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Frontal Crash Testing of a Class V Lift Truck

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Counterbalanced, center control, high-lift trucks with a sit-down, non-elevating operator position are required to have a restraint system. The restraint system is intended to restrain the operator in the normal operating position and assist in reducing the risk of entrapment of the operator between the truck and the ground in the event of a tip-over. This is typically accomplished through the use of a two-point lap belt. This type of restraint also provides a degree of protection in the event of a collision between the lift truck and another object. Lift trucks operate in relatively low-speed environments, and many are limited to a maximum speed of 8 mph through a limiting device or by job site regulations. Though the speeds are low, lift trucks can operate in close proximity to other lift trucks and stationary rigid structures, creating the potential for collisions. The standards governing lift truck restraints do not mandate impact testing or injury criteria. This paper describes instrumented frontal impact and sled testing with a peak acceleration of 51 g performed on a Class V lift truck using an anthropomorphic test device (ATD) to test the effectiveness of lift truck restraints in this scenario. The results of this testing showed ATD injury metrics within automotive safety standards.

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1 Introduction

Lift trucks are industrial vehicles used to move, lift, stack, and load heavy objects. Lift trucks typically operate in warehouses, job sites, and other industrial environments. There are several different types of lift trucks for specialized purposes. This paper focuses on lift trucks with sit-down operator positions subject to American National Standards Institute (ANSI) B56.1 restraint system requirements (ANSI). The literature on lift truck collisions is sparse. A study by Collins et al. looked at 1021 fatalities over the 15 years between 1980 and 1994 [1]. These data were captured in the National Traumatic Occupational Fatality (NTOF) database run by the National Institute for Occupational Safety and Health (NIOSH). The Collins study found that the most common fatal accident scenarios were lift truck overturns, pedestrians, and workers crushed by lift trucks. These scenarios accounted for 22%, 20%, and 16% of fatalities, respectively. Lift truck collisions with other vehicles made up 1.5% of fatalities. The Collins study recommended the installation of seatbelts to reduce the occurrence of operators being crushed by the lift truck in the event of an overturn.

Literature on crash testing of lift trucks has focused on stand-up trucks in off-dock incidents [2–4]. In these types of accidents, lift truck operators can sustain serious injury by crush if caught between the lift truck and the ground or by impact with the ground or other rigid objects. To date, no studies have been published on planar impact crash testing of lift trucks.

Planar collisions, and frontal planar crashes in particular are the most common type of crashes in the automotive world [5]. For frontal impacts, passenger vehicle restraint systems are tested in barrier collisions. In this type of testing a coordinate system where the longitudinal axis (x) is positive pointing forward of the vehicle, the lateral axis (y) is positive pointing to the left of the vehicle, and the vertical axis (z) is positive pointing up from the vehicle is used. In planar impact crashes, the severity of the crash is measured using the metric of delta-v, which is the impact-related change in velocity. Delta-v is a surrogate for acceleration to which it is related by crash duration, delta-t. The average acceleration during a crash is delta-v divided by delta-t (Eq. (1)). Passenger vehicles in the New Car Assessment Program (NCAP) collide with a rigid barrier at 35 mph (56.3 km/h) and due to rebound from the barrier experience delta-v around 39 mph (62.8 km/h) with delta-t between 90 ms and 115 ms and peak acceleration averaging 36–46 g [6].

$$\text{acceleration}_{avg} = \frac{\Delta v}{\Delta t} \tag{1}$$

Lift trucks do not travel as fast as automobiles and are unlikely to experience a delta-v as high as the NCAP velocity. Lift truck impacts are not well studied, and due to the variable geometry of the load-carrying attachment, also known as the forks, and the geometry and stiffness of loads carried, a standard impact configuration is unlikely. The potential exists for lift trucks to have long-duration impacts where the forks might penetrate a soft structure, or a compliant load on the forks might provide a crushable ride down. At the relatively low speeds that lift trucks travel, a long-

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duration impact would not produce significant acceleration and therefore limit the force on the occupant and restraint system. However, due to their relatively rigid bodies, lift trucks have the potential to experience significant acceleration in a relatively low-speed collision with another rigid object.

The Occupational Safety and Health Administration (OSHA) places lift trucks into seven categories. Most of the categories include sit-down trucks that are required to have a restraint system. The Class V truck category is defined as counterbalanced internal combustion engine lift trucks with pneumatic tires. Class V trucks are sit-down vehicles and are required to have a restraint system intended to keep the operator in the seat and assist in reducing the risk of entrapment of the operator's head and/or torso between the truck and ground in the event of a tip-over [7].

