TMA Truck Safety

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16. Abstract

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Disclaimer

The opinions, findings, and conclusions expressed in this document are those of the investigators. They are not necessarily those of the Missouri Department of Transportation, the U.S. Department of Transportation, or the Federal Highway Administration (FHWA). This information does not constitute a standard or specification.

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List of Abbreviations and Acronyms

AI	artificial intelligence
GEBOD	Generator of Body Data
HANS	head and neck restraint
MoDOT	Missouri Department of Transportation
NIC	Neck Injury Criterion
N_{ij}	Normalized Neck Injury Criterion
N_{km}	Neck Protection Criterion
ROM	Range of Motion
TAC	Technical Advisory Committee
THUMS	Total Human Model for Safety
TMA	truck-mounted attenuator

Abstract

This study evaluates the effectiveness of in-vehicle safety countermeasures in reducing injury risk for TMA (Truck-Mounted Attenuator) truck occupants during collisions. With increasing incidents involving TMAs in work zones, understanding the protective impact of advanced safety features has become crucial. A review of historical TMA crash reports revealed that rear-end collisions are the primary issue, with whiplash injuries being the most common type of injury among drivers. Current in-vehicle safety countermeasures were examined, including active headrests, reactive seatbacks, and anti-whiplash systems, which were tested across six simulated collision scenarios incorporating varying vehicle weights, speeds, and impact angles. Using a biomechanical simulation model and telematic data, results indicated that active headrests, particularly with 40 mm displacement, consistently reduced injury criteria values (NIC, N_{ij}, N_{km}), effectively lowering head and neck injury risks in both straight and angled collisions. In contrast, the reactive seatback and anti-whiplash systems demonstrated mixed efficacy, performing well in low-impact conditions but poorly in high-impact scenarios. Limited high-impact telematic data, particularly with 80,000-pound vehicles, highlight the need for further validation for high-impact collision scenarios. Findings suggest that integrating advanced head restraint systems could significantly enhance TMA truck driver safety.

Executive Summary

Truck-Mounted Attenuators (TMAs) are critical for work zone safety, helping to dissipate collision energy and mitigate the severity of collisions. However, factors such as distracted and impaired drivers, speeding in work zones, traffic congestion, and increased road construction and maintenance activities have led to a rise in TMA-involved crashes, posing an increasing safety risk to TMA drivers.

The objective of this project is to evaluate the effectiveness of in-vehicle safety countermeasures aimed at enhancing driver protection in TMA trucks and provide data-driven recommendations to improve TMA truck safety. To accomplish this objective, the project includes a review of TMA-involved crash reports in Missouri, an assessment of current in-vehicle safety features, and a simulation study focused on three specific safety countermeasures: active headrest, reactive seatback, and anti-whiplash system.

A review of Missouri crash data indicates that rear-end collisions are the predominant type of TMA-involved crash, with head and neck whiplash injuries frequently affecting TMA drivers. This finding underscores the importance of countermeasures that target these specific injury mechanisms. The study also conducted a comprehensive review of TMA truck safety features, including seat belts, seat types, steering wheels, airbags, and other systems, outlining the benefits and limitations of each. In collaboration with Missouri Department of Transportation (MoDOT) engineers, the project identified active headrests (20 mm/40 mm displacement), reactive seatbacks (20 degree/30-degree rotation), and anti-whiplash systems as priority countermeasures for detailed simulation analysis.

Active headrests are designed to automatically move forward during a rear-end collision, reducing the gap between the headrest and the occupant's head. Reactive seatbacks are engineered to absorb and manage impact forces by reclining or shifting slightly backward upon impact, minimizing the relative acceleration between the occupant's head and torso. Anti-whiplash systems integrate the reactive seatback with a translational spring in the seat base, effectively absorbing energy and limiting excessive seatback rotation.

Biomechanical simulation modeling was used to evaluate the injury mitigation impact of selected safety countermeasures. As shown in Figure E.1, a digital biomechanical model was created using Adams View to simulate the effects of rear-end collisions on TMA drivers under various scenarios. Telematic data from MoDOT's fleet was integrated into the simulation, providing real-world data on impact accelerations and collision dynamics essential for calibrating the simulations.

The simulation tests involved six collision scenarios, featuring vehicles ranging from 4,000 pounds sedans to 80,000 pounds semi-trucks, at both straight and 30-degree offset collision angles. Injury metrics such as Neck Injury Criterion (NIC), Normalized Neck Injury Criterion (N_{ij}), and Neck Protection Criterion (N_{km}) were used for a quantitative comparison of injury risks across the safety countermeasures.

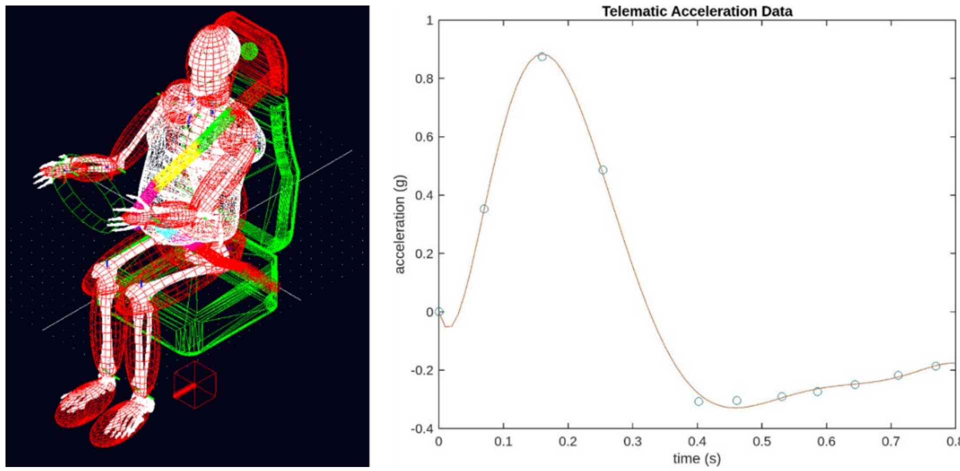

Figure E.1. Digital biomechanical model and sample acceleration profile for a rear-end crash.

Results

1. Active Headrest: The active headrest consistently reduced injury criteria values across most scenarios. The 40 mm active headrest configuration was particularly effective in straight and angled collisions, demonstrating significant reductions in NIC, N_{ij}, and N_{km} values. Active headrests can minimize the backward momentum of the head, thereby decreasing the forces experienced by the neck and reducing the risk of whiplash injuries.

2. Reactive Seatback and Anti-Whiplash System: Results of the reactive seatback and anti-whiplash systems were mixed. While both countermeasures provided modest reductions in injury criteria for low-impact collision scenarios, their performance was less reliable in high-impact collision scenarios, particularly with heavy vehicles at 18g force levels. The reactive seatback's performance was largely dependent on its rotational resistance settings; higher resistance led to increased NIC values due to acceleration spikes, while lower resistance allowed for greater momentum, which could lead to higher injury risks upon impact.

3. Limitations in High-Impact Data: Simulations involving the heaviest vehicles (80,000-pound) may not fully reflect real-world conditions due to the limited availability of high-impact telematic data. Since such collisions are relatively rare and often involve secondary impacts, validating simulation scenarios is challenging. As a result, further studies with expanded telematic data are recommended to verify findings for extreme collision scenarios.

Conclusion

This study highlights the importance of in-vehicle safety countermeasures for protecting TMA truck drivers in work zones. The active headrest, especially at 40mm displacement, was considered as the most effective countermeasure, consistently reducing injury risk in rear-end collisions. The reactive seatback and anti-whiplash system only demonstrated benefits in low-impact collisions. Future research could continue refining these systems to enhance their adaptability and reliability in high-impact scenarios, to create a safer work environment for TMA truck operators.

1. Introduction

A truck-mounted attenuator (TMA) is a safety device mounted on the rear of a truck designed to dissipate collision energy and reduce the severity of rear-end crashes (Figure 1.1). In addition to its primary function, TMAs offer quick deployment, enhance work zone visibility, and help capture drivers' attention (Aroke et al. 2022). Due to these advantages, TMAs have been extensively employed in mobile and short-duration work zone operations (Cottrell 2015). However, due to various reasons such as distracted and impaired drivers, congestion, and increased road construction and maintenance activities, the number of TMA crashes has been on the rise for a few years (Cottrell 2015). In Missouri, the number of crashes involving TMAs and protective vehicles in the past four years is shown in Figure 1.2. The yellow line shows the 4-year average trending upwards every year, from 33 crashes in 2020 to 46 crashes in 2023. Out of the 145 TMA crashes recorded from 2020 to 2022, 56 MoDOT employees sought medical attention (MoDOT 2024).

Figure 1.1. MoDOT TMA.

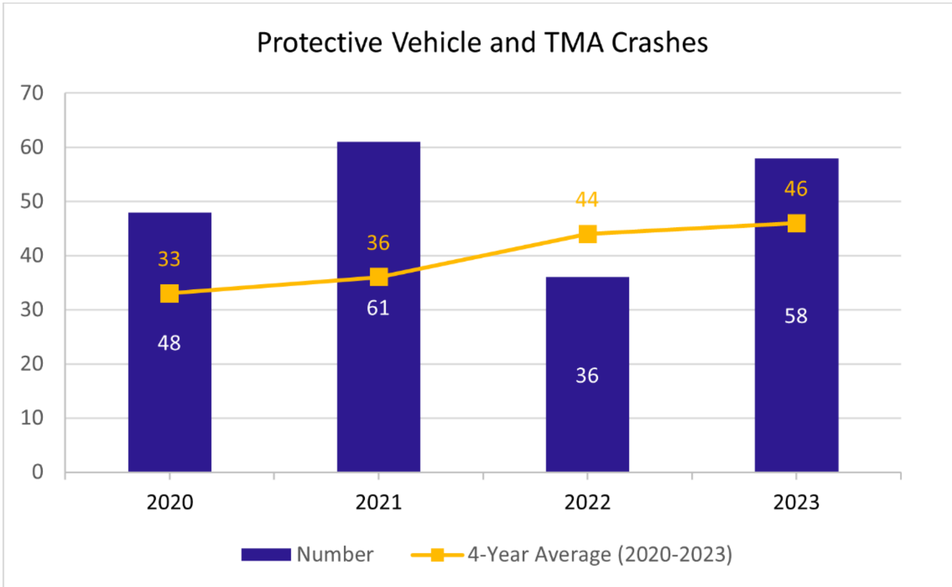

Figure 1.2. MoDOT 2020-2023 protective vehicle and TMA crashes. (MoDOT, 2024)

To address the increasing risks faced by TMA truck drivers and improve their safety, truck and TMA manufacturers, transportation engineers, and researchers are exploring diverse approaches. The first approach focuses on reducing the number of TMA crashes by implementing pre-collision warning systems (Adu-Gyamfi et al. 2017; Brown et al. 2015) and well-designed TMA driver training programs (Kivi et al. 2015). The second approach involves investigating truck and TMA designs (e.g., center of gravity and loading conditions) and crashworthiness (e.g., roof and pillar strength) to mitigate the impact of collisions (Fancher and Winkler 2007; Woodrooffe and Blower 2015; Mikheev et al. 2021). Lastly, significant efforts are directed toward enhancing operator safety through in-vehicle countermeasures to reduce the severity of rear-end crashes (Aroke et al. 2022). These in-vehicle countermeasures include advanced seat belt systems, head and neck support and restraint devices, and improved seat construction (Aroke et al. 2022).

The objective of the project is to investigate the impact of in-vehicle safety countermeasures on TMA driver safety and provide recommendations and implementations to avoid injuries or reduce the severity of injuries. This study involved reviewing crash reports involving TMAs, conducting interviews with TMA vendors, performing an extensive literature review, and utilizing simulation modeling to evaluate selected in-vehicle safety countermeasures across various scenarios.

2. TMA-Involved Crash Review

Between 2021 and 2023, there were 135 recorded crashes involving TMAs in Missouri. The primary types of crashes recorded include front-to-rear collisions, sideswipes in the same direction, and angle crashes. The data provides insights into the severity and types of injuries, highlighting areas where additional measures could enhance safety and mitigate common injury risks associated with these incidents.

Front-to-Rear Crashes

Front-to-rear collisions comprised the vast majority of these crashes, accounting for 79.3% of the total with 107 incidents. In most cases, these collisions led to minimal or no injuries, with 86 cases reported as having no apparent injury. Thirteen cases were classified as probable but not apparent injuries, seven cases involved evident but non-disabling injuries, and one incident was marked as a suspected serious injury. This high frequency of front-to-rear impacts suggests that vehicles approaching TMAs often fail to stop in time, leading to significant rear impacts. These impacts commonly result in whiplash injuries, with brain and neck areas particularly vulnerable due to the sudden acceleration forces in rear-end collisions.

Sideswipes in the Same Direction

Sideswipes in the same direction made up a smaller portion of TMA-involved crashes, accounting for 18.5% of incidents with 25 crashes reported. Similar to front-to-rear collisions, sideswipe crashes generally resulted in minor or no injuries. Of these, 24 incidents had no apparent injuries, while one was classified as having evident but non-disabling injuries. This crash type occurs when drivers attempt to maneuver around TMAs without providing adequate space. Although most sideswipe incidents are less severe, they still represent a significant risk, potentially leading to secondary incidents, particularly if vehicles are pushed into adjacent lanes or obstacles during the maneuver.

Angle Crashes

Angle crashes were rare, making up only 2.2% of TMA-involved crashes, with three incidents recorded. None of these incidents resulted in reported injuries. Despite their infrequency, angle crashes still pose a unique challenge due to the non-perpendicular impact angles, which can lead to complex collision dynamics. Though these incidents did not result in injury, angle crashes can potentially lead to severe outcomes, especially if conditions were to vary, such as speed or angle of impact.

The analysis of TMA-involved crash injuries reveals a recurring concern with whiplash, particularly affecting the brain and neck. Whiplash injuries in these crashes can range from minor discomfort to severe, long-term complications. Given that front-to-rear collisions are the dominant crash type, strategies to mitigate whiplash injuries should be prioritized.

3. TMA Vendors Interview Summary

To gain insights into the safety features of the trucks used with TMAs, interviews were conducted with vendors of TMAs and other safety-related equipment used in work zones. A list of vendor contacts was obtained from MoDOT, and the vendors were asked if they would be willing to participate in interviews. Two vendors agreed to participate in the interviews: Hoosier Company and Gregory Highway.

The interview questions covered topics such as vehicle specifications, seat belt systems, airbags, and availability and cost of other safety features available on trucks used with TMAs. A copy of the interview questions is provided in Appendix B.

The vendor representative from Hoosier Company provided an overview of the current safety equipment installed in TMA trucks. The TMA trucks are equipped with a standard seat belt and a steering wheel airbag, although they lack other typical safety features commonly seen in modern trucks. An air-ride suspension seat can be installed, primarily for driver comfort, especially given the weight of the trucks, which range from 18,000 to 20,000 pounds. The representative has not seen other seat belt configurations, side curtain air bags, or other safety features on the TMA trucks. Additionally, the representative noted that the crew cab versions are heavier due to their larger frame, which impacts overall handling. A significant concern raised by the representative involved driver distraction within the cab, especially given the potential for in-cab cameras or Artificial Intelligence (AI) systems that could monitor and address distracted driving behaviors. These technologies could be considered to enhance focus and situational awareness for TMA drivers, particularly given the unique demands of work zone environments.

The representative from Gregory Highway indicated that his focus is on the TMA unit. Thus, he does not work with the TMA truck and is not familiar with the features for occupant safety on the TMA truck.

Overall, the results from the interviews indicate that standard seatbelts and steering wheel airbags are installed on the TMA trucks, but alternative seat belt configurations, side curtain airbags, and other occupant safety features are not typically available from the manufacturers of TMA trucks.

4. Existing TMA Truck Safety Countermeasure Review

The current in-vehicle safety countermeasures for TMAs were reviewed, including seat belt, seat, steering wheel, airbag, and other systems.

