

Modeling of an Advanced Steering Wheel and Column Assembly for Frontal and Side Impact Simulations

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ABSTRACT

This paper presents the final phase of a study to develop the modeling methodology for an advanced steering assembly with a safety-enhanced steering wheel and an adaptive energy absorbing steering column. For passenger cars built before the 1960s, the steering column was designed to control vehicle direction with a simple rigid rod. In severe frontal crashes, this type of design would often be displaced rearward toward the driver due to front-end crush of the vehicle. Consequently, collapsible, detachable, and other energy absorbing steering columns emerged to address this type of kinematics. These safety-enhanced steering columns allow frontal impact energy to be absorbed by collapsing or breaking the steering columns, thus reducing the potential for rearward column movement in severe crashes. Recently, more advanced steering column designs have been developed that can adapt to different crash conditions including crash severity, occupant mass/size, seat position, and seatbelt usage. These advanced steering columns incorporate adaptive features, mechanically or pyrotechnically activated, to add flexibility in absorbing impact energy of different levels. In addition to complying with safety regulations for steering columns (e.g., FMVSS 203 and 204), these advanced steering column designs are able to handle different load conditions. These load conditions range from high impact loads for larger and unbelted dummies in severe crash tests to low impact loads for small and belted dummies in lower severity crash tests, as required by FMVSS 208 and NHTSA's NCAP safety rating system. The modeling of a steering assembly with advanced safety features becomes more challenging as the steering column designs become more complex.

In the final phase of the study, the focus is the modeling of an advanced steering wheel and column assembly that can be used in frontal and side impact simulations. In the first phase of the study, ten component and subsystem tests were conducted to develop the modeling methodology of an adaptive energy absorbing steering column assembly. Three steering wheel assembly tests and eight steering wheel and column assembly tests, with the steering column being mounted in normal and offset angles, were developed and conducted in the final phase of the study. In addition, various dynamic impact speeds, including quasi-static, were considered so that speed sensitivity of the steering wheel and column assembly could be obtained. The final modeling methodology of the steering wheel and steering column assembly is developed based on reasonable correlation achieved with twenty one tests. The developed modeling methodology can be applied to other advanced steering wheel and column assemblies and will enhance evaluation of occupant responses in full vehicle or subsystem simulations. It can also be used in finite element analysis programs (LS-DYNA) and/or coupling of finite element and occupant analysis programs (LS-DYNA & MADYMO coupling). The final goal of this study is to utilize the developed modeling methodology in vehicle development to occupant safety systems, optimize prototype testing and enable faster development cycle time.

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INTRODUCTION

A conventional steering system consists of several main components; a steering wheel, a steering column with an intermediate shaft and a steering gear box. In passenger cars built before 1960s, the steering column was designed to steer vehicle direction with a simple rigid rod as illustrated in [Figure](#)

1. The design could often be displaced towards the driver during frontal collisions due to front-end crush of the vehicle. Consequently, more complex columns with collapsible, detachable or other energy absorbing designs emerged, such as the example shown in [Figure 2](#). These column designs allow frontal impact energy to be absorbed by collapsing or breaking the steering columns, thus reducing the potential for

the column being displaced rearward toward the driver. Recently, more advanced steering column designs have been developed that can adapt to different crash conditions including crash severity, occupant mass/size, seat position, and seatbelt usage. These advanced steering columns incorporate adaptive features, mechanically or pyrotechnically activated, to add flexibility in absorbing impact energy of different levels. In addition to complying with safety regulations for steering columns (e.g., FMVSS 203 and 204), these advanced steering column designs are able to handle different load conditions. These load conditions range from high impact loads for larger and unbelted dummies in severe crash tests to low impact loads for small and belted dummies in lower severity crash tests, as required by FMVSS 208 and NHTSA's NCAP (New Car Assessment Program) safety rating system. [Figure 3](#) illustrates the deformation modes of an advanced steering system before and after an impact. The advanced steering systems, sometimes including adaptive energy absorbing features, used in today's automotive industry have been influenced by the analysis of field accident data, safety standards, research, and emerging safety technologies throughout the years. A comprehensive literature review was conducted and documented below to help understand the evolution of steering system designs.



Figure 3. Steering system deformation modes before and after an impact.

Requirements and Regulations

For passenger cars built before 1967, steering systems were designed to control vehicle direction with a simple rigid rod configuration, as shown in [Figure 1](#), but had limited energy absorbing capabilities. The automotive industry started designing and developing energy absorbing steering assemblies in the late 1950's [1, 2]. The Society of Automotive Engineers (SAE), recognizing the need for a test procedure to evaluate the characteristics of steering systems, issued Recommended Practice J944 [3, 4] in 1965. This procedure consists of a body form ([Figures 4a & 4b](#)), also known as body block or blak tuffy, weighing 75 pounds (34.02 kg), that impacts a steering assembly mounted in the production configuration ([Figures 5a & 5b](#)). A load cell mounted between the wheel and column is instrumented to measure the force imparted to the system.



Figure 1. Single-piece steering column design.



Figure 2. Energy absorbing steering system design.

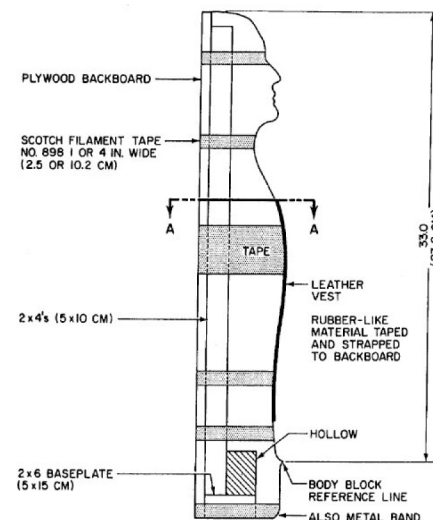


Figure 4a. SAE J944 body form specifications.