The effectiveness of seatbelts in automotive frontal collisions has been demonstrated by several authors [8–10] Automotive seatbelts reduce injury by preventing ejection of the occupant from the vehicle and by limiting occupant contact with the vehicle interior. In comparison, lift truck seatbelts are designed for the purpose of keeping the occupant within the confines of the operator compartment during a tip-over. ANSI/Industrial Truck Standards Development Foundation (ITSDF) B56.11.8 gives strength requirements for seatbelts when pulled forward and up, rearward and up, and laterally. Automotive seatbelt systems also have strength criteria and are additionally tested in full-scale barrier impact tests with an Anthropomorphic Test Device (ATD). This type of testing demonstrates the performance of the restraint system in limiting injury criteria measured by the ATD in a crash of a specified severity.

Federal Motor Vehicle Safety Standard 208 (FMVSS 208) is a government regulation that provides pass/fail criteria for automotive frontal crash testing in the form of injury assessment reference values (IARVs). Injury criteria for frontal crash testing include metrics for the head, neck, chest, and lower extremities. In automotive injury testing and research, injuries are ranked using the Abbreviated Injury Scale (AIS) published by the Association for the Advancement of Automotive Medicine (AAAM). The AIS scale classifies injuries based on severity. AIS is a six-point scale, with AIS 1–6 corresponding to minor, moderate, serious, severe, critical, and maximal, respectively. A severe head injury is defined as an AIS 4 or greater injury [11].

The head injury criteria (HIC15) is a unitless value that takes into account the peak head acceleration over a 15-ms time duration (Eq. (2)). The HIC15 is based on several decades of biomechanical research, and risk curves have been developed that relate the HIC15 value recorded in an ATD to the risk of head injury in a human [12]. FMVSS 208 requires that head injury potential in a crash test be assessed using the HIC15 measured in the Hybrid III 50th percentile male ATD. The pass/fail value for automobile compliance testing is a HIC15 of 700 [13]. A HIC15 of 700 is equivalent to a 6% risk of AIS 4 injury [14].

$$HIC15 = \text{Max}\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \tag{2}$$

The neck injury criterion (*Nij*) is used to assess the probability of a neck injury, where *ij* represents indices for the four injury mechanisms, namely N_{te}, N_{tf}, N_{ce}, and N_{cf}. N_{ij} takes into account axial force along the vertical (z) axis (F_z) and bending moment around the lateral (y) axis (M_y) into its calculation (Eq. (3)). During an event, the axial force can be either tension (t) or compression (c), and the bending moment can be either extension (e) or flexion (f). A total of four neck injury criterion are evaluated: tension-extension (N_{te}), tension-flexion (N_{tf}), compression-extension (N_{ce}), and compression-flexion (N_{cf}). Only one of the four neck injury criteria can be computed at each instance in time. When calculating N_{ij}, critical values for F_z and M_y are used: F_{zc} and M_{yc}. The critical values represent the injury tolerances derived by research and designated by the FMVSS. For a Hybrid III 50th percentile male ATD, when the neck is in tension, an F_{zc} value of 1530 lbf (6806 N) is used, while a value of −1385 lbf (−6160 N) is used when in compression. The corresponding Hybrid III 50th percentile male ATD M_{yc} values are 229 ft-lbf (310 Nm) for flexion and −100 ft-lbf (−135 Nm) for extension.

$$N_{ij} = \frac{F}{F_c} + \frac{M}{M_c} \tag{3}$$

where F is the axial force, M is the y-axis moment, and Fc and Mc are intercepts specific to different sizes of ATD. The pass/fail value for automobile compliance testing is a N_{ij} of less than 1.0. A N_{ij} value of 1.0 represents a 22% risk of AIS3+ (serious) neck injury [15].

FMVSS 208 also includes limits for neck tension and compression. For the 50th percentile male Hybrid III ATD used in this testing, the IARV for neck tension is 937 lbf (4170 N). The IARV for neck compression is 900 lbf (4000 N) [15].

Potential injury to the thorax is measured in FMVSS 208 using relative displacement of the sternum to spine and acceleration at the T4 vertebral level. The limit values for the 50th percentile male Hybrid III ATD are 63 mm and 60 g over 3 ms, respectively. In automotive frontal impact testing, the shoulder belt is the primary source of chest displacement. Though the two-point restraint of a class V lift truck does not include a shoulder restraint, it was anticipated that the ATD chest could contact other structures in the operator compartment, and this metric was measured in the testing.