4.1 Seat Belt

Seat belt systems can involve different number of points at which the belt is attached. Figure 4.1 shows six configurations ranging from three to six points.

3-point system: Three-point system is the most common system used to keep vehicle occupants strapped down during a collision. The triangle-shaped configuration can catch the occupants from riding the momentum in the direction of the strike. However, the 3-point systems does not optimally restrain occupants in all types of crashes (Kubiak 1997; Rouhana et al. 2003). For example, the three-point system may not fully prevent upper body movement or rotational forces, which can lead to injuries like whiplash or side-impact trauma.

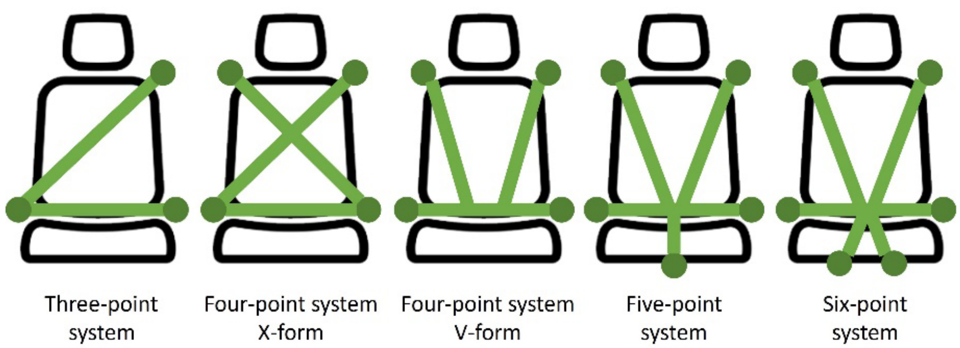

Figure 4.1 Seat belt systems.

4-point system: Four-point seat belt systems connect to the seat at four points, providing two shoulder straps and two lap belts. There are two main forms: the X-form and V-form configurations (Rouhana et al. 2003). Both configurations offer enhanced restraint compared to the three-point seat belt, as the additional points of contact help keep occupants securely in place during a collision. The distribution of pressure across a larger area also reduces the force on any single body part, potentially lowering the risk of injury. However, four-point belts are more restrictive, limiting the wearer's movement within the vehicle. Another issue is that these systems can concentrate forces on the clavicles and pelvis, and, without lower body restraint, there's an increased risk of the occupant sliding or "submarining" beneath the belt in a severe impact.

5-point system: The five-point seat belt system connects to the seat at five points in a star-shaped configuration, building on the four-point design by adding an additional contact point to enhance safety. This fifth point, located between the legs in the groin area, prevents the occupant from sliding forward or out of the seat, offering improved stability and protection (Aroke et al. 2022). However, the main drawback is its restrictiveness, as the additional restraint points limit movement within the seat, making it less comfortable and more constraining for everyday use.

6-point system: The six-point seat belt system is one of the safest seat belt options, providing six points of contact with the seat to keep the occupant securely in place during a collision (Melvin et al. 2006). This design minimizes movement and greatly reduces the risk of injury by distributing crash forces across multiple points. However, as with other multi-point systems, comfort is a primary drawback. With six points of restraint, the system restricts movement, limiting flexibility and comfort for the occupant, making it less practical for regular use.

Progressive, pre-tension seat belt: The progressive, pre-tension seat belt is designed to reduce the force experienced by the driver’s body in the event of a collision. When the system detects an impact or sudden deceleration, it automatically tightens, removing any slack and increasing tension to secure the driver firmly against the seat. By restraining the driver in place and decelerating the body, the seat belt limits movement due to inertia, helping to prevent injury (Forman et al. 2009; Jakobsson et al. 2015). Though the pre-tension mechanism activates only once per incident, it significantly enhances driver safety.

4.2 Seat

Suspension seat with a B-pillar anchored seat belt: A suspension seat with a B-pillar anchored seat belt enhances comfort by reducing vibrations and shocks, making it ideal for long drives. The B-pillar anchoring ensures reliable crash restraint while allowing the seat to move independently. However, in severe vertical impacts, this setup may be less effective, as the independent seat movement can lead to slight misalignment or temporary slack in the belt (Mooren and Williamson 2013).

Suspension seat with an integrated seat belt: A suspension seat with an integrated seat belt provides enhanced comfort and consistent restraint, as the belt moves with the seat. Compared to a suspension seat with a B-pillar anchored seat belt, this design improves safety by maintaining a snug fit, reducing seat belt slack during vertical movements, and minimizing back ramping in rear-end collisions (Mooren and Williamson 2013; Rashidy et al. 2001; Seyer and Jonas 2002). However, it’s typically more expensive, adds weight, and can require more frequent maintenance due to the combined seat belt and suspension mechanisms (Bahouth et al. 2007).

Active headrest: An active headrest, such as Toyota Active Headrest (Toyota, 2009) and Honda Head Restraint (Honda 2018), enhances safety by automatically moving forward and upward in a rear-end collision to support the head, reducing the risk of whiplash and neck injuries (Kullgren et al. 2007; Viano 2008). The design provides effective whiplash protection without compromising comfort during regular use. However, the added complexity and cost of the sensors and moving parts can increase vehicle expenses and may require occasional maintenance. While highly effective in moderate to severe collisions, active headrests may offer minimal extra benefit in low-speed impacts and may not be compatible with all seat designs.

Reactive seatback: The reactive seatback, such as Volvo Whiplash Protection System (Volvo 2015), enhances safety in rear-end collisions by automatically reclining and moving backward, which helps reduce whiplash and minimize impact forces on the spine (Jakobsson et al. 2015; Kullgren et al. 2007). However, the added complexity and cost, limited effectiveness in non-rear impacts, and potential maintenance needs make it a specialized feature.

Seat material and frame: Energy-absorbing materials in the head and back rests improve safety and comfort by cushioning impact forces, effectively reducing injury risks in low to moderate collisions (Jakobsson et al. 2015). However, their protection is limited in high-speed crashes, and they may require maintenance. A combination of low seat stiffness, a strong seat frame, and forward-positioned head restraints further enhances safety by minimizing whiplash risk and providing a more supportive, comfortable seat structure (Viano 2008; Viano and Parenteau 2015).

4.3 Steering Wheel

Collapsible safety steering column: A collapsible safety steering column enhances driver safety by absorbing impact energy in a frontal collision, reducing injury risk to the chest and head, and working effectively with airbags (Tyan et al. 2014). It has been widely used due to its reliable protection benefits. However, its impact is limited to frontal crashes, and minor impacts can cause partial collapse, potentially requiring costly repairs.

4.4 Airbag

Steering wheel airbag: The steering wheel airbag provides essential frontal protection for the driver, reducing injuries to the head, neck, and chest during a frontal collision (Kubiak 1997). It works effectively alongside seat belts to minimize the severity of injuries. However, it offers limited protection to side or rear impacts.

Side airbag: Side airbags are crucial for protecting the torso and pelvis impact by absorbing impact forces and preventing door intrusion injuries. They are particularly effective in reducing injuries associated with rollover and side impact collisions (Simon et al. 2001).

Knee bolster airbag: Knee bolster airbags protect the lower body by reducing leg and knee injuries in frontal impacts, preventing occupants from sliding under the seat belt, and providing added stability. In conjunction with seat belts, they also help reduce the forces on the driver's chest and abdomen. However, knee airbags increase cost and complexity.

4.5 Other Systems

Head and neck restraint device: Head and neck restraint (HANS) devices are designed to minimize movement during a crash, reducing the risk of whiplash and severe injuries. These devices work by securing the driver's head and neck to limit forward or sideways motion, often attaching to a helmet and integrated with a five- or six-point harness (Melvin et al. 2006).

However, they come with some drawbacks: they restrict neck movement, require the driver to wear a helmet, need a multi-point seat belt system, and can be costly to implement.

Weight: The weight of a truck impacts occupant safety in collisions. Increased truck weight enhances stability and reduces roll-ahead distance, contributing to improved overall stability (Theiss and Bligh 2013). If ballast is added to a TMA truck, it must be properly secured to prevent it from shifting and detaching during a collision, which could pose significant hazards to workers and other road users (TrafFix 2018).

TMA mounting: TMA mounting options are categorized into truck-mounted and trailer-mounted attenuators. Truck-mounted attenuators are securely attached to the frame of the host truck, while trailer-mounted attenuators are equipped with an axle and wheels and connect to the host truck using a trailer hitch, pintle hook, and Lunette eye. While truck-mounted attenuators offer greater stability and quicker setup, trailer-mounted attenuators provide more flexibility in deployment. Previous studies indicate no significant differences in truck trajectories during collisions between truck-mounted and trailer-mounted attenuators (Theiss and Bligh 2013).

The findings of current in-vehicle safety countermeasures for TMAs have been summarized in Table 4-1.

Table 4-1. Summary of current safety countermeasures for TMAs.

Systems	Type	Pros	Cons
Seat belt	Three-point system	• Standard system	• Not optimally restraining an occupant for all types of crashes
	Four-point system (x-form and v-form)	• Add constraints to the torso • Reduces chest impact and thoracic injury and shift the load to clavicles and pelvis	• More restrictive than 3-point system. • Increase risks of sliding without lower body restraint
	Five-point system	• Prevent driver from sliding down in seat • Significantly prevents torso forward motion	• More restrictive than a 4-point system
	Six-point system	• Safest option	• Most restrictive
	Progressive, pre-tension seat belt	• Reduces peak belt tension and mid-spine acceleration	
Seat	Suspension seat with a B-pillar anchored seat belt	• Similar comfort level to a light passenger vehicle	• Slowly tightens after the suspension seat moves.
	Suspension seat with an integrated seat belt	• Similar comfort level to a light passenger vehicle • Reduce seat belt slack during vertical movements	• Incurs additional costs and requires extra maintenance.

Systems	Type	Pros	Cons
		• Reduce seat back ramping	
	Active headrest	• Reduce whiplash injury risk	• Added complexity and cost • Compatibility issue
	Reactive seatback	• Reduce whiplash injury risk	• Complexity and cost • Limited effectiveness in non-rear-end collisions
Steering wheel	Collapsible safety steering column	• Absorb the frontal impact energy	• Limited to frontal crashes
Airbag	Steering wheel airbag	• Optimized for frontal crashes. • Reduce the contact force with the steering wheel	• Limited to frontal crashes
	Side airbag	• Optimized for rollover and side impact collision • Effectively reduce fatalities and injured risk	• Added complexity and cost
	Knee bolster airbag	• Reduce lower body injuries • Reduce forces on the driver's chest and abdomen	• Added complexity and cost
Other	Head and neck restraint device	• Prevent whiplash and severe injuries • Effective head padding	• Require a five- or six-point seat belt system • Need to wear a helmet • Restrict head and neck movements • Incur additional cost
	Weight	• Heavier trucks enhance stability • Heavier trucks shorten roll-ahead distance	• Unsecured ballast weight may cause safety hazards
	TMA mounting	• Truck-mounted attenuators offer greater stability and quicker setup • Trailer-mounted attenuators offer flexibility in deployment	• No significant difference in truck trajectories during collisions between truck-mounted and trailer-mounted attenuators.

5. Simulation Methodology

5.1 Digital Biomechanical Model

Digital biomechanical models were developed to enable cost-effective testing of various safety countermeasures and configurations across different scenarios to optimize occupant safety during vehicle collisions. These models were developed using the modeling software Adams, a leading multibody dynamics simulation platform that enables researchers to analyze the dynamics and understand how loads and forces are distributed (Hexagon 2024).

As shown in Figure 5.1, a digital biomechanical multi-body model was developed to assess the impact of safety countermeasures, based on an anthropomorphic 50th-percentile male, incorporating average height and weight. Joint locations, segment mass, and inertial properties were determined using regression equations from the Generator of Body Data (GEBOD) program (Cheng et al. 1996). Adams applies these equations to calculate model properties such as centers of mass, volumes, and densities (Jahandar 2015). The software enables precise measurements of motions and forces at any point in the model, providing accurate readings of accelerations and forces at specific nodes or key joints, which are crucial for evaluating occupant safety during vehicle collisions.

The joints in the human body model were represented as nonlinear torsional springs and linear dampeners, allowing the model to realistically simulate the movements an occupant would experience in a collision. Joint range of motion (ROM) values were applied, considering the model's posed position relative to a standing, resting posture (Soucie et al. 2010). Joint stiffness values were negligible within a small initial angular displacement, but as the joint approached the limits of its ROM, an exponential increase was applied until reaching a maximum value. Dampening values were modeled linearly, with static coefficients restricting joint motion based on movement velocity (Silva et al. 1997).

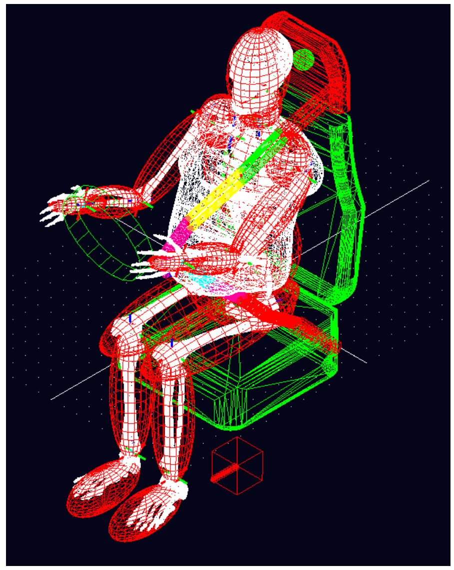

Figure 5.1. Digital biomechanical model in Adams.

The in-vehicle environment was modeled by taking measurements of the interior cab portion of a MoDOT TMA truck during field studies and converting them into Adams using the 3D modeling software AutoCAD. The measurements used in the simulation included the dimensions of the seatback and seat bottom, as well as the location and dimensions of the B-pillar connected seat belt used in the vehicle. The interactions between the digital human body model and the simulation environment were modeled using a Hertzian contact model, which simulates deformable contact between two rigid bodies. This approach allowed for accurate simulation of accelerations and forces, incorporating the deformation that occurs between the solid surfaces during contact. The parameters for the deformable contact model applied between the occupant model and the simulation environment were based on values established by Fu et al. (2021).

Model validation was achieved by comparing and correlating it to the widely used Total Human Model for Safety (THUMS) model (Iwamoto et al. 2015). Validation testing involved recreating and analyzing specific impact scenarios represented in the THUMS model, allowing for detailed cross-referencing of outcomes with real-world vehicle collision data, crash test dummy results, and previously established THUMS model data. Validation scenarios included simulations of frontal impacts, side impacts (Wismans et al. 1987), and rear impacts (Ono et al. 1997). These validation efforts ensured that the model accurately reflected occupant kinematics and injury mechanics across various types of collisions, reinforcing its reliability for evaluating the effects of safety countermeasures in simulated crash environments.

5.2 Safety Countermeasure Simulation

Safety countermeasure simulations were conducted to evaluate the effectiveness of specific safety equipment in reducing occupant injury risk under different conditions, with a focus on forces and accelerations impacting the body, particularly the head and neck. After a comprehensive literature review and consultations with MoDOT Technical Advisory Committee (TAC) members, two safety countermeasures, active headrest and reactive seatback, were selected for simulation tests. The design features and configurations of these devices are outlined as follows:

Active headrest: this feature prompts the headrest to move forward and upward automatically in a rear-end collision, to reduce backward head movement and counter opposing accelerations between the head and torso. By limiting backward momentum before initial headrest contact, this mechanism is designed to reduce impact forces at the base of the head (Bigi et al. 1998).

In simulations, two configurations were tested: one with 20mm of vertical and horizontal travel and the other with 40 mm of travel. The active headrest's performance was evaluated at each travel level to determine its effectiveness in reducing head impact forces.