Figure 4b. SAE J944 body form.

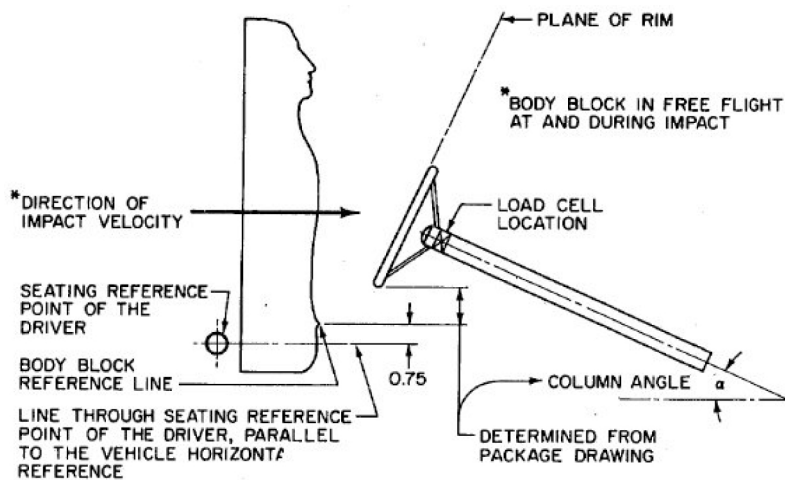


Figure 5a. SAE J944 Body form impact test setup.



Figure 5b. Body form impact test.

In 1966, the General Services Administration (GSA) issued GSA Standard 515/4a [5], a steering assembly performance standard, which became effective in October 1967. The standard required that the force imparted to the SAE J944 body form must not exceed 2,500 pounds (11,120 Newton) when impacting the steering assembly at 15 mph (6.71 m/s). The standard also required that the rearward horizontal displacement of the upper end of the column must not exceed 5 inches (127 mm) during a 30 mph (13.41 m/s) frontal barrier test. In 1967, National Highway Traffic Safety Administration (NHTSA) adopted the GSA standard, but separated the energy absorption and rearward displacement requirements into two standards, FMVSS 203 [6] and 204 [7]. These standards became effective on January 1, 1968. FMVSS 203 specifies requirements for steering control systems intended to reduce chest, neck, and facial injuries to the driver resulting from hard impact. FMVSS 204 sets a requirement limiting the rearward displacement of the steering control into the passenger compartment to reduce the likelihood of chest, neck, or head injuries. The FMVSS 203 and 204 standards were subsequently extended to light trucks and vans effective September 1, 1981[1].

Based on FMVSS 203 and 204, ECE R12 [8] was introduced in Europe and consists of three annex tests, which were designed to limit the injury risk to an occupant when in contact with the steering system during a frontal impact. Annex 3 was designed to limit the rearward displacement of the steering column in a 30 mph (13.41 m/s) full frontal test. Annex 4 was designed to limit the forces on the driver's chest via a 15 mph (6.71 m/s) body form test against the steering system. Annex 5 was designed to limit the forces on the driver's head via a 15 mph (6.71 m/s) head form test (rigid, with a mass of 6.8 kg and a diameter of 165 mm, [Figure 6](#)) against various points on the steering wheel.

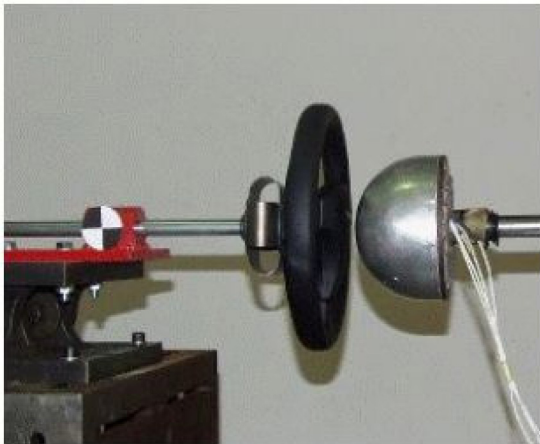


Figure 6. ECE R12 head form impact test.

Energy Absorbing Steering Systems

To understand the performance of several ball-sleeve energy absorbing steering assemblies, Horsch and Culver [9] designed and conducted a series of Hyge sled tests with different column mounting angles and dummy sitting postures. From the steering assemblies and test conditions studied, it was found that axial impacts resulted in almost negligible wheel deformation, with the column acting as the main energy absorbing component. Off axis impacts resulted in initial steering wheel deformation, with the wheel and column sharing energy absorption. Impact energy can be absorbed either by steering wheel deformation, column compression, or both depending on the steering wheel and column designs. Steering wheel deformation is dependent on its design and the load distribution exerted by the occupant. Similarly, the force needed to compress the steering column depends on the column energy absorbing design and the loading condition on the column. Wheel deformation and column compression are interrelated and depend on the relative load and strength between the two components.

In the 1980s, NHTSA conducted a program to evaluate steering assembly designs for unrestrained drivers [10]. The program was separated into three phases; an initial problem determination phase, an analytical phase to evaluate potential safety concepts, and a hardware development and testing

phase to evaluate safety designs in sled and crash tests. In the problem determination phase, data on injuries and fatalities from impacts with the steering assemblies were compiled [11]. A Passenger And Driver Simulation (PADS) computer model was selected for simulating an unrestrained driver in frontal impacts during the second phase of the study. The PADS is a two-dimensional model with a four-mass occupant (head/neck, torso, lower body, and sternum) and a vehicle compartment geometry defined by seven contact planes and a steering assembly. The hardware development and testing phase of the program was performed, under NHTSA contract, by Calspan Corporation Advanced Technology Center. The program concluded that a steering assembly with energy management features, based on designs developed from the computer modeling, reduced thoracic responses measured by the Hybrid III dummy in sled tests.

