel and column) and suspension components were modeled but some compartment components such as the seat, dashboard, and the restraint systems were not considered. The passive restraint system, i.e., the airbag and seatbelt, is important for occupant protection in a crash event. Although it may not contribute significantly to the overall vehicle responses, the passive restraint system is critical to reduce the impact forces and accelerations on the occupant. Without passive restraint system, it is impossible to incorporate an occupant (dummy) model into the vehicle model and study occupant responses in roadway crashes. In this study, the FE models of the airbag (see Fig. 1b), steering wheel and column, dashboard, and seatbelt were added to the FE model of the Ford F250 along with a Hybrid III dummy model (see Fig. 1c).

#### 2.1.1. Airbag modeling

Modeling airbag deployment and its after-deployment interaction with external objects such as the steering wheel has been a challenging task, particularly when considering fabric density, bag elasticity, inflation and venting rate, etc. [33,34]. The deployment of an airbag starts with the inflator that triggers a rapid chemical reaction to generate and pump nitrogen gas into the fabric bag to inflate it.

To simulate the airbag, the inflator needs to be characterized on the mass flow rate during deployment, which can be done using an airbag tank test [35]. In the tank test, the inflator was ignited and exploded inside a constant volume tank and the gas pressure history