Reactive seatback: This feature allows the seatback to recline in response to occupant force during a rear-end collision, thereby reducing opposing accelerations at the neck. The seatback begins its motion with a high initial breakaway torque that activates the device, allowing it to rotate to a maximum angle under occupant force. As it reclines, the spring system's stiffness gradually increases, reaching an exponential rise just before reaching its maximum rotation. Additionally, the damping coefficient remains constant in the intended direction while a higher damping coefficient opposes any rebound, preventing harmful recoil effects on the occupant (Himmetoglu et al. 2009).

For testing, the reactive seatback was simulated with maximum rotation values of 20 degrees and 30 degrees, allowing for analysis of the resistance applied at different angular displacements.

Anti-whiplash system: This system integrates the reactive seatback with a translational spring in the seat base to absorb energy and prevent excessive seatback rotation. The translational component functions as a torsional spring-damper, featuring a high initial breakaway torque and an exponentially increasing damping coefficient as deformation rises. A high opposing damping coefficient further mitigates rebound forces that could impact the occupant during a collision (Himmetoglu et al., 2009).

Testing variables for this system were consistent with those used for the reactive seatback, with deformation levels represented at 20 degrees and 30 degrees.

5.3 Scenario Simulation

To evaluate the overall performance of the selected safety countermeasures, six rear-end collision scenarios were chosen for simulation testing in consultation with MoDOT TTAC members. The scenarios outlined in Table 5-1 involve a TMA truck with a weight set at 20,000 pounds. The test scenarios cover a range of highway collisions in work zones, involving various vehicle types—including sedans, trucks, and semi-truck—with differing weights and varied collision angles.

Table 5-1. Test scenarios

Scenario	TMA speed	Striking vehicle speed	Striking vehicle weight	Collision angle
1	15 mph	70 mph	4,000 pounds	Straight
2	15 mph	70 mph	4,000 pounds	30-degree offset
3	15 mph	70 mph	20,000 pounds	Straight
4	15 mph	70 mph	20,000 pounds	30-degree offset
5	15 mph	70 mph	80,000 pounds	Straight
6	15 mph	70 mph	80,000 pounds	30-degree offset

To estimate the collision impact experienced by the occupant of the TMA truck, both physical simulation and telematic data from colliding TMA trucks were used. First, the g-force was estimated using a physical simulation engine based on inelastic collision formula:

$$v_f = \frac{M_1 v_1 + M_2 v_2}{M_1 + M_2}$$

Then, the g-force was estimated as follows:

$$a = \frac{v_f - v_1}{\Delta t}$$

Where:

M = vehicle weight

V = vehicle speed

Δt = collision time

Then, the results were calibrated using telematic data obtained from MoDOT from vehicle collisions involving a TMA truck. The telematic data, collected through the Geotab platform, provided acceleration details during the collision. For example, as shown in Figure 5.2, the telematic data shows a positive acceleration phase of slightly under 1 g lasting approximately 300 milliseconds, followed by a weaker, extended deceleration phase. The collision involved a distracted driver in a sedan weighing around 4,000 pounds colliding with the rear of the stopped TMA at 65 miles per hour. Incorporating this data enables the simulations to be more accurately calibrated to real-world conditions and the effectiveness of the TMA during the collisions.

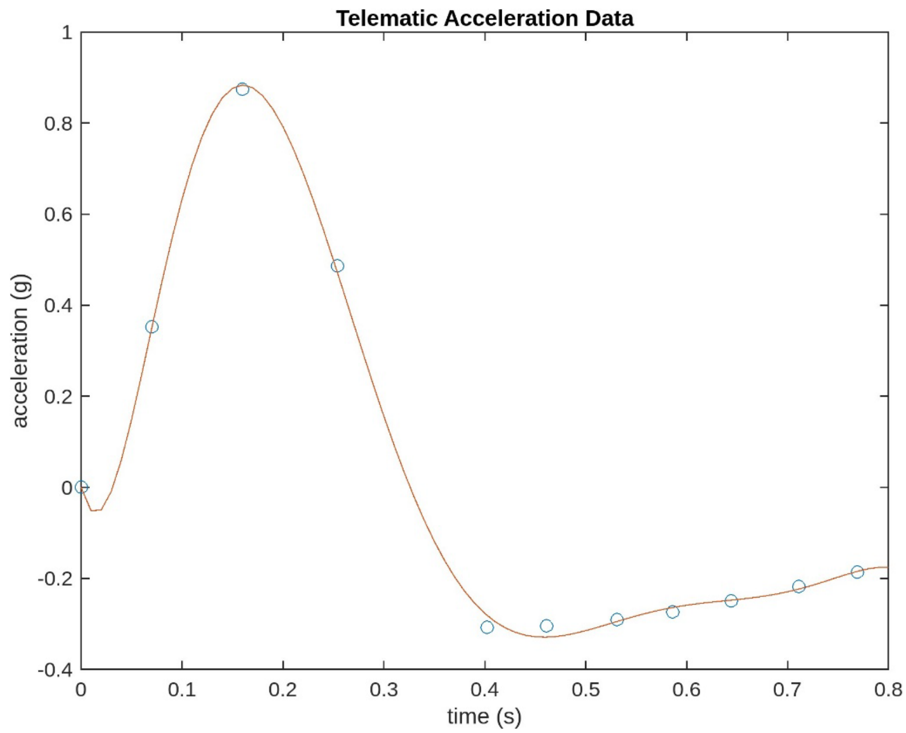

Figure 5.2. Telematic acceleration data for simulation input.

Using the physical simulation and telematic data, the maximum g-force and corresponding acceleration curves were generated for six test scenarios. The maximum g-forces for striking vehicles weighing 4,000 pounds, 20,000 pounds, and 80,000 pounds. were 1 g, 5 g, and 18 g, respectively. Additional testing was conducted to examine angled collisions, simulated by adjusting the input acceleration to 30 degrees clockwise from the occupant's perspective.

5.4 Injury Severity Measurement

The main injury-related measurements gathered included the relative acceleration from the top and bottom of the cervical spine, the bending moment at the base of the head, as well as the shear and axial forces applied to the joint connecting the head to the neck. After the application of a low-pass filter to account for noise in the simulation, these measurements allow us to calculate the following injury criteria to more effectively understand occupant safety during the collision simulations, with a decrease in the injury criteria value meaning a lower chance for possible occupant injury.

5.4.1 Neck Injury Criterion

The Neck Injury Criterion (NIC) assesses the relative accelerations and velocities at opposite ends of the cervical spine, specifically measured at the occipital condyle and the first thoracic vertebrae. This criterion is closely associated with whiplash injuries, although thresholds for various degrees of injury remain under review. Comparing the NIC values across countermeasures and scenarios can provide insights into their relative effectiveness at reducing the risk of injuries like whiplash (Wheeler et al. 1998).

The NIC is calculated using the following equation:

$$NIC(t) = 0.2 \cdot a_{rel}(t) + (v_{rel}(t))^2$$

Where:

a_{rel} = relative acceleration from the top of the cervical spine to the bottom of the cervical spine (meters per second squared)

v_{rel} = relative acceleration from the top of the cervical spine to the bottom of the cervical spine as an integral of a_{rel} (meters per second)

5.4.2 Normalized Neck Injury Criterion

The Normalized Neck Injury Criterion (N_{ij}) includes measurements of the axial forces and bending moment at the base of the head. It is typically measured by a load cell placed in the upper neck region at the C1 vertebrae (Schmitt et al. 2001). The injury mechanism addressed by this criterion is based on the idea that excessive stretching between ligaments could lead to rupture and whiplash injuries (Smotrova et al. 2021). Although N_{ij} is mainly used for frontal impacts involving airbag deployment, it also has merit when comparing testing in rear impacts by offering more information about head and neck interactions during collisions (Schmitt et al. 2001). Current research suggests that injury may occur at around or exceeding 0.09 (Ivancic and Sha 2010).

The injury criteria Nij is computed using the following equation:

$$Nij = \frac{F_Z}{F_{\text{int}}} + \frac{M_Y}{M_{\text{int}}}$$

Where:

F_z = Axial force applied to the base of the head (Newton)

F_{int} = Critical intercept axial force (Newton)

M_y = Sagittal bending moment at base of the head (Newton meters)

M_{int} = Critical intercept sagittal bending moment (Newton meters)

5.4.3 Neck Protection Criterion

The Neck Protection Criterion (N_{km}) assesses the shear forces and bending moment applied to the head-neck connection in the upper neck region, measured by a load cell placed at the C1 vertebrae in dummy testing. This criterion is a modified version of the N_{ij} criterion, specifically aimed at explaining the relationship between injury and applied kinetics in rear-end collisions. It simulates neck injury mechanisms, the "S-shape" formation and neck curvature where the torso and head move in opposite directions, to observed load and moment combinations (Schmitt et al. 2001). Current research correlates values around or exceeding 0.33 with the occurrence of neck injuries (Ivancic and Sha 2010).

The injury criteria N_{km} is computed using the following equation:

$$N_{km}(t) = \frac{F_x(t)}{F_{int}} + \frac{M_y(t)}{M_{int}}$$

Where:

F_x = Shear force applied to the base of the head (Newton)

F_{int} = Critical intercept shear force (Newton)

M_y = Sagittal bending moment at base of the head (Newton meters)

M_{int} = Critical intercept sagittal bending moment (Newton meters)

6. Results

With the fine-tuning of the human model, safety countermeasures, and scenarios, the driver responses during the collision were obtained through the simulation software, Adams. The data of the shear force, axial force, bending moment, and relative acceleration were reported for each tested safety countermeasure along with their configuration and condition within the collision periods.

For example, as shown in Figure 6.1., the shear force, axial force, bending moment, and relative acceleration of control, active headrest (20 mm), and active headrest (40 mm) were plotted under Scenario #1. This scenario involved a 4,000-pound vehicle in a straight rear-end collision and covered the timeframe from the initial impact up to 400 milliseconds post-impact. Simulations were conducted up to 400 milliseconds to capture the initial crash dynamics, as this timeframe encompasses the critical impact phase. Data beyond this point were not included, as they reflect model settling rather than relevant injury criteria. Given the large number of simulations conducted, figures for each simulation are provided in Appendix A.

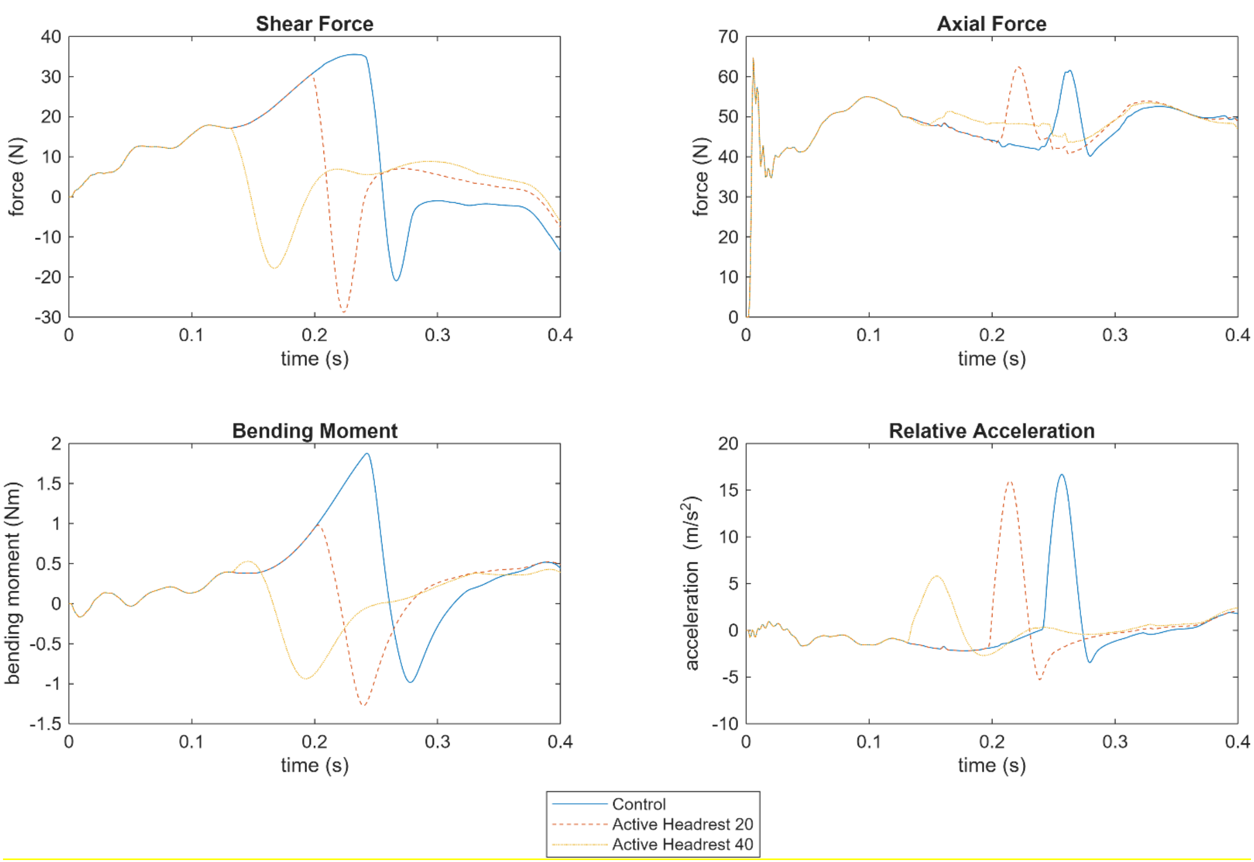

Figure 6.1. Simulation results of active headrest for Scenario #1.

Based on the simulation results, the maximum values for NIC, N_{ij}, and N_{km} are calculated and presented in the Tables 6-1 – 6-6, organized by scenarios. A control configuration, without the active headrest or reactive seatback, was included as a baseline to evaluate the overall performance of each safety countermeasure.

As shown in Table 6-1, for Scenario #1, a straight collision involving a 4,000-pound vehicle, the active headrest configurations (20 mm and 40 mm) consistently reduce injury criteria values (NIC, N_{ij}, N_{km}) compared to the control setup. The 40 mm headrest configuration shows the most significant improvement, indicating that increased headrest travel reduces head impact forces. Meanwhile, the reactive seatback and anti-whiplash system show mixed effectiveness, with the 20-degree reactive seatback providing some improvement in N_{km}. This suggests that while the active headrest is effective at lowering injury risk in a straight collision, the reactive seatback may offer limited additional benefits.

Table 6-1. Injury criteria result for Scenario #1.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	3.35	n/a	0.02	n/a	0.08	n/a
Active Headrest (20 mm)	3.20	-4%	0.01	-47%	0.06	-32%
Active Headrest (40 mm)	1.16	-65%	0.00	-73%	0.03	-64%
Reactive Seatback (20 degree)	3.75	+12%	0.02	+7%	0.07	-9%
Reactive Seatback (30 degree)	2.87	-14%	0.01	-13%	0.08	+4%
Anti-Whiplash System (20 degree)	2.89	-14%	0.01	-13%	0.06	-21%
Anti-Whiplash System (30 degree)	2.64	-21%	0.01	-20%	0.09	+7%

As shown in Table 6-2, for Scenario #2, a 30-degree offset collision with a 4,000-pound vehicle, The active headrest, especially at 40mm, provides clear reductions in injury criteria across all metrics, underscoring its adaptability to angled impacts. The reactive seatback shows some improvement, particularly in N_{km}, but varies between configurations. Similarly, the anti-whiplash system presents moderate injury reductions but does not perform as consistently as the active headrest. The results emphasize the active headrest's adaptability in offset collisions and suggest that further tuning of the reactive seatback and anti-whiplash configurations could improve efficacy.