In 1991, Kawase, Shinto, and Yoshida [12] developed a one-piece, lightweight magnesium steering wheel frame for a steering wheel with an airbag system. The die cast magnesium frame was designed to balance stiffness, strength, and characteristics of energy absorption. Magnesium alloys with various aluminum contents were tested and AM60B alloy was selected because of its favorable properties of strength and elongation. New manufacturing techniques, including a vacuum hot chamber die casting system and a surface defect inspection system, were also developed in order to produce high quality castings. The magnesium steering wheel frame was about 45% (550g) lighter than those of comparable steel designs. Satisfactory results were found after evaluation of its energy absorption characteristics in the laboratory and via actual vehicle crash tests.

The development of energy absorbing steering system by General Motors was documented by Horsch, Viano, and DeCou [13]. This paper provided an overview of the programs and studies conducted in the development of GM energy absorbing steering systems, including the GM safety research program, Safety Car, Invertube, and the biomechanics projects at Wayne State University. Additionally, the paper also reported the engineering efforts from various GM divisions, government interactions and regulations, field accident data analyses as well as the thoracic and abdominal tolerance studies that led to the development of the Viscous Injury Criterion and self-aligning steering wheel.

Field Data Analyses

In addition to the field accident data discussed in [13], Frampton [14] assessed real world steering wheel performance characteristics and their implications to head and face injuries of restrained drivers in frontal impacts. The likelihood and severity of head and face injuries from direct wheel contact was shown to increase with the Equivalent Test Speed when collision severity was considered. Steering wheel rearward and upward displacements were also seen to increase with collision severity.

Similarly, Yamazaki et al. [15] conducted a study by using field accident data in Japan to determine how injuries were caused by a steering wheel to a driver's head and face in frontal collisions. The study included regions of injuries and types of injuries as well as specific parts of the steering wheel causing the injuries. The field accident data and the analyses of occupant facial and head injuries led to the creation of a steering wheel impact test procedure that reflected actual accident conditions in Japan.

Experimental Studies

Steering column movement in severe frontal crashes and its potential effect on airbag performance were investigated by Zuby and O'Neill [16]. Based on results from 106 IIHS (Insurance Institute for Highway Safety) frontal ODB (Offset Deformable Barrier) tests at 40 mph (64 km/h) and real-world accident data, the authors concluded that steering column movement in severe frontal crashes can influence airbag performance. A similar effect of steering column motion on airbag performance can also be found in the IIHS SORB tests [17, 18, 19]

Fileta and Liu [20] conducted an experiment study to understand the effects of intrusion on steering column movement, as well as the mechanics of steering column movement during frontal impact tests. In the experiment, a front part of a midsize front-wheel drive vehicle was used as the baseline design for test structures. Four primary factors, "rail into dash-panel", "subframe into toe-board", "shotgun/shock tower into cowl", and "powertrain into dash-panel", were selected in four tests in order to study their effects on the steering column movement separately. The interactions between these primary factors were also studied by conducting three tests which have the combined effects of two factors. Additionally, a test case was included to study the effects of combining three factors. A static testing crusher was used in the experimental investigation in accordance with the test matrix that included the eight different tests. The study found that the "rail into dash-panel" had the strongest effect on the upward displacement of the steering column. The brake pedal bracket and the steering intermediate shaft were found to push against the lower end of the steering column in the "rail into dash-panel" test. Subsequently, a sensitivity study was conducted to evaluate different designs of column support. The upward displacement of steering column obtained from three designs with "cross-car beam mounted" support were found to be lower than that of the traditional "cowl mounted" support.

Heavy Truck Steering Systems

Heavy truck occupant injuries associated with steering wheel rims in frontal accidents also have been investigated. Sukegawa, Matsukawa, and Masuda [21] studied field accident data and evaluated the crash safety performance of heavy trucks in Japan. Heavy truck drivers were often injured in the

chest and abdomen by the steering wheel rim in fatal or serious accidents. The size and the installation angle of the steering wheel are very different between a heavy truck and a passenger car. The chest and abdomen of a heavy truck driver are often struck by the bottom part of the steering rim in a frontal accident. The difference in the steering wheels was found to be a significant factor in particular injury patterns found in heavy truck drivers. A similar study conducted in Europe by Gwehenberger et al. [22] also found different injury patterns between heavy truck occupants and those of other vehicle users. Intrusions in the lower part of the truck cab led to injuries to the lower limbs while abdominal injuries were caused by the steering wheel rim. A low seat belt usage rate among heavy truck drivers was believed to be one major reason for this difference.

Computer Simulations

The research conducted on the steering system in the automotive industry has helped greatly in the understanding of the role of the steering system in occupant protection. As a result, different energy absorbing collapsible steering systems, such as Halacka et al. [23, 24, 25, 26, 27], have been developed and are now widely used. In the development of steering systems, mathematical models and computer simulations are an effective approach to supplement physical tests. Lakkad [28] developed dynamic mathematical model in Matlab and ADAMS to simulate different steering systems. Ozan et al. [29] also used ADAMS to model and optimize the steering system of a heavy-commercial vehicle. Computer simulations using FEA (finite element analysis) methods and/or simplified FEA methods were developed to model the components of different steering systems since the early the 1990s. A review of the finite element studies conducted on the steering system is provided below and divided into several categories, including steering wheel, steering column, material constitutive law, strain-rate, subsystem, simplified model, coupled LS-DYNA and MADYMO method, and racing cars.