In moderate and higher severity frontal crashes in automotive applications, it is common for the lower legs and knees to make contact with the steering column and/or instrument panel creating a compressive axial load on the femur. FMVSS includes a pass/fail criterion for femur loading. The FMVSS standard for axial femur load is force less than 2248 lbf (10,000 N). This level of axial femur load correlates to a 35% risk of an AIS2+ (moderate) injury for a Hybrid III 50th percentile male ATD [16–18].

Though high acceleration frontal collisions appear to be rare in lift trucks, the potential exists for them to occur. In this study, we tested a Class V lift truck in a high acceleration frontal impact, using a 50th percentile ATD and the injury metrics described in FMVSS 208.

2 Materials and Methods

2.1 Lift Truck. A Class V lift truck (Hyster SN: B299V01573L) was acquired for testing (Fig. 1). The load-carrying attachment was removed to ensure uniform full-width engagement with the barrier. In this configuration, the mast directly engaged the barrier. It was recognized that impacting the stiff mast structure would result in a crash pulse with the highest acceleration potential. Accelerometers were installed on the lift truck, including an accelerometer array on the floor plate of the cab under the operator's seat. The lift truck restraint system consisted of the production two-point lap belt attached to the seat. The belt was instrumented to measure tension near the left and right mounts.

2.2 Anthropomorphic Test Device. Federal Motor Vehicle Safety Standard (FMVSS) 208 was chosen as a guide for ATD setup and injury criteria. FMVSS 208 is intended to reduce the severe injury and death of vehicle occupants by specifying crashworthiness requirements in terms of forces and accelerations measured on ATDs. An instrumented Hybrid III 50th percentile male ATD (Humanetics, Part 78051-218-H, Detroit, MI) was utilized. This ATD is a regulated test device in the USA Code of Federal Regulations (CFR Part 572, Subpart E) with a weight of 171.3 ± 2.6 lbs (77.2 ± 1.2 kg). and a stature of 5-ft, 8½-in. (1.74 m) and is specified in FMVSS 208. The ATD was instrumented according to the FMVSS 208 procedure. The Hybrid III 50th percentile male ATD is the most widely used crash test dummy in the world for the evaluation of automotive safety restraint systems in frontal crash testing [19]. Though frontal impact ATDs ranging in size from

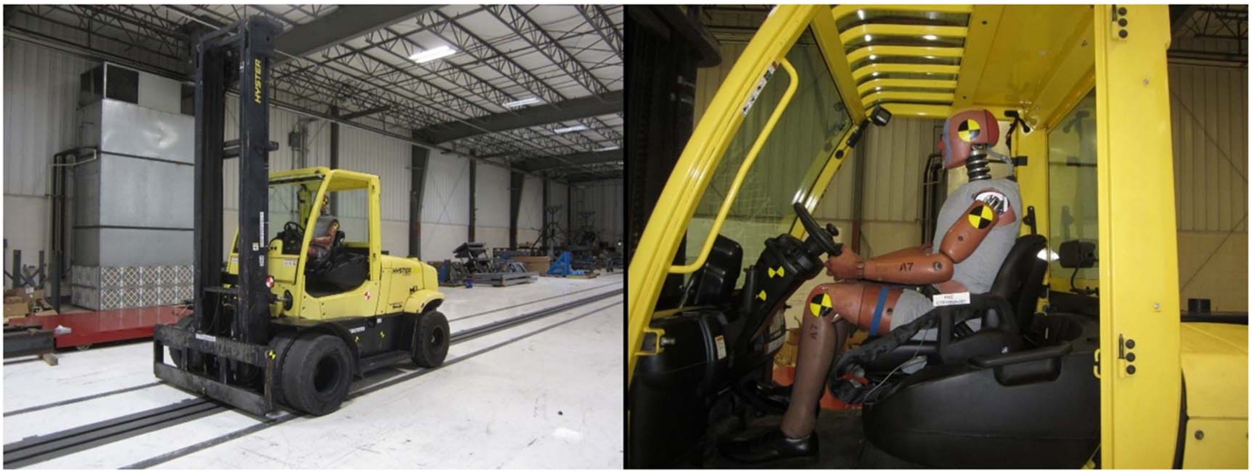

Fig. 1 Left pane: Class V Hyster lift truck with attachment removed; right pane: ATD positioning for test.

the 5th percentile female to the 95th percentile male exist, their use was beyond the scope of this testing.