Table 6-2. Injury criteria result for Scenario #2.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	2.55	n/a	0.01	n/a	0.07	n/a
Active Headrest (20 mm)	2.89	+13%	0.01	-45%	0.05	-27%
Active Headrest (40 mm)	1.36	-47%	0.00	-74%	0.03	-58%
Reactive Seatback (20 degree)	2.62	+3%	0.04	147%	0.05	-25%
Reactive Seatback (30 degree)	1.78	-30%	0.02	26%	0.05	-37%
Anti-Whiplash System (20 degree)	2.41	-5%	0.03	126%	0.05	-25%
Anti-Whiplash System (30 degree)	2.24	-12%	0.03	74%	0.07	-6%

As shown in Table 6-3, for Scenario #3, a straight collision involving a heavier 20,000-pound vehicle, both the 20 mm and 40 mm active headrest configurations markedly reduce injury criteria. While the 40 mm configuration yields the best results, the reactive seatback and anti-whiplash system show varied outcomes, with some reductions in N_{ij} but higher N_{km} values. These results indicate that for heavier vehicles, the active headrest remains effective, while the reactive seatback and anti-whiplash system may require additional adjustments to handle increased impact forces effectively.

Table 6-3. Injury criteria result for Scenario #3.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	10.32	n/a	0.06	n/a	0.16	n/a
Active Headrest (20 mm)	6.66	-35%	0.01	-79%	0.08	-49%
Active Headrest (40 mm)	1.95	-81%	0.01	-87%	0.04	-72%
Reactive Seatback (20 degree)	11.33	+10%	0.05	-11%	0.26	+62%
Reactive Seatback (30 degree)	9.59	-7%	0.05	-4%	0.26	+67%
Anti-Whiplash System (20 degree)	12.12	+18%	0.05	-13%	0.26	+65%
Anti-Whiplash System (30 degree)	10.25	-1%	0.05	-9%	0.27	+69%

In Scenario #4, with a 30-degree offset collision and a 20,000-pound vehicle, the active headrest continues to demonstrate consistent reductions in NIC, N_{ij}, and N_{km} values, particularly in the 40 mm configuration. The reactive seatback and anti-whiplash system, however, do not perform as favorably, showing increases in some injury criteria, particularly in N_{km}. This scenario highlights the active headrest's ability to mitigate injury in offset impacts with heavier vehicles, while the reactive seatback and anti-whiplash systems may need reconfiguration for effectiveness in angled impacts.

Table 6-4. Injury criteria result for Scenario #4.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	9.57	n/a	0.02	n/a	0.16	n/a
Active Headrest (20 mm)	6.20	-35%	0.01	-44%	0.08	-47%
Active Headrest (40 mm)	1.63	-83%	0.01	-51%	0.04	-77%
Reactive Seatback (20 degree)	10.93	+14%	0.11	+412%	0.28	+74%
Reactive Seatback (30 degree)	11.40	+19%	0.13	+542%	0.34	+116%
Anti-Whiplash System (20 degree)	11.63	+22%	0.13	+504%	0.36	+125%
Anti-Whiplash System (30 degree)	9.77	+2%	0.10	+404%	0.32	+99%

The results for Scenario #5, which simulate a straight collision involving a significantly heavier 80,000-pound vehicle, are shown in Table 6-5. The 40mm active headrest remains effective, substantially reducing NIC, N_{ij}, and N_{km} values compared to the control. However, the reactive seatback and anti-whiplash systems show inconsistent results, with some improvement in Nij but increases in other injury criteria. This suggests that, under high impact from an 80,000-pound vehicle, the active headrest offers the best safety benefits, while other countermeasures may be less suitable due to the higher force levels involved.

Table 6-5. Injury criteria result for Scenario #5.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	21.24	n/a	0.39	n/a	0.21	n/a
Active Headrest (20 mm)	21.08	-1%	0.38	-2%	0.27	+26%
Active Headrest (40 mm)	10.84	-49%	0.02	-94%	0.19	-10%
Reactive Seatback (20 degree)	27.62	+30%	0.21	-47%	1.07	+406%
Reactive Seatback (30 degree)	26.18	+23%	0.35	-9%	1.06	+402%
Anti-Whiplash System (20 degree)	30.18	+42%	0.21	-46%	1.06	+400%

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Anti-Whiplash System (30 degree)	26.22	+23%	0.35	-11%	1.07	+406%

In Scenario #6, a 30-degree offset collision with an 80,000-pound vehicle, the 40 mm active headrest again provides the most significant reduction in injury criteria values, demonstrating resilience across NIC, N_{ij}, and N_{km} metrics. The reactive seatback and anti-whiplash system show possible effectiveness, with significant improvements in NIC values, but higher N_{ij} and N_{km} values, indicating desirable behaviors for minimizing the relative accelerations but facing potential challenges dealing with the applied forces in offset collisions at high vehicle weights. These findings reinforce the active headrest's adaptability across various collision angles and weights, while the reactive seatback and anti-whiplash system may need refinement to offer consistent safety improvements in offset impacts.

Table 6-6. Injury criteria result for Scenario #6.

Configuration	NIC	NIC Change	N_{ij}	N_{ij} Change	N_{km}	N_{km} Change
Control	19.20	n/a	0.04	n/a	0.22	n/a
Active Headrest (20 mm)	19.32	+1%	0.03	-3%	0.26	+22%
Active Headrest (40 mm)	8.60	-55%	0.02	-34%	0.18	-18%
Reactive Seatback (20 degree)	8.76	-54%	0.15	+340%	0.70	+225%
Reactive Seatback (30 degree)	9.12	-53%	0.14	+306%	0.55	+156%
Anti-Whiplash System (20 degree)	8.43	-56%	0.15	+340%	0.69	+219%
Anti-Whiplash System (30 degree)	11.12	-42%	0.14	+300%	0.54	+149%

The active headrest demonstrated consistent reductions in injury criteria across various scenarios, with greater displacement effectively lowering injury values. This design minimizes the head's momentum by reducing space for rearward movement, aligning head and torso motion to decrease opposing accelerations. However, for maximum efficacy, the headrest must be stationary upon initial contact; any movement during high-impact simulations in Scenario #6, resulted in diminished effectiveness.

The reactive seatback showed mixed results, offering minimal reductions in injury criteria or, in some cases, adverse effects. The reactive seatback's performance depended on its rotational angle and resistance, as excessive resistance produced acceleration spikes and elevated NIC values, while too little resistance allowed the occupant to gain more momentum before impact. In high-acceleration, angled collisions, the reactive seatback reduced NIC but also increased N_{ij} and N_{km} due to heightened shear forces and bending moments, suggesting that precise tuning might optimize its safety potential, though applicability across diverse scenarios remains limited.

The anti-whiplash system performed similarly to the baseline, with behavior that varied depending on scenarios and settings. For example, the translational component showed improved outcomes in angled Scenario #4 at higher rotational ranges but adverse effects in Scenario #3 straight impacts. Lower rotational ranges reversed this pattern, and in Scenarios #1 and #2, the system's performance was inconsistent. This variability underscores the potential need for further configuration adjustments to ensure predictable performance across scenarios.

During higher impact scenarios it should be noted that a general trend of higher injury criteria values was observed, independent of the tested countermeasures. It is important to note that the tested countermeasures were not fully optimized for high-impact scenarios. The active headrest showed slightly diminished efficacy when the occupant model contacts the headrest during the forward motion of the active headrest system, as was seen in the criterion values during the higher impact scenarios with the 20 mm active headrest countermeasure, meaning the occupant would likely be at higher risk of injury if the behavior is observed. The reactive seatback and anti-whiplash system simulations do include considerations for the rebound effects as initial collision dynamics end and the occupant begins its rebound motion during the deceleration phase of the collision. Nevertheless, at higher acceleration collisions those considerations have diminished effect at minimizing occupant accelerations as the seatback rebounds significantly more, displaying a behavior that could potentially increase occupant injury risk. These countermeasure behaviors do suggest that further research could be performed for higher accelerations to mitigate the potentially diminishing effects.

The overall performance of each safety countermeasure across scenarios is summarized in Table 6-7. The percentage changes in injury measures reported in Tables 6-1 to 6-6 were used to create three qualitative ratings – 'Improved', 'comparable', and 'worsened'. A countermeasure is rated as 'improved' if it outperforms the control configuration on all injury measures. Conversely, a rating of 'worsened' means the countermeasure underperformed the control configuration on all injury measures. A rating of 'comparable' means the performance of countermeasure was better than the control configuration on some measures but not all. The active headrest consistently demonstrated 'improved' results across scenarios, especially for the 40 mm travel level. Meanwhile, both the reactive seatback and the anti-whiplash system were rated as "comparable" to the control for most scenarios except for Scenario #4.

Table 6-7. Qualitative ratings of countermeasure performance across scenarios compared to control configuration.

Configuration	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5	Scenario #6
Active headrest (20 mm)	Improved	Comparable	Improved	Improved	Comparable	Comparable
Active headrest (40 mm)	Improved	Improved	Improved	Improved	Improved	Improved
Reactive seatback (20 degree)	Comparable	Comparable	Comparable	Worsened	Comparable	Comparable
Reactive seatback (30 degree)	Comparable	Comparable	Comparable	Worsened	Comparable	Comparable
Anti-whiplash system (20 degree)	Improved	Comparable	Comparable	Worsened	Comparable	Comparable
Anti-whiplash system (30 degree)	Comparable	Comparable	Comparable	Worsened	Comparable	Comparable

Based on the simulation results, Table 6-8 provides a comprehensive grading of safety improvements for TMA truck configurations. The baseline configuration (Configuration #1) featured a standard cab and floating seat equipped with a three-point seat belt. This configuration provided the basic protection without optimizing for rear-end collisions and served as the reference for assessing alternative safety enhancements.

For configuration#2, simulation results demonstrated that the implementation of an active headrest, designed specifically for rear-end impact scenarios, substantially improved safety by reducing the risk of head and neck injuries across six test scenarios.

Further safety improvements can be achieved through the adoption of a driver seat with a built-in three-point seat belt and a crew cab. Based on existing research, a seat-integrated seat belt can provide a more secure fit than a standard floating seat with a B-pillar anchored seat belt, effectively minimizing seat belt slack during vertical movements and reducing back ramping during rear-end impacts (Mooren and Williamson 2013; Rashidy et al. 2001; Seyer and Jonas 2002). While a direct comparison between standard and crew cabs was not evaluated, crew cabs are generally regarded as safer in high-impact scenarios due to the additional space, which helps prevent collisions between the seat and the rear cab wall, as rear cab wall deformation was observed in one high-impact crash.

For the highest level of safety, configurations incorporating a four-point or more seat belt and a HANS device offer maximum occupant protection. These systems are particularly effective in high-speed environments with elevated crash risks. However, their practical application in daily operations may be constrained by reduced comfort and increased complexity, making them most appropriate for high-risk, specialized scenarios.

Table 6-8. Comprehensive grading of TMA truck safety configurations.

Configuration	Truck Type	Seat Belt	Seat Type	Grading
#1	Standard cab	Three-point	Standard seat	Baseline
#2	Standard cab	Three-point	Standard seat + active headrest	Good
#3	Crew cab	Three-point	Integrated seat + active headrest	Better
#4	Crew cab	Four or more-point seat belt and HANS devices	Integrated seat + active headrest	Best

7. Conclusion

In order to enhance TMA truck safety, this project conducted a comprehensive review of historical TMA crash data alongside interviews with TMA vendors on current in-vehicle safety features. Analysis of Missouri crash reports confirmed that rear-end collisions are the predominant type of TMA-involved accident, with drivers frequently experiencing whiplash injuries. These findings emphasize the importance of countermeasures that specifically target neck and head injury risks.

The review of existing in-vehicle safety countermeasures examined various safety features, including seat belts, seats, steering wheels, airbags, and other systems. Each feature's effectiveness, applicability, and potential limitations were assessed to guide selection for further testing. Based on these insights and consultations with MoDOT engineers, active headrests, reactive seatbacks, and anti-whiplash systems were identified as priority countermeasures for simulation analysis.

The simulation study assessed the effectiveness of in-vehicle safety countermeasures, including active headrests, reactive seatbacks, and anti-whiplash systems, in reducing injury risks for TMA truck occupants across various collision scenarios. The results consistently demonstrated that the active headrest system, particularly with greater travel level (40 mm), yielded significant reductions in injury criteria values (NIC, N_{ij}, N_{km}) across different impact conditions, effectively minimizing head and neck injury risks. The system's design allows it to mitigate opposing accelerations between the head and torso, proving particularly effective in both straight and angled collisions.

On the other hand, the reactive seatback and anti-whiplash system provided mixed results. While both countermeasures provided modest reductions in injury criteria for low-impact collision scenarios, their performance was less reliable in high-impact collision scenarios, particularly with heavy vehicles at 18g force levels. The reactive seatback's performance was largely dependent on its rotational resistance settings; higher resistance led to increased NIC values due to acceleration spikes, while lower resistance allowed for greater momentum, which could lead to higher injury risks upon impact.

This study has a few limitations. Simulations involving high-impact collisions, particularly with heavier vehicles (i.e., 80,000-pound), may not fully capture realistic outcomes. This is due to the limited availability of real-world high-impact telematic data, as collisions involving such heavy vehicles are much rarer than those involving smaller, lighter vehicles. Consequently, while the physical simulations and available telematic data provide a useful model, high-impact scenarios may require further investigation to confirm the reliability of these findings. Real-world telematic data for high-impact collisions will help refine future simulations to evaluate safety countermeasure performance.

In addition, high-impact collisions, often leading to secondary collisions due to the increased force and energy, could not be effectively simulated. An analysis of MoDOT TMA crash reports from 2020 to 2023 revealed that four out of five (80%) injured TMA drivers in high-impact scenarios experienced their trucks striking median barriers or being struck by other vehicles following the initial impact. While in-cab safety countermeasures are critical in mitigating injury risks, drivers can further mitigate the likelihood or severity of secondary collisions by maintaining situational awareness before a crash. Proactive measures, such as applying brakes to reduce speed and retaining steering control to maneuver the truck away from obstacles or other vehicles, can minimize the impact of such events.

In conclusion, integrating advanced safety measures, especially active headrest systems, could play a critical role in enhancing TMA truck driver safety by reducing injury severity. Future research should focus on optimizing resistance levels and rotational limits for reactive seatback and anti-whiplash systems and expanding the data available for high-impact scenarios to validate and enhance safety features across various collision types.