Steering Wheel Modeling

Many studies have been conducted to model steering wheels since the early 1990s. Shyu et al. [30] developed a finite element model of the body form required in the SAE J944/FMVSS 203 [3, 4, and 6] test procedure and a magnesium steering wheel by using PAM-CRASH. The finite element impact simulation led to the design of a magnesium steering wheel and good correlation was seen between the final results of the finite element analysis and the physical test. Similar work was also performed by McKie [31] using LS-DYNA to design steering wheels meeting the ECE-R12 [8] requirements. Based on the correlation achieved, the technique developed was recommended as a design tool for steering wheels. Altenhof et al. [32, 33, 34, 35, 36, 37] conducted extensive research on the dynamic simulations and impact responses of different steering wheel armatures. An investigation [33] was conducted

specifically to compare numerical and experimental observations from the impact loading of geometrically identical aluminum and magnesium steering wheel armatures. The investigation led to the conclusion that the predictive capabilities of the aluminum material model are better developed than those of the magnesium material model. The magnesium model behaves structurally stiffer than the aluminum material model. The predictive capabilities of the die-cast magnesium model are most likely influenced by the anisotropic behavior of the material, the nonhomogeneous structure, and the inability to experimentally determine the mechanical properties of the alloy. To facilitate the development of steering wheels, Yang et al. [38] and Kodwani et al. [39] outlined a simulation procedure to predict steering wheel responses involving modal, static, and impact test conditions. Difficulties and challenges in the modeling process were also addressed in the paper.

Many studies relative to heavy truck steering wheel have been conducted by using finite element impact simulations. Boesch and Reid [40] developed heavy truck suspension and steering models for roadside safety research. Holmqvist et al. [41, 42, and 43] adopted Hybrid III dummy and human body models to evaluate chest injuries in heavy vehicle frontal collisions. Rehman and Najafabadi [44] used sled tests and finite element models to study the impact responses of a heavy truck steering wheel with different tilt angles.

Steering Column Modeling

The finite element studies conducted to model steering columns are rather limited due to the complex designs of different energy absorbing features and adaptive mechanisms. Gotoh et al. [45] made the first attempt to use FEA to model the collapse behavior of a steering column in 1992. A thin steel plate able to bend and tear was used as an energy absorber in the steering column studied. A ductile fracture model with boundary spring elements was developed to simulate the bending and tearing of the thin steel plate. In 2003, Kubota [46] made another attempt to model a collapsible steering column with a breakable resin pin. Static tests were conducted to quantify the loads needed to break the pin and to overcome the friction of the column shafts. The loads were converted to equivalent shearing loads and included in a bar element.

A different energy absorbing device in a steering column was modeled by Hamid et al. [47 and 48]. The energy absorbing device was composed of a metal strap and a pin. During the column stroke, the metal strap is drawn over the pin that resists the deformation. A dynamic strap pull test was conducted to develop the metal strap-pin finite element model. The correlated finite element model was used to investigate the effects of the metal strap with different thicknesses, widths, geometries, and friction coefficients. Liu et al. [49] studied a crushable energy absorbing device located inside the shafts of an adaptive steering column. Finite element simulations were conducted to correlate with two body form tests, impacting with the steering wheel and the steering wheel-column assemblies.

The performance of the crushable energy absorbing device with different hole-opening patterns was assessed by using the correlated finite element model.

Lee et al. [50] modeled a collapsible steering column, with a breakable “capsule pin”, a “curling plate-pin”, and a “collapse ring”, which is more complex compared to those from Kubota [46] and Hamid et al. [47 and 48]. Tied contact and a stress-based failure criterion were used to model the fracture of the plastic “capsule pin”. Similar to that of Hamid et al. [47 and 48], the thickness, width, and geometry of the curling plate contribute to the collapse load of the steering column. Friction coefficient was adjusted in the “curling plate-pin” model to correlate with the F-D curve obtained from the static curling plate pull test. The collapse load also depends on the pre-stressed “collapse ring” which was modeled with “INITIAL STRESS SHELL”. Breakaway steering linkages [51] also have been designed to decouple steering columns which can be modeled by using a simple approach described by Valentin and Makowski [52]. Recently, Jeoung [53] adopted failure criteria developed for fibrous anisotropic materials [54] to model a steering column component made of carbon fiber reinforced plastic (CFRP).

Material Constitutive Laws

Material constitutive laws play a very important role in the modeling of steering wheels and columns. Steering wheels had been made of mild steel in the past. Increasingly, lightweight materials, such as aluminum and magnesium, have been utilized to manufacture steering wheels to reduce vehicle weight. Magnesium, about one-third lighter than aluminum and two-thirds lighter than steel offers the advantages of part consolidation, better natural frequency response, and better damping characteristics, making it a good material choice in the design of steering wheels and steering column components from noise/vibration/harshness perspective.

The material models for steels and aluminum have been studied and good predictive capabilities have been reported extensively in open literature. However, it is known that modeling of magnesium components is quite challenging due to the associated die casting processes [33]. Inhomogeneous micro-structures are usually found in die cast magnesium components. Most die cast components contain an outer surface with dense small grains and an inner core with considerably more pores [55]. These pores are formed by the soluble and physically entrapped gases during the die casting processes. Various process parameters such as the melting temperature, die cooling system, injection speed, die lube spraying time, and the vacuum system [12] can be adjusted to reduce the porosity in die-cast magnesium alloys. As a result, the mechanical properties of magnesium components are highly affected by their microstructures and local porosities. Rodrigo et al. [56] reported the effects of section size and microstructural features on the mechanical properties of two magnesium alloys, AZ91D and AM60B. The mechanical properties of die cast magnesium alloys also depend on the

aluminum content as described by Kawase [12] and Aune [57]. In general, the strength of magnesium alloy increases and the ductility decreases as the aluminum content increases. To better predict the responses of magnesium components, the above factors need to be considered when defining the mechanical properties of die cast magnesium components [58].