2.3 Barrier Testing. The ATD was installed in the operator's seat, and the two-point seat belt was fastened (Fig. 1). Both ATD hands were held in pre-crash position on the steering wheel using ½-in. gaffer's tape at the 5 o'clock and 7 o'clock positions. The right foot was placed on the accelerator pedal, while the left foot was placed flat on the floor just behind the brake pedal. Chalk was applied to the ATD's face and knees to determine interior contact locations. The instrumented lift truck with instrumented ATD in position was set to collide with a 2.2 million lb (997,903 kg) reinforced concrete barrier at an impact speed of 8 mph (12.9 km/h), a typical in-warehouse operating speed. Due to the rigid nature of the lift truck's construction and the removal of the load-carrying attachment, a short-duration crash pulse was expected, with peak acceleration at or above the 36–46 g seen in automotive barrier testing. The impact face of the barrier was covered with ¾-in.(1.9 cm)-thick plywood.

2.4 Sled Testing. Dynamic sled testing was conducted in addition to the full-scale barrier crash testing. The sled was set to replicate the crash pulse measured in the barrier testing. The operator compartment of the lift truck used in the barrier crash test was mounted to the test sled. In the sled testing, the seat rails and seat back were welded in place to prevent movement of these components. The two-point belt used in the barrier test was replaced with a new unit. The floor plate-mounted accelerometers remained in the same location as in the barrier crash test. The same 50th percentile male Hybrid III ATD was placed in the driver's seat. The ATD was instrumented according to the FMVSS 208 procedure. The ATD was installed in the operator's seat, and the two-point seat belt was fastened. The ATD positioning was as in the barrier test. Both ATD hands were held in pre-crash position on the steering wheel using ½-in. (1.3 cm) gaffer's tape at the 5 o'clock and 7 o'clock positions. The right foot was placed on the accelerator pedal, while the left foot was placed flat on the floor just behind the brake pedal. Chalk was applied to the ATD's face and knees to determine interior contact locations.

3 Results and Discussion

3.1 Barrier Test. The lift truck impacted the rigid barrier at 8.05 mph (12.9 km/h). The resulting crash pulse had a peak acceleration of 51 g measured at the floor plate accelerometer. The duration of the primary crash pulse was 30 ms. Due to rebound from the barrier, the delta-v was 11.3 mph (18.2 km/h). The longitudinal acceleration tracing is shown in Fig. 2. Belt tension measured in the test was 339 lbf (1508 N) left and 577 lbf (2567 N) right.

Compared to automotive barrier testing, this was a very stiff, short crash pulse. The reason for this difference is that lift truck bodies must serve as counterweights for the intended purpose of lifting loads and are therefore massive and rigid. Passenger vehicles are significantly less rigid and use deformation of the body and frame at relatively lower force levels to manage acceleration and extend the time duration of the crash pulse. In this test, the 25,370 lb (11,508 kg) lift truck exerted a force of 1.3 million lbf (5.8 million N) against the barrier in an 8 mph (12.9 km/h) crash test. For comparison, a large heavy-duty pickup weighing 7423 lb (3367 kg) exerted a force of 240,546 lbf (1.1 million N) against the barrier in a 35 mph (56.3 km/h) crash test with a crash pulse duration of 100 ms [20].

At impact, the ATD was restrained by the lap seat belt. However, during the test, the operator's seat adjustment system unexpectedly released, allowing the seat to shift forward. The ATD moved forward with the shifted seat and restraint. When the seat movement stopped, the ATD re-loaded the belt and flexed forward. The seat actuation altered the expected kinematics and allowed the ATD's head to make contact with the windshield (Fig. 3). The glass fractured on contact. The ATD's left knee loaded into the steering column, resulting in damage to the column (Fig. 4). The abdomen contacted the lower steering wheel rim.

Similar to the lack of standards or regulations defining frontal crash test parameters, there are no industry or governmental standards establishing injury criteria thresholds for lift trucks in frontal barrier crash tests. Therefore, FMVSS 208 Standards for vehicle occupant protection in frontal crashes were utilized. The HIC15 metric is used to assess the potential for head injury in

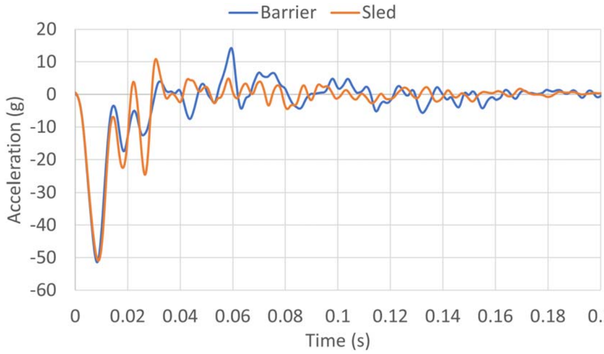

Fig. 2 Longitudinal acceleration for barrier test and sled test. Peak accelerations were 51.4 g for the barrier test and 50.9 g for the sled test.