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Appendix A: Simulation Results

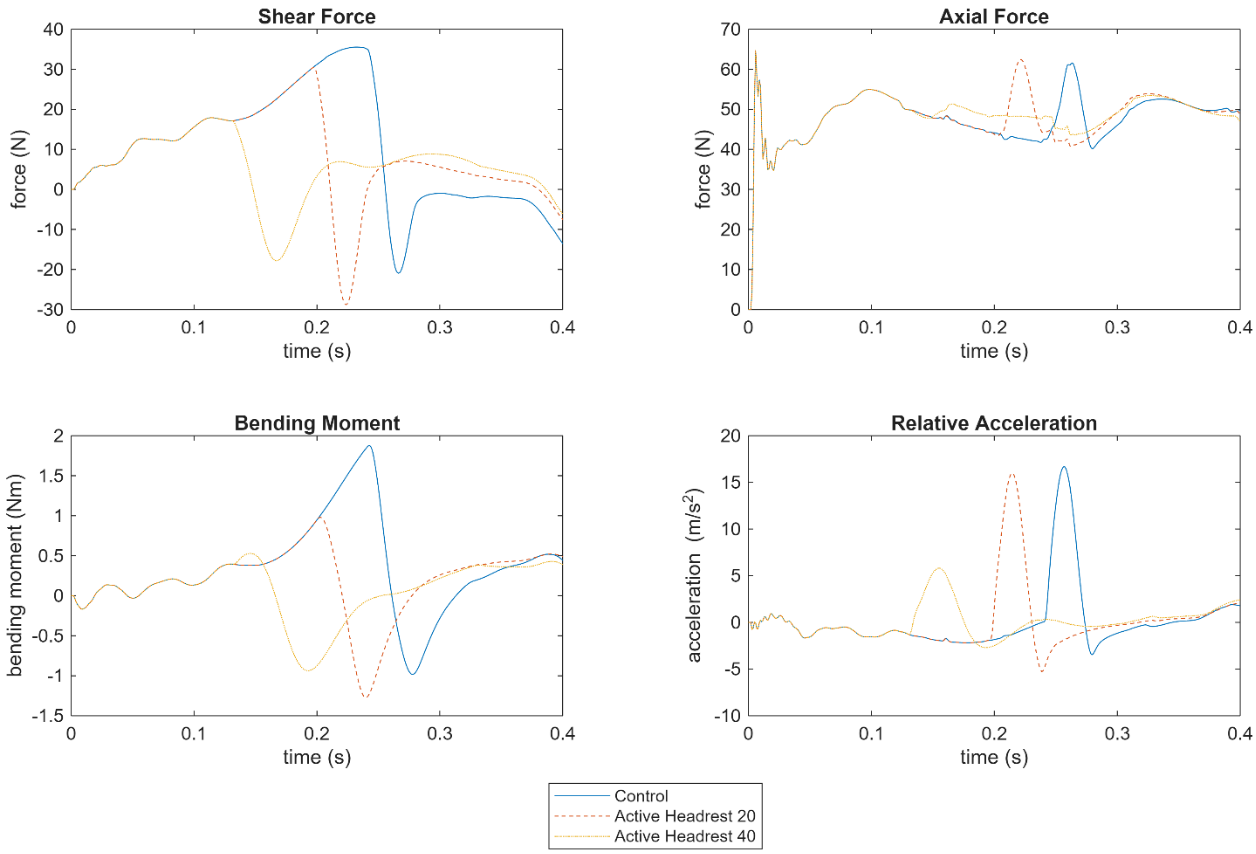

Figure A.1. Simulation results of active headrest for Scenario #1.

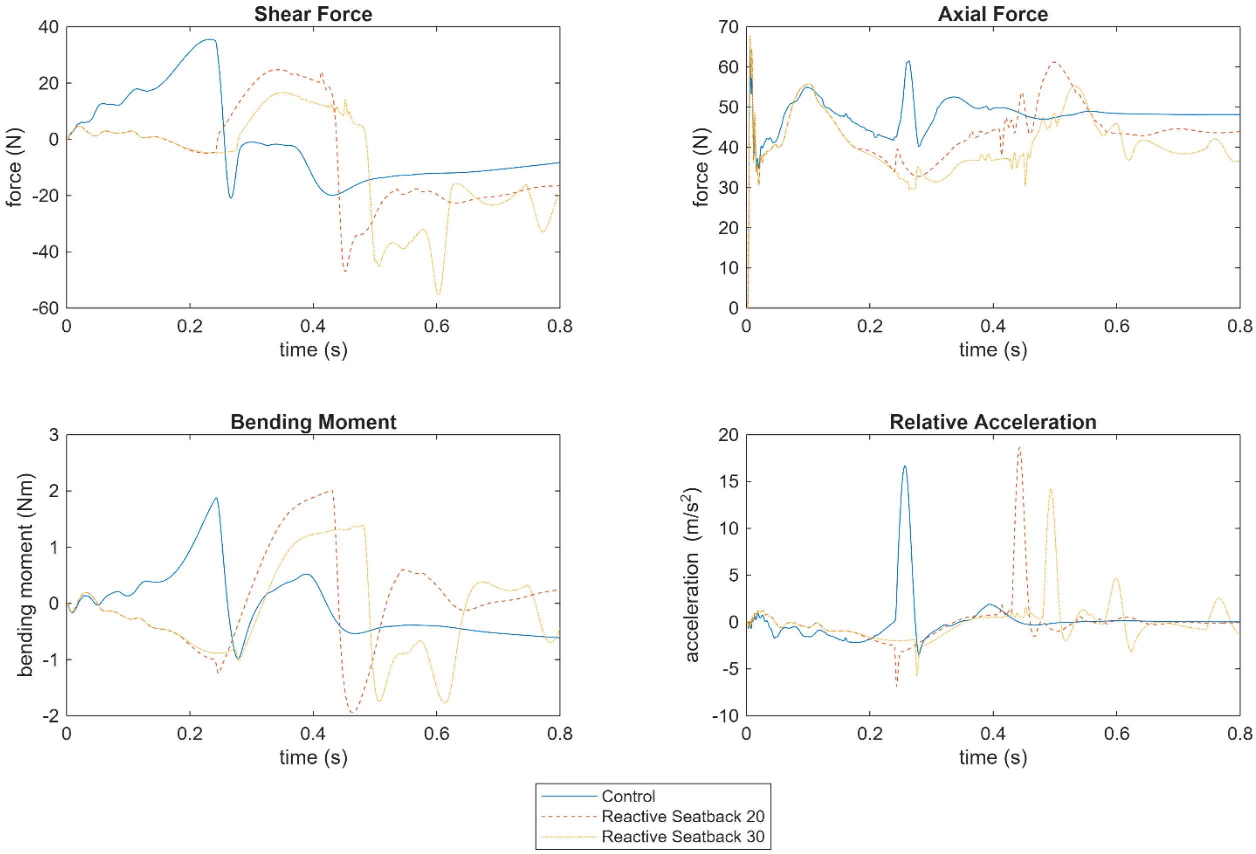

Figure A.2. Simulation results of reactive seatback for Scenario #1.

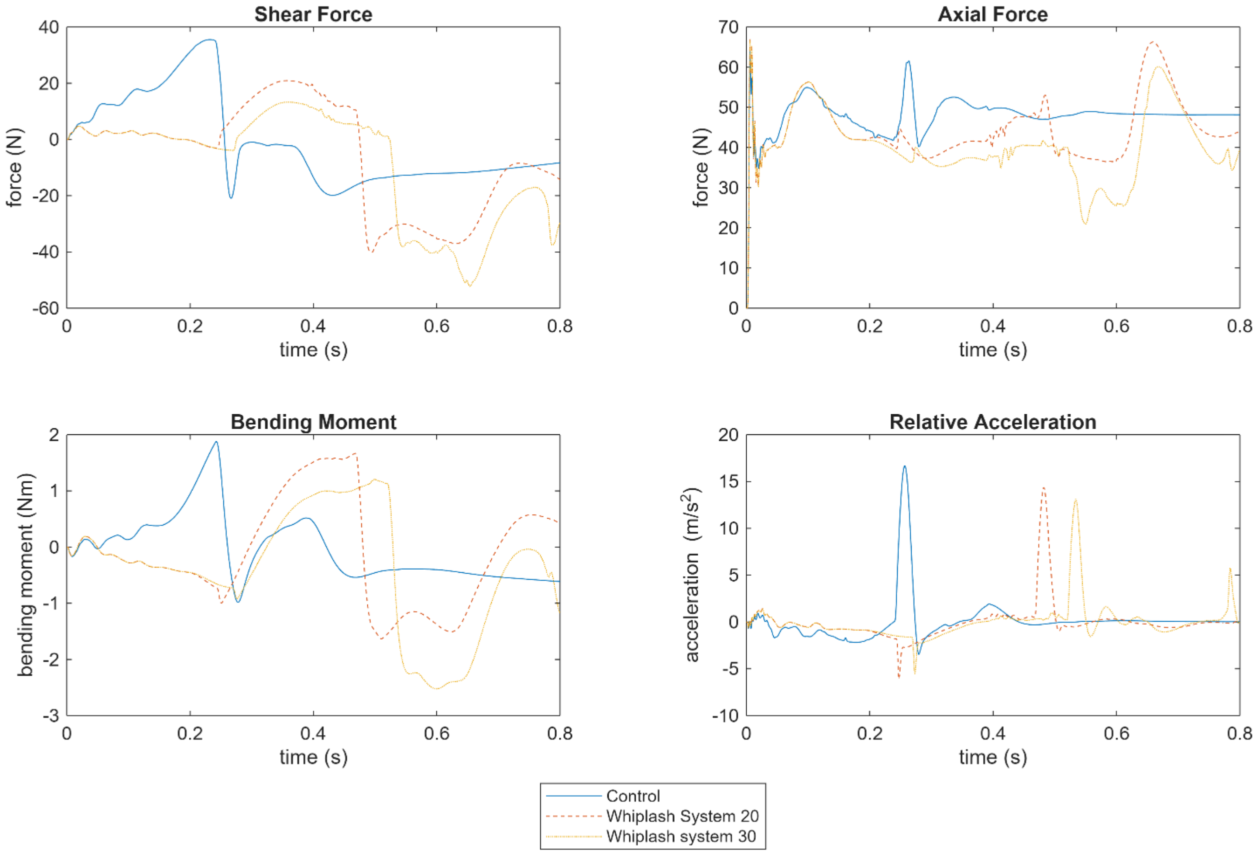

Figure A.3. Simulation results of anti-whiplash system for Scenario #1.

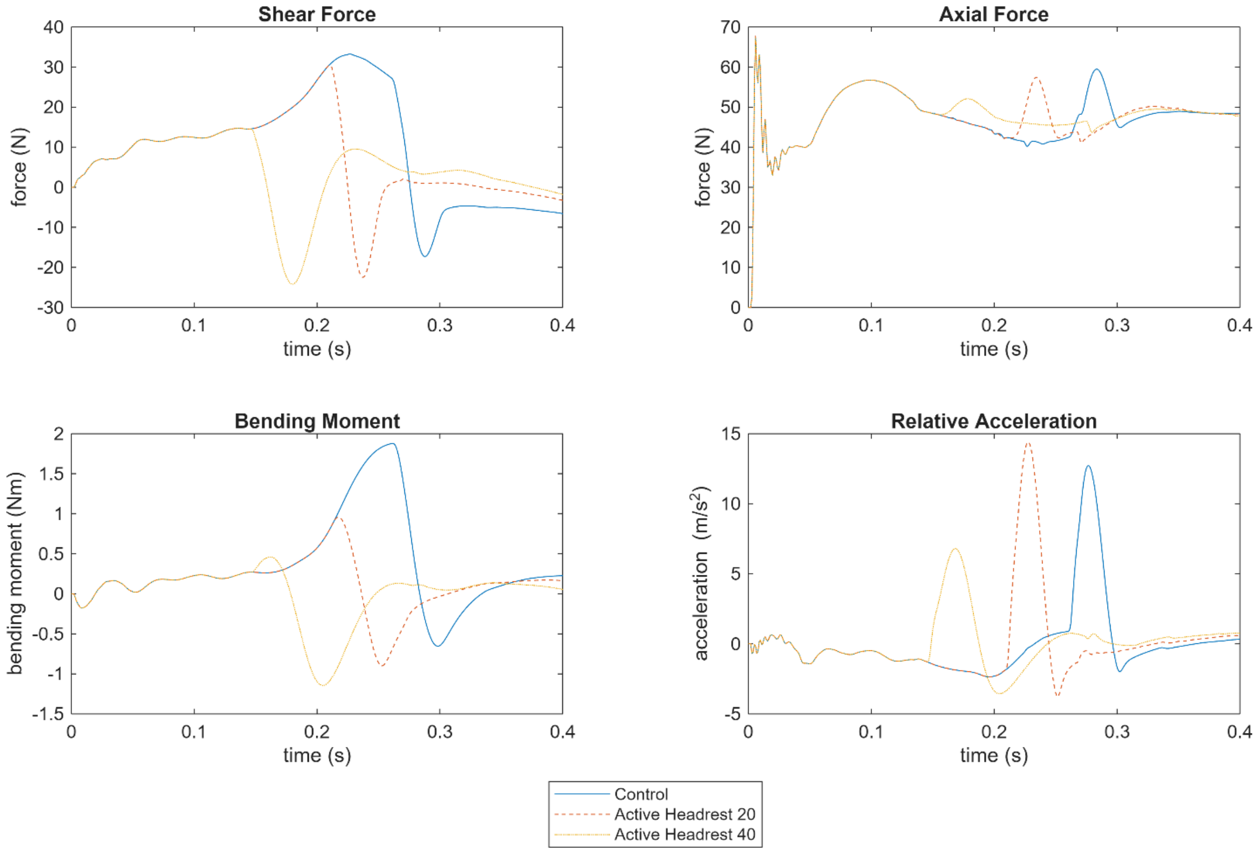

Figure A.4. Simulation results of active headrest for Scenario #2.

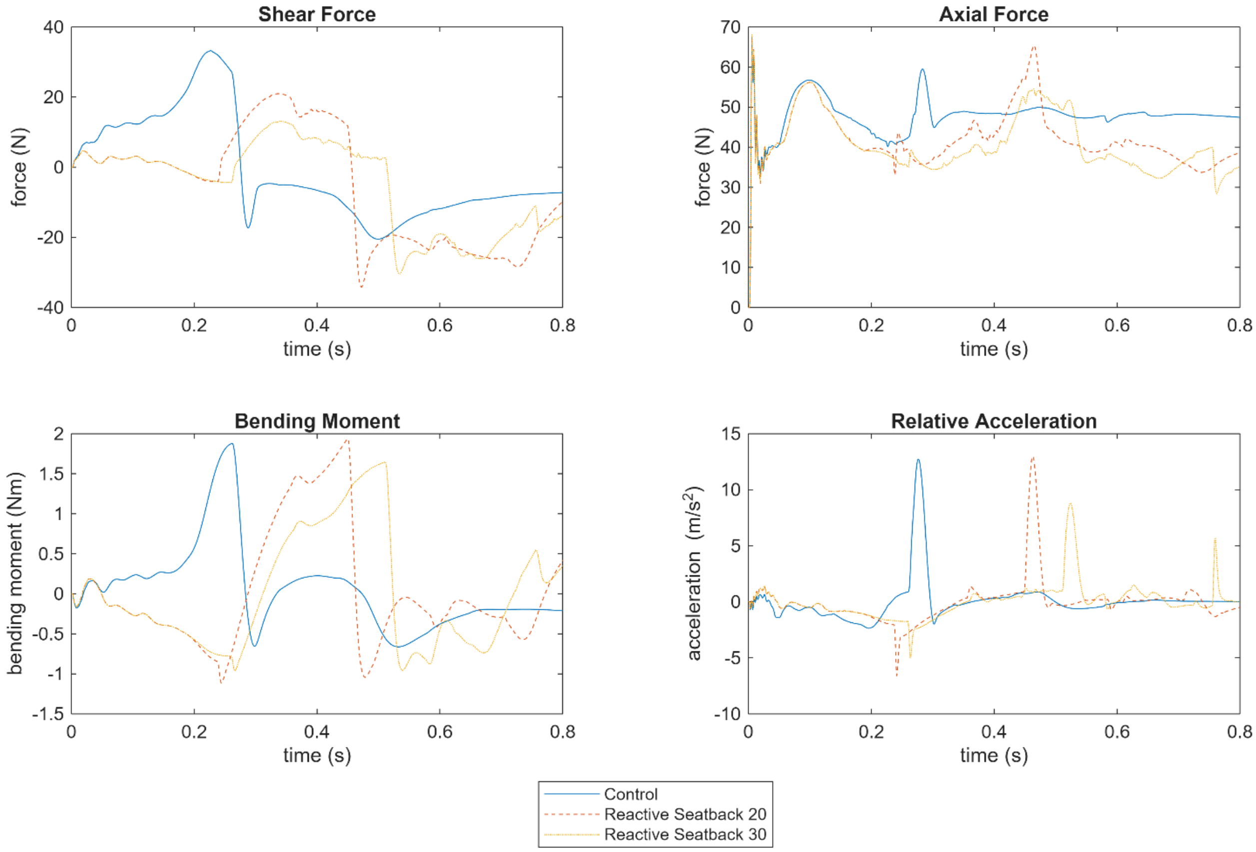

Figure A.5. Simulation results of reactive seatback for Scenario #2.