Strain Rate Effects

Kawase [12], Aune [59], and Carlson [60 and 61] reported that the yield strength, strain hardening rate, ultimate tensile strength (UTS), and fracture elongation of some magnesium alloys increase with strain rate. Extensive research [62, 63, 64, 65, 66, 67, 68, 69, 70] has been conducted to model material constitutive laws with strain rate dependency and to investigate the strain rate effect of different materials since the 1960s. Recently strain rate tests have been conducted for a large amount of steels, especially advanced high strength steel (AHSS), under several Auto/Steel Partnership, AISI (American Iron and Steel Institute), and DOE (Department of Energy) research programs [71, 72, 73]. The availability of strain rate test data allowed for more accurate material models [71, 72, 73, 74, 75, 76, 77, 78] to be considered in crash simulations. The inclusion of material models with strain rate dependency made it possible to use a single model to execute crash simulations with different impact speeds and test conditions [71, 75, and 76]. The strain rate sensitivity of aluminum alloys has been investigated by many researchers [64, 65, 66, 68, 79, 80]. In general, the strain rate dependency of aluminum alloys is significantly less than that of steel. Altenhof and Ames [81] conducted a finite element investigation to understand the strain rate effects on steering wheel armatures made of aluminum and magnesium alloys. It was concluded that strain rate sensitivity should be considered in finite element simulations of aluminum and magnesium steering wheel armatures under impact loads. However, the improvement of simulation accuracy with inclusion of strain rate is less for magnesium armatures than aluminum armatures.

Simplified Models

The steering system affects the response of a driver in frontal impact tests. Steering system models are usually simplified in full vehicle crash simulations due to the various modeling challenges mentioned above. To save computation time, sled or subsystem models are adopted to assess occupant safety responses in frontal impact tests. Kovacic et al. [82] proposed a simplified FMVSS 208 sled model to assess occupant performance. Jeon et al. [83] evaluated the folding pattern and tear seam of an airbag using sub-system simulations. Brown et al. [84] developed methods to simplify finite element models with frontal occupant restraint systems.

Coupled LS-DYNA and MADYMO Methods

To save simulation time, coupling methods combining calculations from both a finite element program (LS-DYNA) and an occupant analysis program (MADYMO) are also performed regularly. Gunasekar et al. [85] developed a LS-DYNA and MADYMO coupled model to simulate a frontal offset crash test. A "Versatile Occupant Analysis Model" was proposed by Musale et al. [86] to optimize restraint systems and interior components by coupling LS-DYNA and MADYMO calculations. Canadas et al. [87] presented an integrated process to conduct occupant safety simulation with the coupling of LS-DYNA and MADYMO, including a link between CAD (Computer Aided Design) and CAE (Computer Aided Engineering).

Racing Car Steering Systems

After the death of Formula One driver Ayerton Senna in 1994, in a crash with a steering column failure, the Federation Internationale de l'Automobile, the sport's governing body, began to study potential safety regulations that could help prevent similar incidents. The Expert Advisory Safety Committee was formed and the committee recommended, among other safety measures, the use of collapsible steering columns in all Formula One cars. To comply with ECE R12, Williams [88] used finite element analysis to guide the design of collapsible steering systems for sports cars. Moncur et al. [89] and Chandra et al. [90] created finite element models for Formula One race cars with steering and suspension systems. High speed crashworthiness simulations were conducted to improve occupant safety by enhancing the monocoque body structures.

OBJECTIVE

The objective of this study is to develop a high fidelity steering wheel and column assembly model that can be used for frontal (FMVSS208, IIHS 40% ODB, and IIHS SORB) and side (FMVSS214 Side MDB, oblique and perpendicular pole, and IIHS Side MDB) impact simulations. The developed model will enable evaluation of occupant responses in full vehicle or sub-system simulations. It can also be used in finite element analysis programs (LS-DYNA) and/or coupled calculations with finite element and occupant analysis programs (LS-DYNA & MADYMO coupling). The entire study is divided into two phases. In the first phase of the study, the modeling methodology of an adaptive energy absorbing steering column was developed and has been reported [91]. This paper documents the results obtained from the second (final) phase of the study with focus on the modeling of an advanced steering assembly with a safety-enhanced steering wheel and an adaptive energy absorbing steering column. Similar to the first phase, various component and sub-system tests were designed and conducted to simulate the mechanical behaviors of different components that can occur in frontal and side impact crash tests. With the high number of different materials

used in the steering wheel and column assembly, the strain rate effects of these materials cannot be ignored. As a result, quasi-static and different dynamic impact speeds were considered in the test matrices. The final modeling methodology of the steering wheel and column assembly is presented based on the correlations obtained from the first and second phases of the study. The final goal of this study is to utilize the modeling methodology in vehicle safety system development, optimization of prototype testing, and enable faster development cycle time.

STEERING WHEEL AND COLUMN ASSEMBLY

The advanced steering wheel and column assembly chosen in this study is composed of several components, including a steering wheel, steering wheel shroud, steering column, sliding portion, bend tear sheet (BTS), pyrotechnically activated pin, fixed housing, telescope/tilt adjustment mechanism, and an intermediate shaft. The airbag mounting to the center hub of the steering wheel was not included since it is outside the scope of this study. The different components are illustrated in Figures 7 and 8 in which the assembly was mounted to a test fixture. The main objective of this study is to develop a modeling methodology for the steering wheel and column assembly so that occupant performance assessments can be conducted using computer simulations. Therefore, only the components affecting the occupant response were included in the study. For example, turn signal and windshield wiper switches, horn button, airbag cover, and steering wheel mounted paddle shifters were not included. The telescope/tilt adjustment mechanism is not part of the energy management characteristics, however removing it would affect the press fit of the assembly. Therefore, the telescope/tilt adjustment mechanism was left in place for the study.