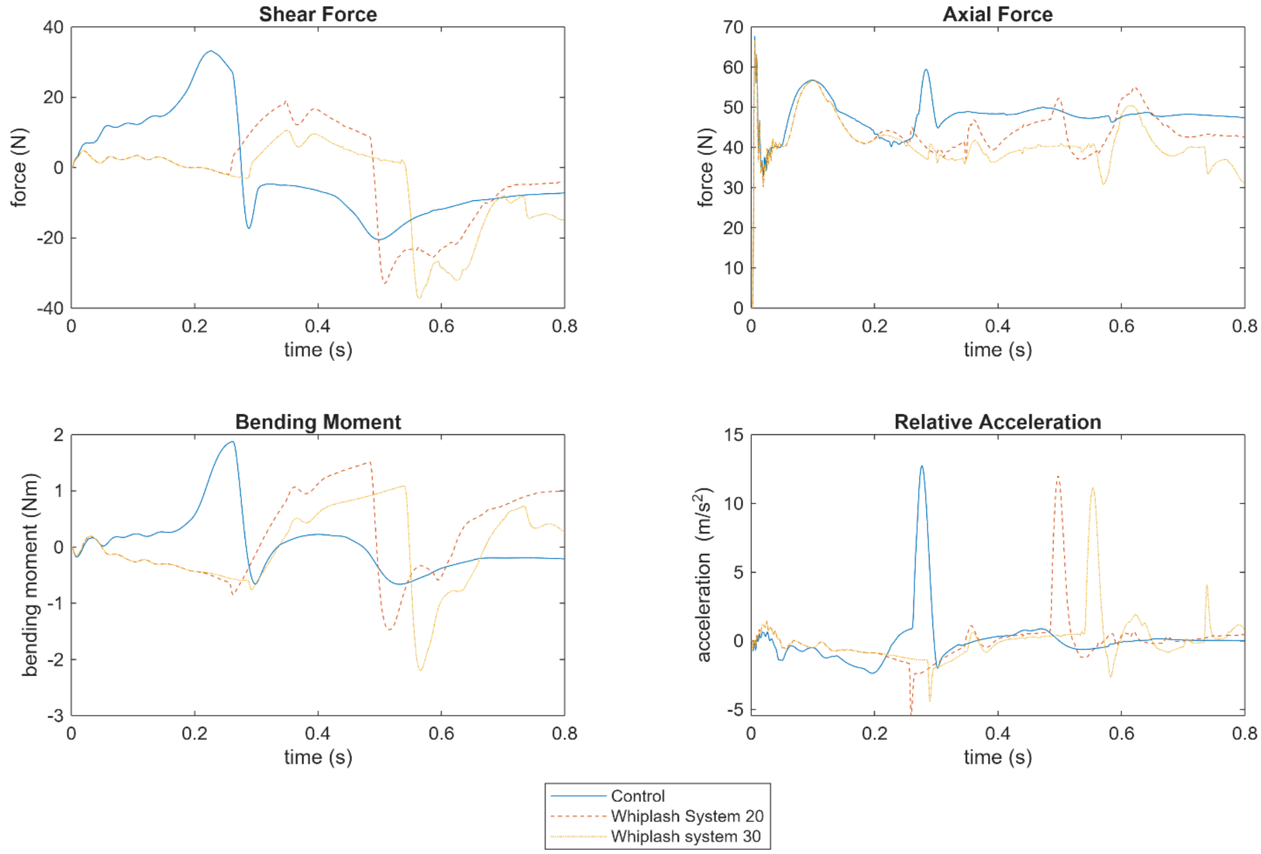

Figure A.6. Simulation results of anti-whiplash system for Scenario #2.

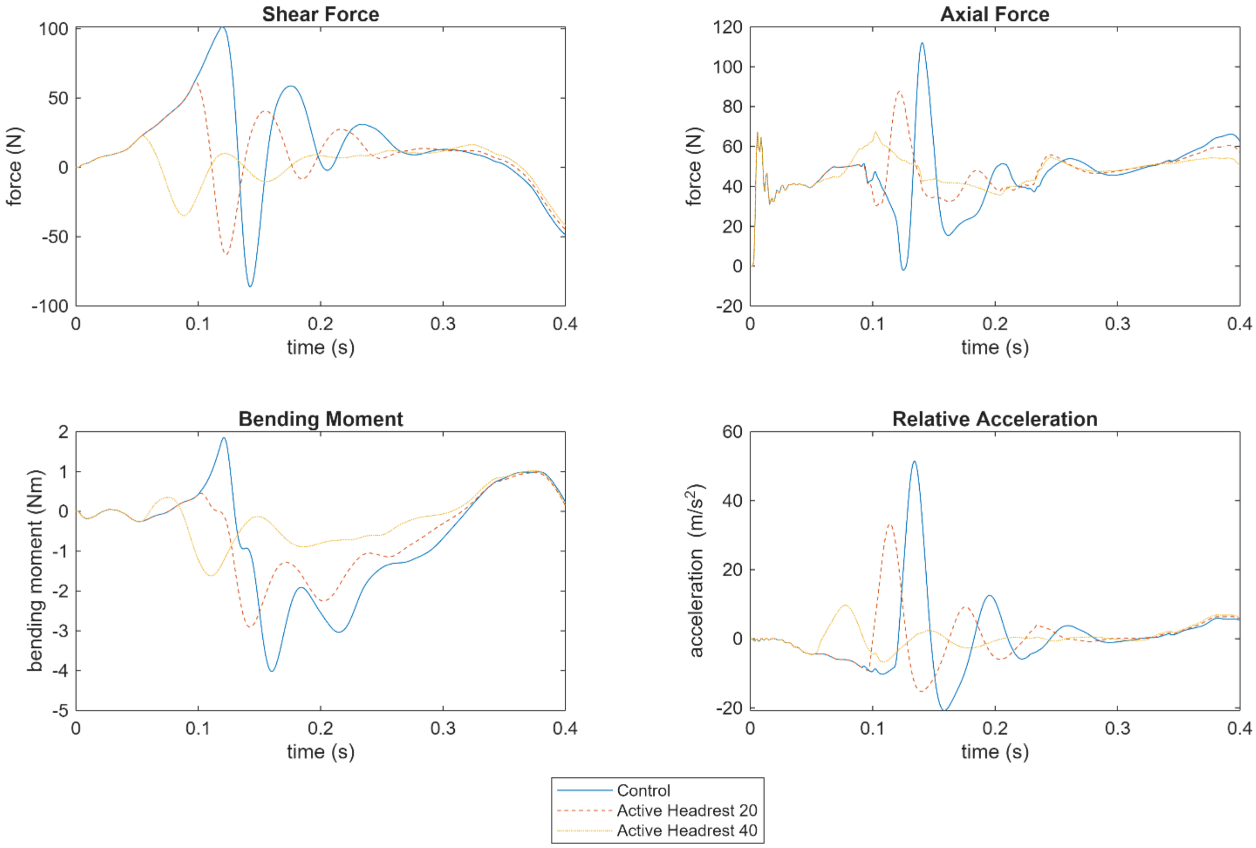

Figure A.7. Simulation results of active headset for Scenario #3.

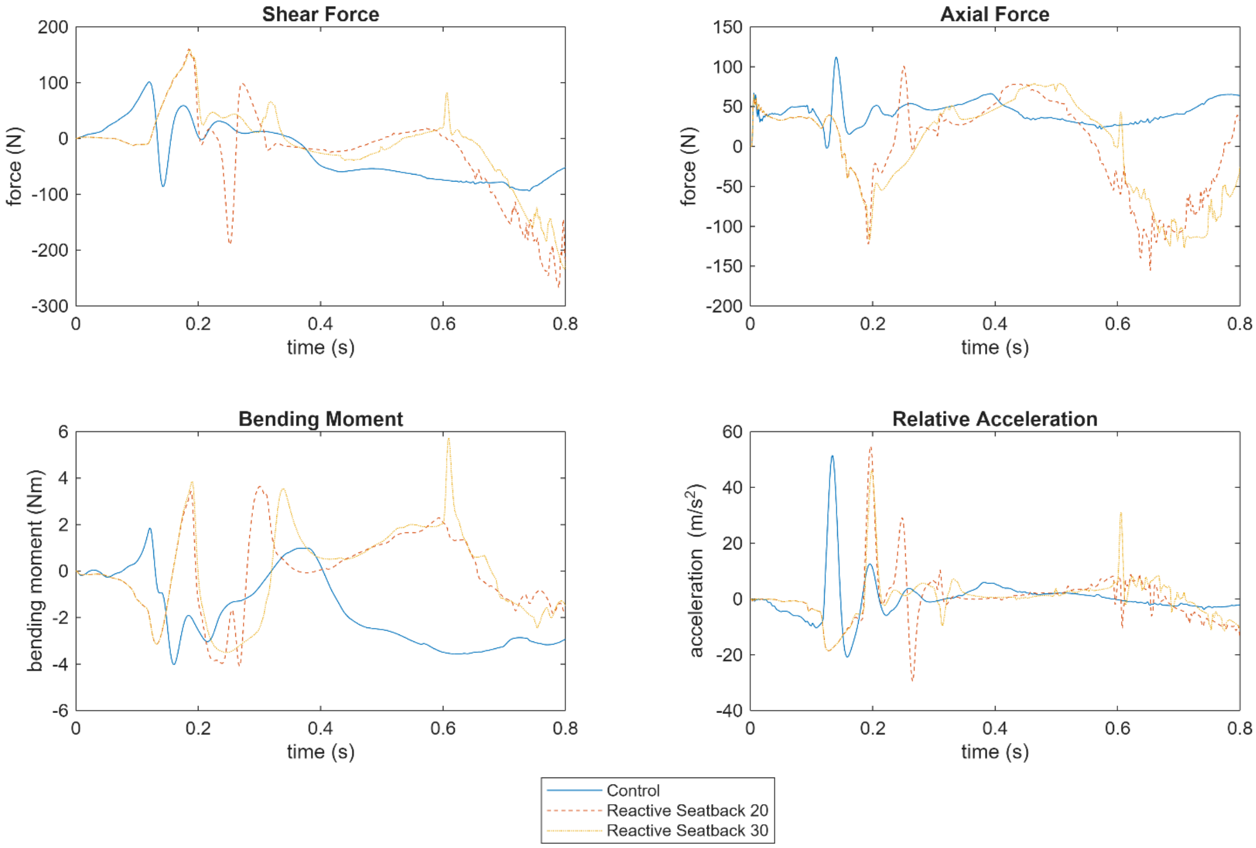

Figure A.8. Simulation results of reactive seatback for Scenario #3.

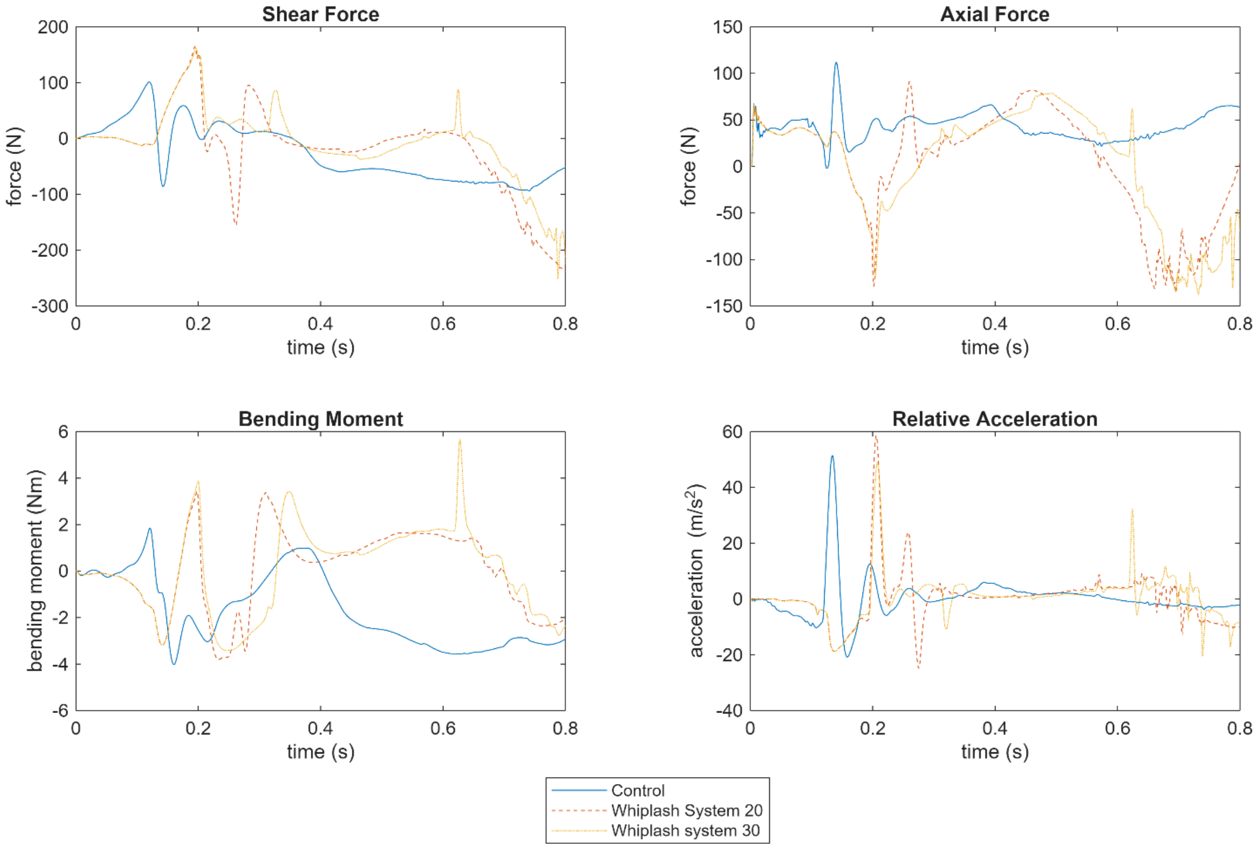

Figure A.9. Simulation results of anti-whiplash system for Scenario #3.

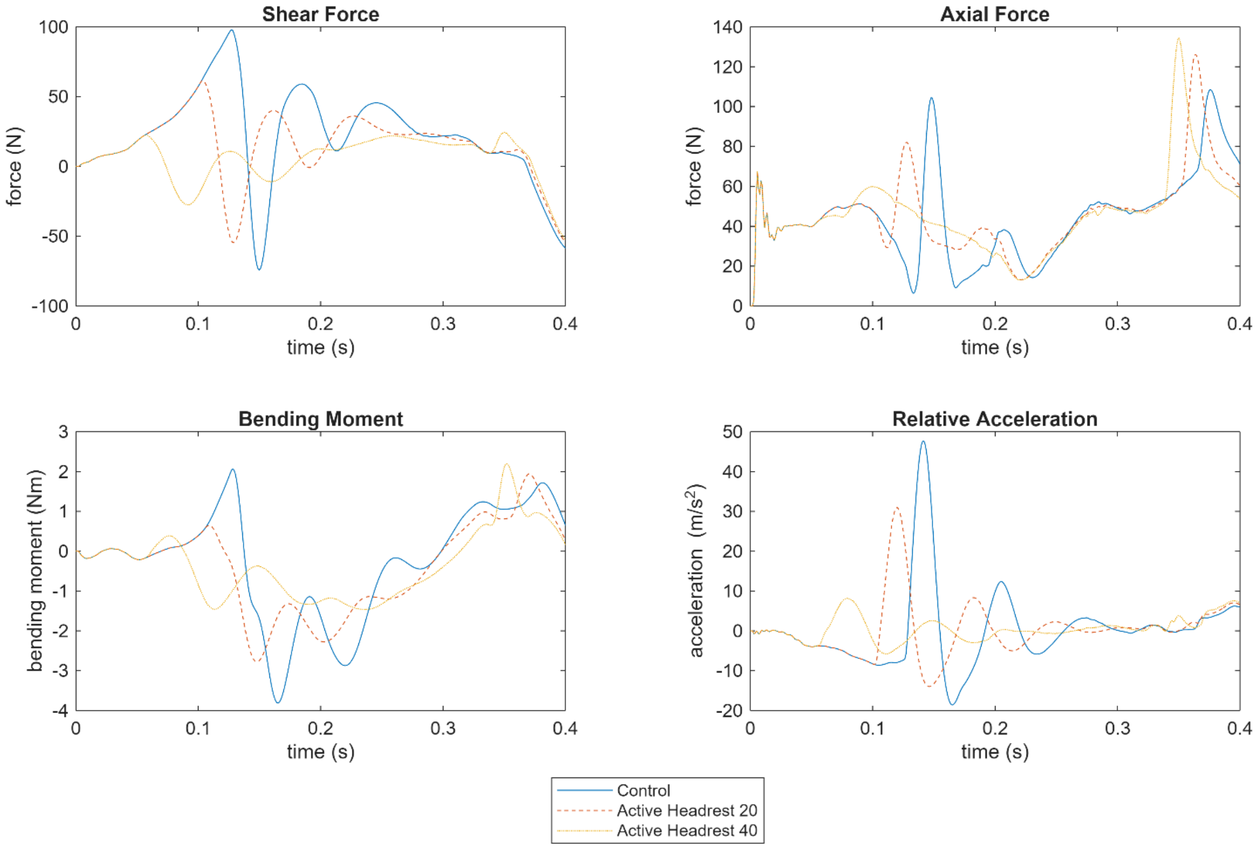

Figure A.10. Simulation results of active headrest for Scenario #4.

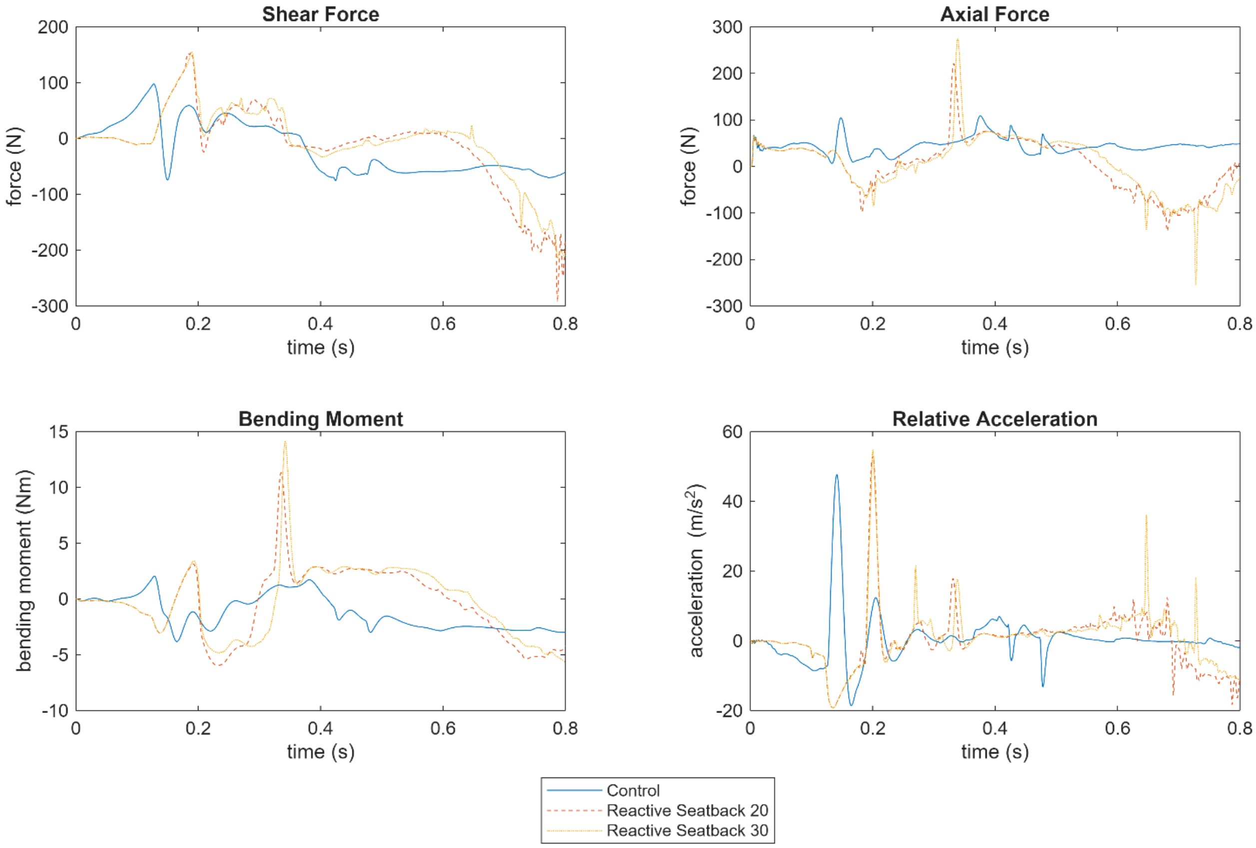

Figure A.11. Simulation results of reactive seatback for Scenario #4.

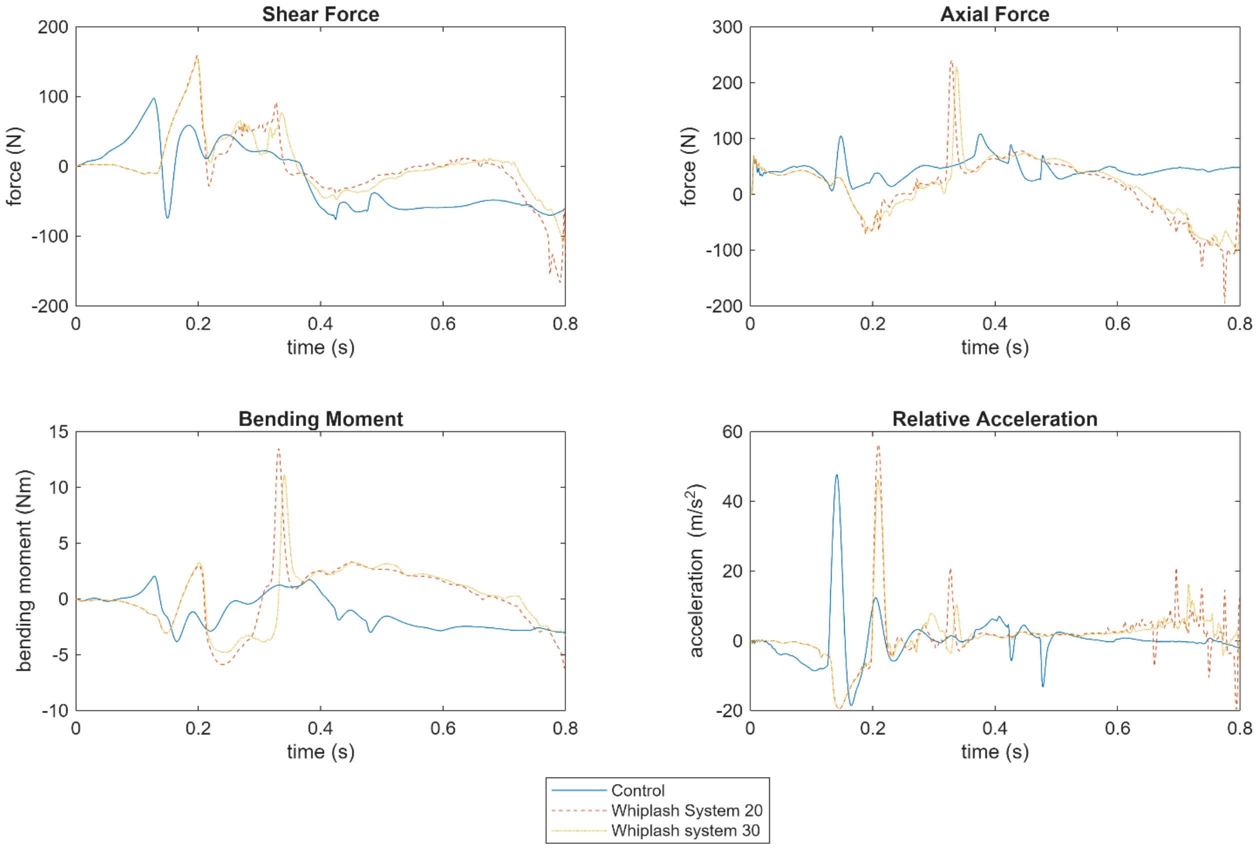

Figure A.12. Simulation results of anti-whiplash system for Scenario #4.

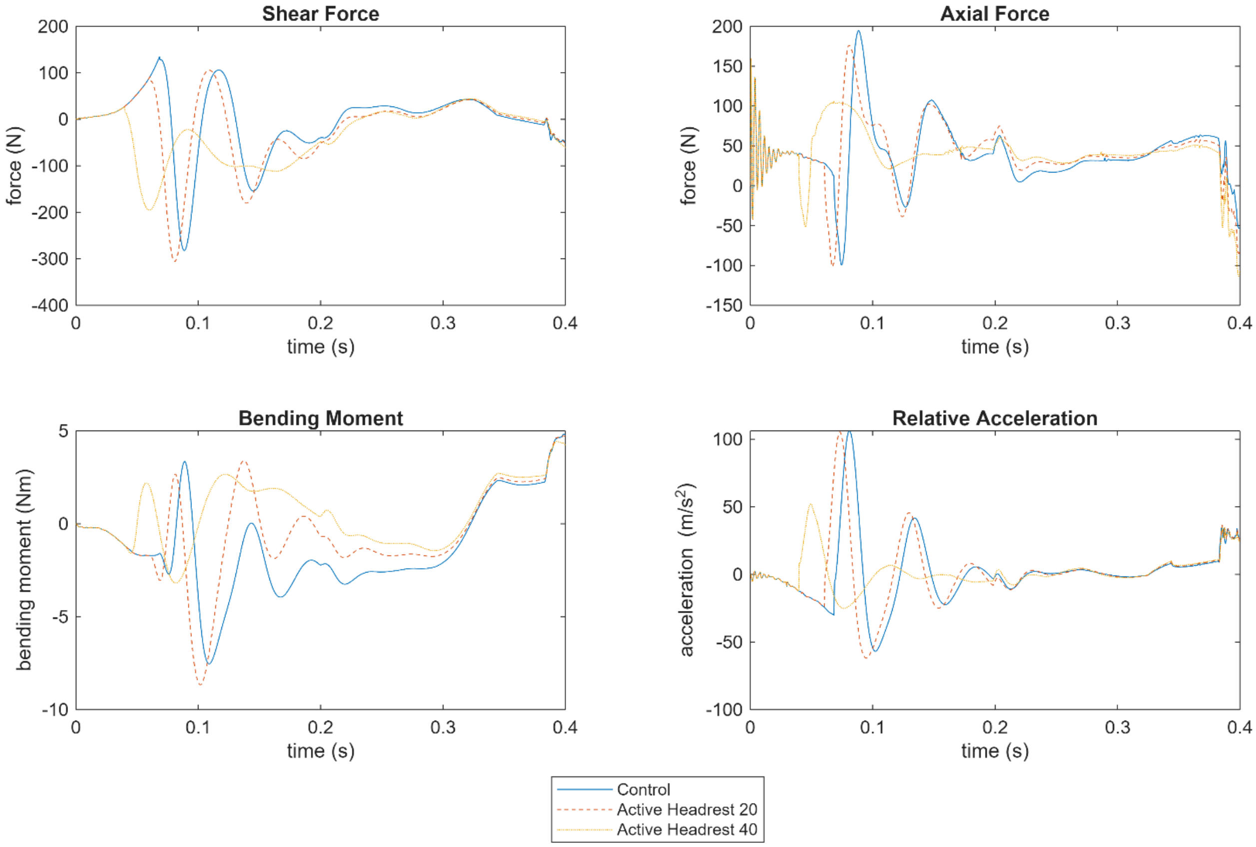

Figure A.13. Simulation results of active headrest for Scenario #5.

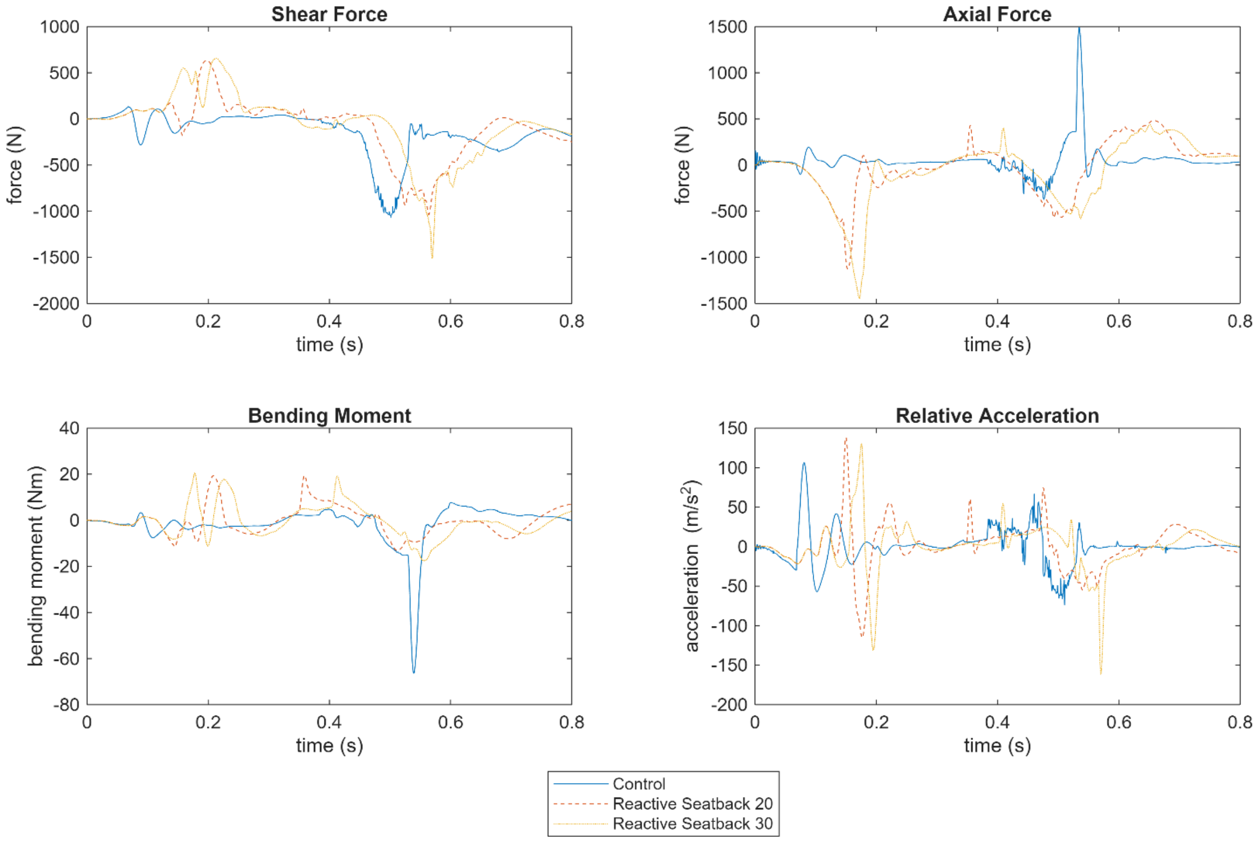

Figure A.14. Simulation results of reactive seatback for Scenario #5.