A steering wheel, in general, is comprised of a metal steering wheel armature that is enclosed in an material such as elastomeric foam, wood, or a combination of the two. In the steering wheel assembly studied, the armature is made of an AM60 magnesium alloy through a die-casting process. The magnesium steering wheel armature provides the required structural stiffness and is covered with polyurethane foam which was produced via an injection molding process. As shown in Figure 9, a mass damper and cruise and media control buttons were kept in the steering wheel assembly. The steering column has several safety-enhanced features that were designed by using the sliding portion, BTS, pyrotechnically activated pin, and fixed housing, to adjust the energy absorption level for different impact conditions. The safety-enhanced features, shown in Figure 8, have been described in detail in Tyan et al. [91], which is not repeated here.

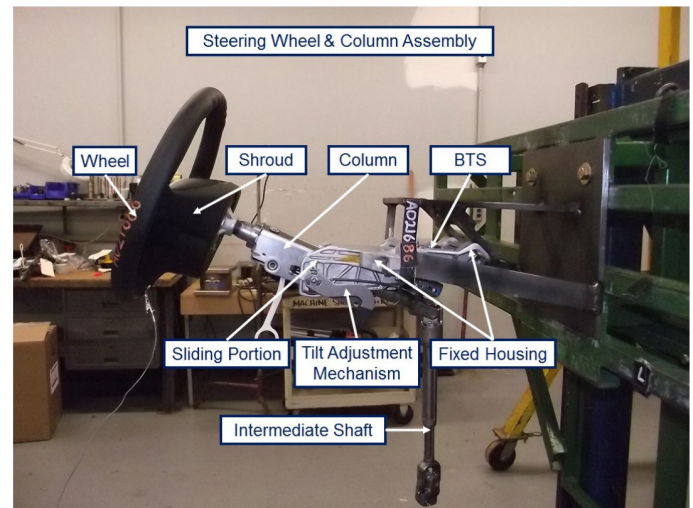


Figure 7. Steering wheel and column assembly.

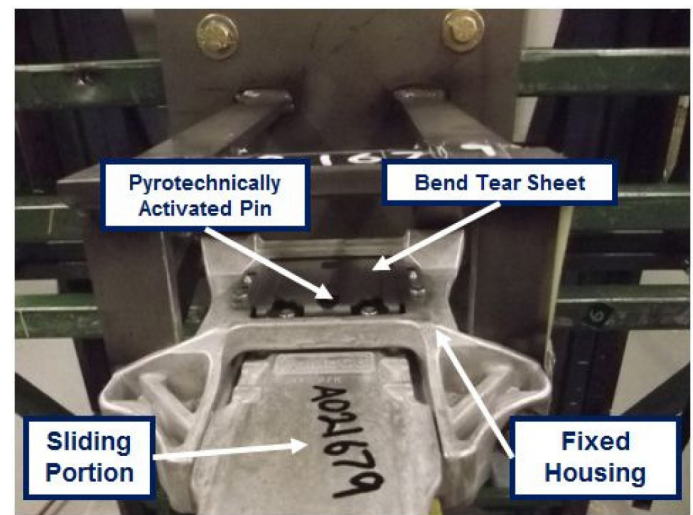


Figure 8. Adaptive energy absorbing features.

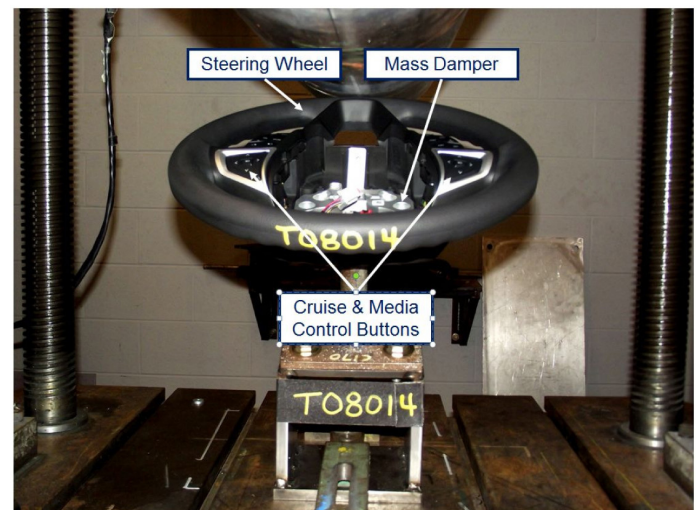


Figure 9. Steering wheel assembly.

Table 1. Steering wheel assembly performance test.

Test # (Run #)	Test Condition	Impact Direction	Impact Speed	Impact Mass (Sample Size)
1 T08012 T08013 T08014	Steering Wheel (production configuration)	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
2 A021704 A021705 A021706	Steering Wheel (production configuration)	Forward	8.10 mph 8.15 mph 8.13 mph	40Kg/87.15 lbs (3)
3 A021707 A021708 A021709	Steering Wheel (production configuration)	Forward	11.97 mph 12.04 mph 12.01 mph	40Kg/87.15 lbs (3)

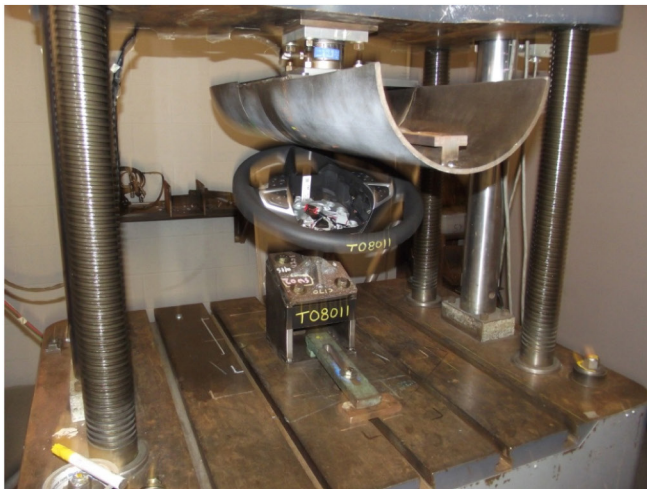


Figure 10a. Quasi-static test.

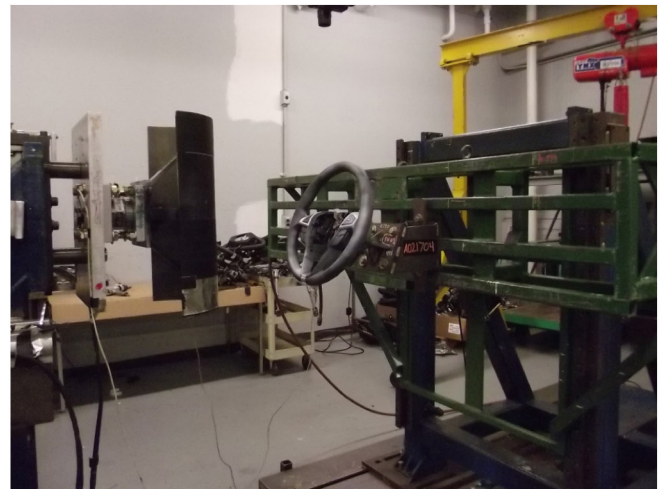


Figure 10b. Dynamic test.

Figure 10. Test fixture and impactor designed for the steering wheel assembly tests.

COMPONENT AND SUBSYSTEM TESTS

A total of eleven tests were developed for this study to understand the response of the advanced steering wheel and column assembly and to obtain reliable data for model methodology development. Among the eleven tests, three component tests were designed for the steering wheel assembly alone. [Table 1](#) summarizes the loading conditions for the three steering wheel assembly tests, with one quasi-static test (Test no. 1) and two dynamic tests (Test nos. 2 and 3). The quasi-static tests were conducted using a hydraulic powered loading device and the dynamic tests were conducted using a gas fired impactor. As seen in [Figures 10a](#) and [10b](#), a rigid test

fixture was designed in this study to mount the steering wheel in the vehicle orientation. The same test fixture was used in both the quasi-static and dynamic tests. Instead of the flat rigid impactor used in the steering column assembly study [91], two cylindrical impactors with 10 inch diameters were fabricated for this study to conduct the component and subsystem tests seen in [Figures 10a](#) and [10b](#).

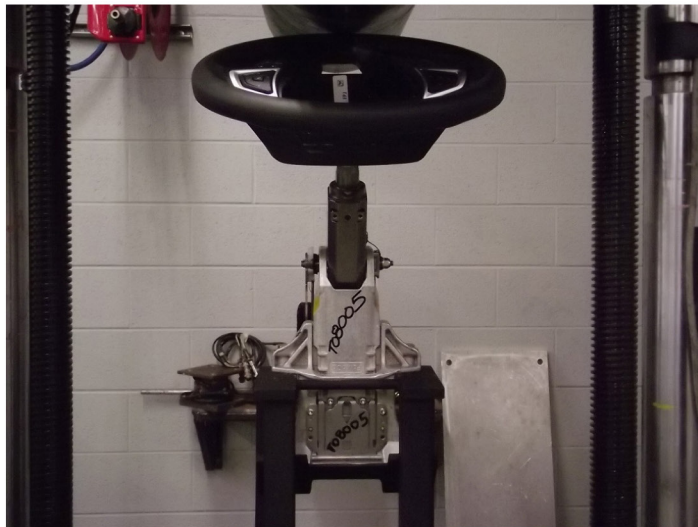
In addition to the three component tests, eight subsystem tests were developed to understand the responses of the steering wheel and column assembly under different loading conditions. The loading conditions for the eight steering wheel and column

assembly tests are summarized in Table 2. Similar to the steering column assembly tests conducted previously [91], both “pin-disengaged” (Test no. 1, 2, 5, and 8) and “pin-engaged” (Test no. 3, 4, 6, and 7) conditions were considered in this study. The loading conditions summarized in Table 2 include two quasi-static tests (Test no. 1, and 3) and six dynamic tests (Test no. 2 and 4 to 8). To simulate frontal and side impact conditions, both normal (Test no. 1, 2, 3, and 4) and offset (Test no. 5, 6, 7, and 8) column mounting angles were considered. Figure 11 shows the setup for the quasi-static and dynamic tests. The test fixture designed for the steering column assembly test [91] could be re-used in this study. Since the developed modeling methodology is intended for various impact conditions, four offset loading conditions were determined. The steering wheel and column assembly was offset 30 degrees to the left, to the right, upward, and