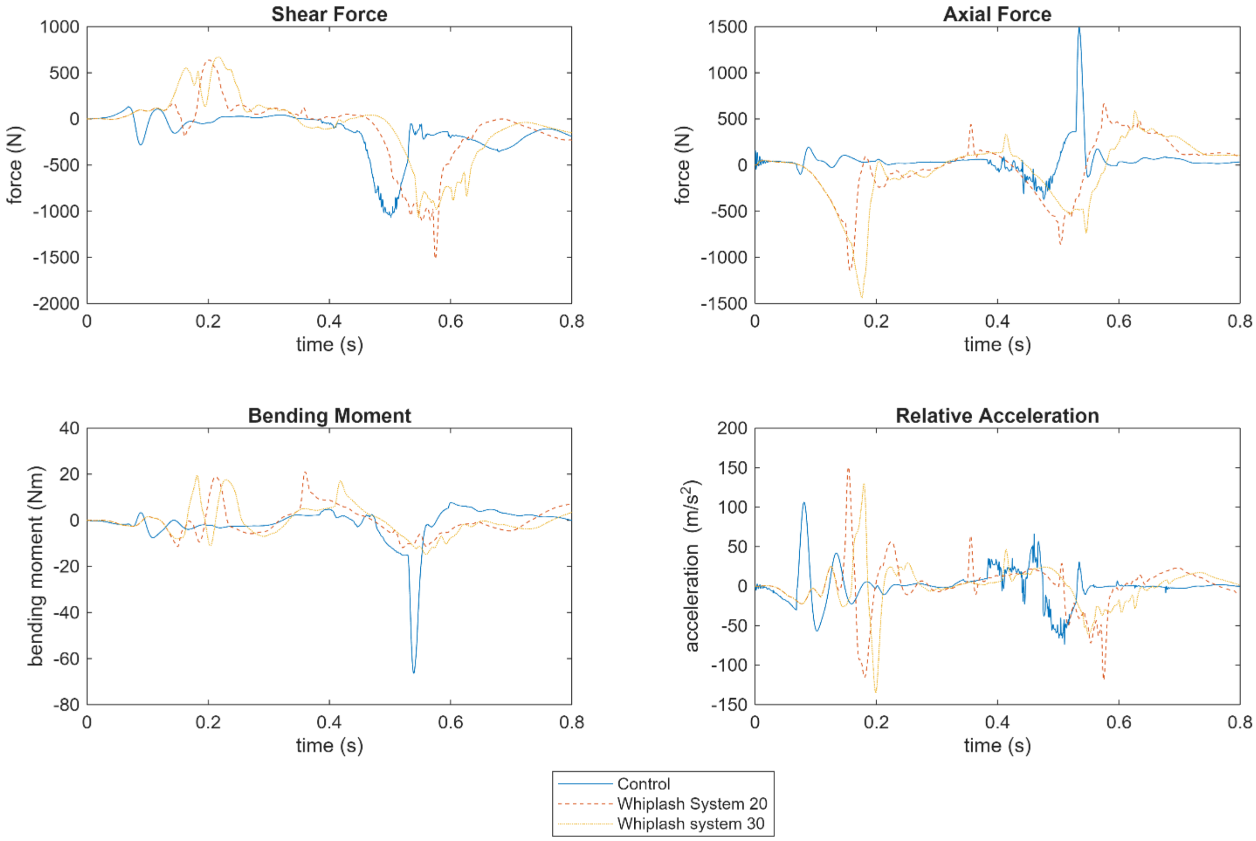

Figure A.15. Simulation results of anti-whiplash system for Scenario #5.

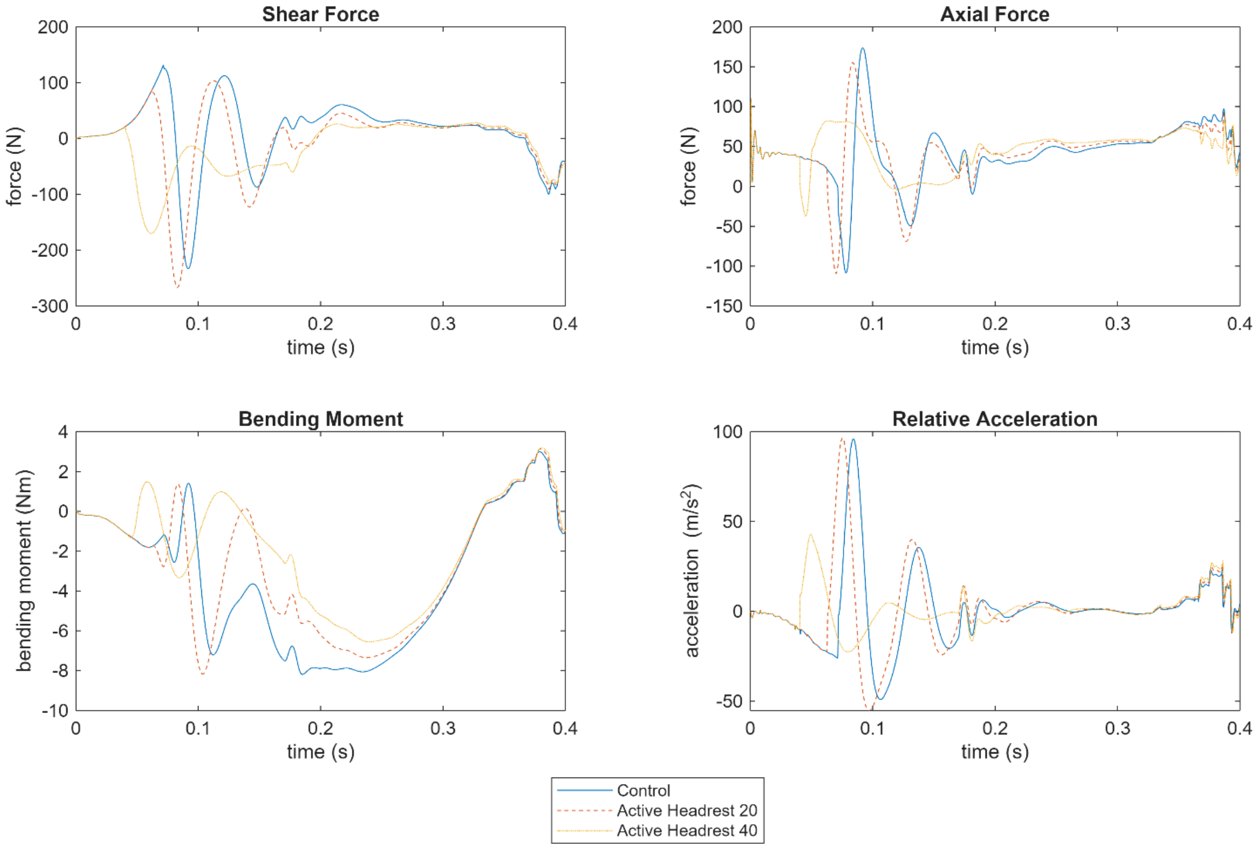

Figure A.16. Simulation results of active headrest for Scenario #6.

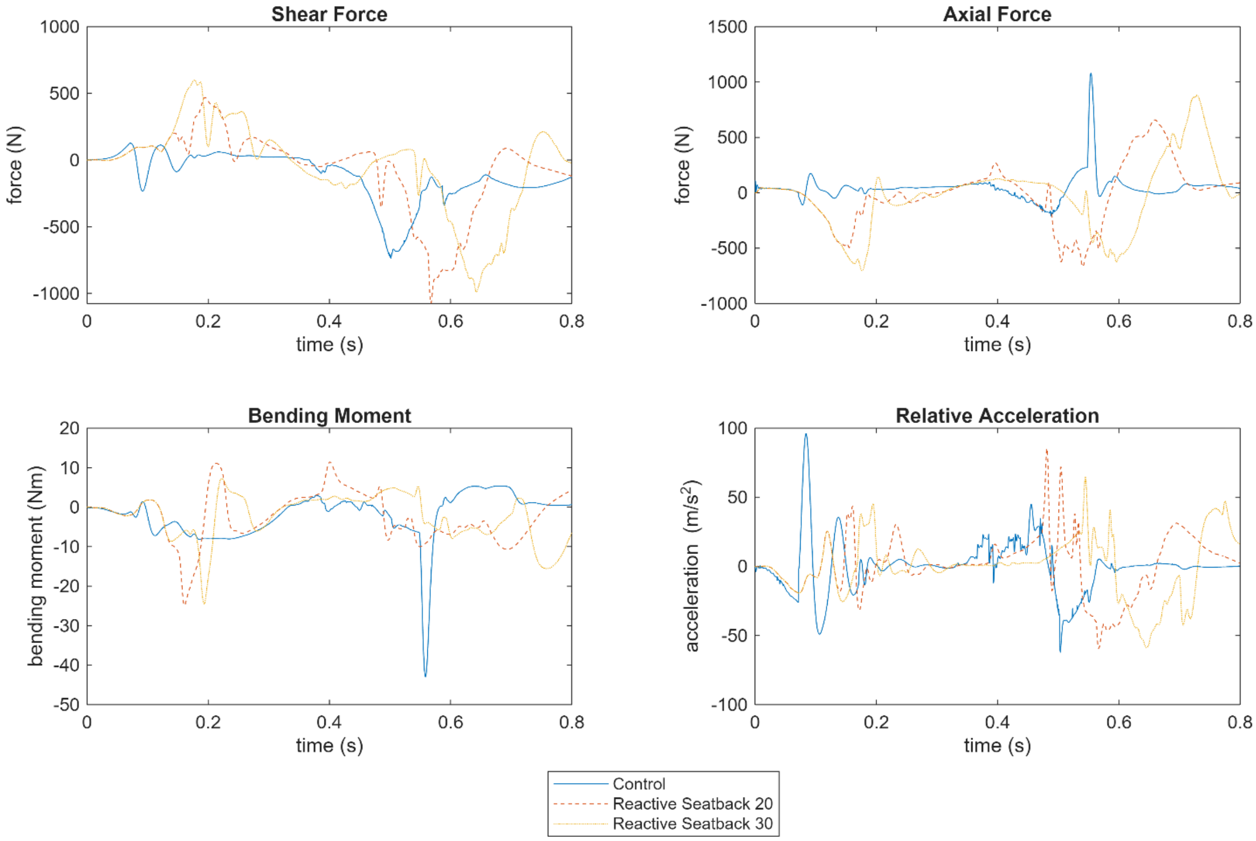

Figure A.17. Simulation results of reactive seatback for Scenario #6.

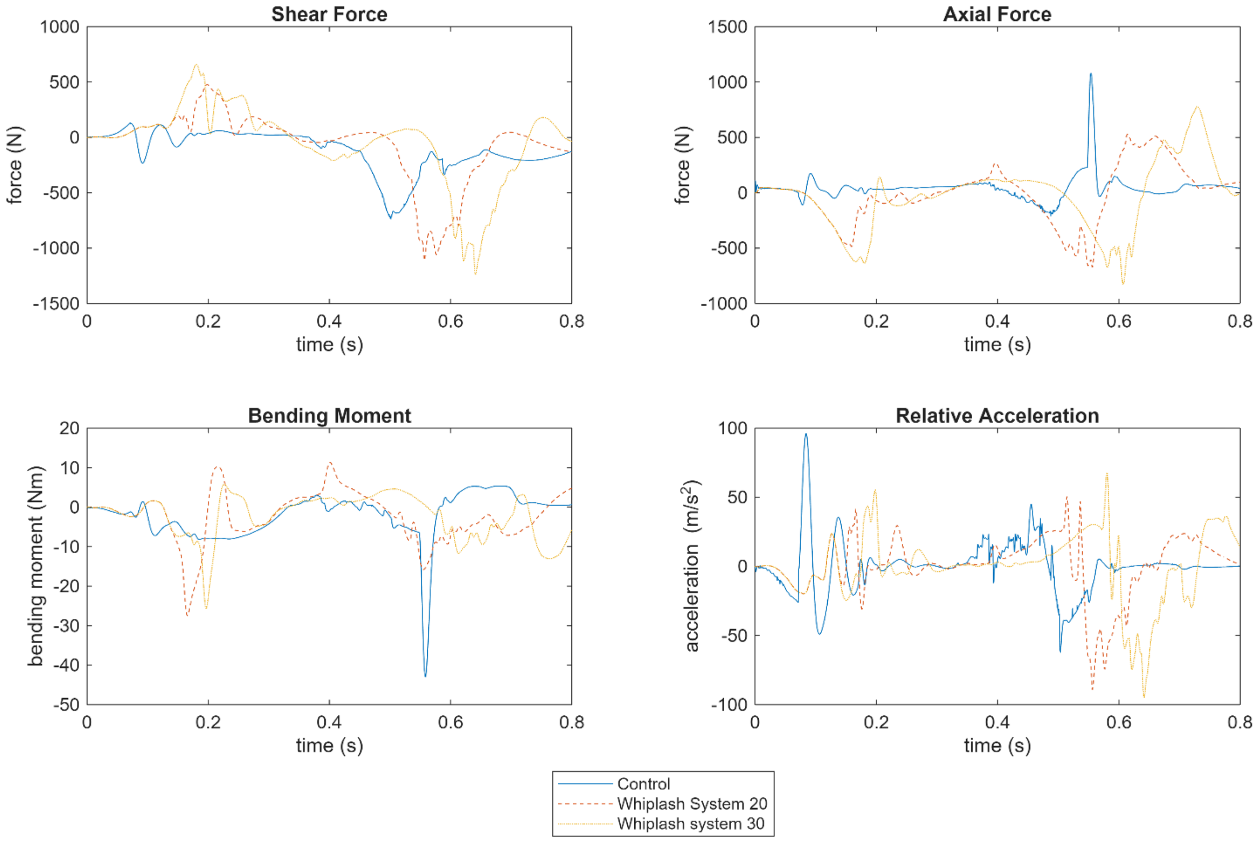

Figure A.18. Simulation results of anti-whiplash system for Scenario #6.

Appendix B: Interview Questions for Heavy Vehicle Manufacturers/TMA Vendors

1. Regarding TMA truck drivers and the prevalence of rear-end collisions, what are the **standard safety features** equipped on your trucks and TMA units? (the systems of seatbelt, head and neck restraints, seat, airbag, and cab designs)
2. What other types of safety features are available on your vehicles?
3. Are these features standard equipment or available as options?
4. How frequently are other types of safety features installed on your vehicles?
5. Do you have any information on additional costs of these features?
6. Have you performed any safety evaluations for other types of safety features? If so, what were the results?
7. What types of **seat belt** systems do you think can better protect drivers after the impact?
8. Are different **seat belt** systems (e.g., three-point, four-point x-form, four-point v-form, five-point, six-point, progressive, B-pillar anchored seat belt and suspension seat, integrated seat belt with suspension seat) available on your vehicles?
9. Which **seat belt** systems are most commonly used?
10. Is a **head and neck restraint** device available on your vehicles?
11. Is a **head and neck restraint** device commonly installed?
12. What is the relative cost difference between different types of **seat belt** systems?
13. Have you performed any safety evaluations of different types of **seat belt** systems? If so, what were the results?
14. What types of **seat** options (e.g., lower seat back, reactive headrests, energy-absorbing material for head and back rests, low seat stiffness, strong seat frame) are available for your vehicles?
15. Are these **seat** options standard equipment or add-ons?
16. How commonly are different types of **seat** options installed on your vehicles?
17. What is the relative cost difference between different types of **seat** options?
18. Have you performed any safety evaluations of different **seat** options? If so, what were the results?
19. What types of **airbag** systems (e.g., steering wheel, side, knee bolster, rear-window curtain) are available on your vehicles?
20. Are these types of **airbag** systems standard equipment or available as add-ons?
21. How frequently are different types of **airbag** systems installed on your vehicles?
22. What is the relative cost difference among different types of **airbag** systems for your vehicles?

23. Have you performed any safety evaluations of different types of **airbag** systems? What were the results?
24. Is a crew/extended **cabin** available as an option on your vehicles? If so, how frequently do customers purchase it?
25. What is the additional cost (if any) for a crew/extended **cabin**?
26. What are the range of weights and typical **weights** for your vehicles?