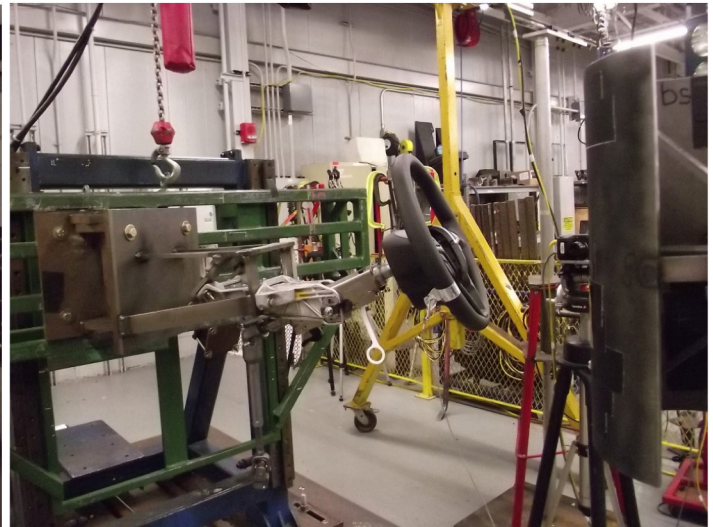
downward (Test no. 5 to 8). An adaptor as shown in Figure 11b was constructed specifically for the four offset tests. The adaptor was a simple 30 degrees ramp structure connecting the test fixture to the supporting structure. The adaptor can be rotated to create a desired 30 degrees offset angle for the steering wheel and column assembly. The steering wheel and column assembly was bolted (tightened to nominal torque) to the test fixture to simulate its normal in-vehicle attachment to the IP (Instrument Panel) structure. Additionally, the steering wheel and column assembly was set to the midpoints of tilt and telescope (mid/mid position) for every test. A load cell, an accelerometer, and a contact switch were instrumented and mounted to the cylindrical impactor so that the force-deflection data for each test could be obtained. The devices are accurate to within 1 N, 1 mm, and 1 ms.

Table 2. Steering wheel and column assembly performance test.

Test # (Run #)	BTS Condition (Load Condition)	Assembly Orientation (Column Position)	Impact Speed	Impact Mass (Sample Size)
1 T08005 T08006 T08007	Pin disengaged (Low load)	Normal (mid/mid)	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
2 A021686 A021687 A021688	Pin disengaged (Low load)	Normal (mid/mid)	16.04 mph 16.05 mph 16.08 mph	40Kg/87.15 lbs (3)
3 T08008 T08009 T08010	Pin engaged (High load)	Normal (mid/mid)	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
4 A021690 A021691 A021692	Pin engaged (High load)	Normal (mid/mid)	20.18 mph 20.15 mph 20.22 mph	40Kg/87.15 lbs (3)
5 A021700 A021701	Pin engaged (High load)	30° offset to the left (mid/mid)	16.03 mph 16.0 mph	40Kg/87.15 lbs (2)
6 A021702 A021703	Pin dis-engaged (Low load)	30° offset to the right (mid/mid)	16.02 mph 15.98 mph	40Kg/87.15 lbs (2)
7 A021695 A021696	Pin dis-engaged (Low load)	30° offset upward (mid/mid)	15.97 mph 16.03 mph	40Kg/87.15 lbs (2)
8 A021697 A021699	Pin engaged (High load)	30° offset downward (mid/mid)	16.01 mph 15.99 mph	40Kg/87.15 lbs (2)



(a) Quasi-static test.



(b) Dynamic test.

Figure 11. Test fixture and impactor designed for the steering wheel and column assembly tests.

MODELING METHODOLOGY

The final finite element model developed for the steering wheel and column assembly is shown in Figure 12. The steering wheel and column assembly model is composed of 69 parts with 106,700 nodes, 111,772 elements, 28,304 shells, 2,097 beams, and 81,371 solid elements. The finite element model contains the components of the physical steering wheel and column assembly that was used in the subsystem test (Table 2). The steering wheel and column assembly model is mainly composed of a steering wheel assembly model and a steering column assembly model. The bolt connecting the steering wheel assembly and the steering column assembly was modeled using a spring element. The steering column assembly model has 40 parts, 56,149 nodes, 67,697 elements, 16,990 shells, 1,532 beams, and 49,175 solid elements. The model details for the steering column assembly have been introduced in Tyan et al. [91] and are not repeated here.

The steering wheel assembly model (shown in Figure 13), with 29 parts, 50,552 nodes, 44,075 elements, 11,314 shells, 565 beams, and 32,196 solid elements, is slightly smaller than the steering column model. As can be seen, the number of solid elements used in the steering wheel assembly model is three times as many as the shell elements. The majority of the solid elements come from the steering armature and the polyurethane foam as shown in Figures 14 and 15. The steering armature was modeled with 9,602 hexahedral solid elements and the polyurethane foam model with 21,798 hexahedral solid elements. The hexahedral solid elements, ranging from 3 to 5 mm, have a 4 mm average element size. The mass damper was also modeled with hexahedral solid elements, as shown in Figure 16. A total of 940 solid elements,

with a 4 mm average element size, were used to model the mass damper. Other components such as the shroud and electronic control buttons were modeled with shell elements. The shell elements also range from 3 mm to 5 mm with a 4 mm average element size. The test fixture and the cylindrical impactor (Figure 10) designed for the steering wheel assembly tests were also modeled with shell elements according to their geometries and dimensions as shown in Figure 17. Similarly, test fixture and the cylindrical impactor models used in the steering wheel and column assembly simulations are shown in Figures 18 and 19 for quasi-static and dynamic test conditions respectively.

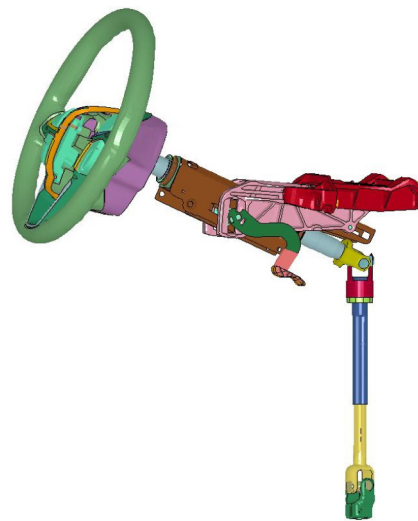


Figure 12. Steering wheel and column assembly model.