Fig. 3 ATD Head contact with windshield in the barrier test

FMVSS 208. The FMVSS 208 Standard requires a HIC15 lower than 700. In the barrier crash test, the ATD recorded a HIC15 of 67 representing a 0.05% chance of severe head injury. FMVSS 208 requires that neck injury potential in a frontal crash test be assessed using the N_{ij} measured in the Hybrid III 50th percentile male ATD. N_{ij} must be lower than 1 to meet the FMVSS 208 Standard. In the barrier crash test, the maximum N_{ij} occurred when the ATD head made contact with the windshield glass, inducing a compression-flexion motion (N_{cf}). The resulting N_{ij} of 0.61 represents a 12% chance of AIS3 + injury. FMVSS 208 limits for neck tension and compression for the 50th percentile male Hybrid III ATD used in this testing are tension less than 938 lbf (4172 N) and compression less than 899 lbf (4000 N). In the barrier test, peak neck tension was 312 lbf (1388 N) and peak neck compression was 781 lbf (3474 N). Both values are within the FMVSS 208 Standard. Potential injury to the thorax is measured in FMVSS 208 using chest displacement and acceleration. The limit values for the 50th percentile male Hybrid III ATD are 2.5 in. (6.4 cm) and 60 g over 3 ms. The values measured in the barrier test were 0.08 in. (0.2 cm) and 11.7 g. These values are within the FMVSS 208 Standard. The 726 lbf (3229 N) left femur and 71 lbf (316 N) right femur compressive loads measured by the ATD in the barrier test correlate to a 1.6% and 0.4% chance of an AIS2 + injury, meeting the injury criteria of FMVSS 208.

3.2 Sled Test. The sled pulse was tuned according to the results of the longitudinal acceleration measured by the floor plate accelerometer during the barrier test. The sled was able to closely match the barrier pulse in acceleration magnitude with a peak longitudinal acceleration of 51.4 g for the barrier test and 50.9 g for the sled test. Both crash pulses had a duration of approximately 30 ms. The crash pulses are compared in Fig. 2. During the sled test, the seat track maintained its position and the lap seat belt restrained the ATD in the operator's seat. The ATD flexed forward and made head contact with the steering wheel (Fig. 5). There was no head contact with the windshield. The left knee made minor contact with the steering column. There was no resultant deformation or damage to the steering column or the instrument panel, and the abdomen did not contact the lower steering wheel rim, as was seen in the barrier crash test. As in the barrier crash test, FMVSS 208 Standards for occupant protection in frontal crashes were utilized to evaluate the injury potential of the sled test. In the sled test, the ATD recorded a HIC15 of 109 representing a 0.17% chance of severe head injury. The maximum N_{ij} in the sled test occurred when the ATD head made contact with the steering wheel rim, inducing a compression-flexion motion (N_{cf}). The resulting N_{cf} of 0.33 relates to a 7% chance of AIS3 + injury. Neck tension and compression were 125 lbf (556 N) and 108 lbf (480 N), respectively. The chest acceleration was 9.34 g, and the chest displacement was 0.07 in. (0.2 cm). Axial femur compression loads were 239 lbf (1063 N) for the left femur and 49 lbf (218 N) for the right femur. These compressive loads correlate to a 0.5% and 0.3% chance of an AIS2 + injury. As in the barrier test, all injury metrics for the sled test were within the requirements of FMVSS 208.

3.3 Summary and Comparison of Barrier and Sled Test. The results from the barrier crash and sled tests were compared. When comparing the ATD kinematics between the two tests, the main difference was the effect of the seat actuation in the barrier test (Fig. 6). At time zero (0 ms), the ATD was in a very similar position for both tests. In the barrier test at 120 ms, the whole seat had shifted forward with the ATD in an upright position. At the same time of 120 ms in the sled test, the ATD torso was flexed forward due to restraint by the lap belt, with the forehead starting to make contact with the steering wheel. The steering wheel-to-head contact created compression force in the ATD's neck. At 240 ms in the barrier test, the top of the ATD's head broke through the windshield glass inducing a compression load on the neck, while at this point in the sled test, the ATD had already rebounded from the steering wheel contact. The difference in ATD kinematics was also confirmed when comparing the belt loads between the two tests (Fig. 7). Belt loading occurred later in the barrier test due to the activation of the seat adjustment and

Fig. 4 ATD Knee contact with steering column in barrier test

Fig. 5 ATD Head contact with a steering wheel in sled test

Fig. 6 Comparison of ATD kinematics at 0 ms (left), 120 ms (center), and 240 ms (right) with barrier test on top and sled test on bottom

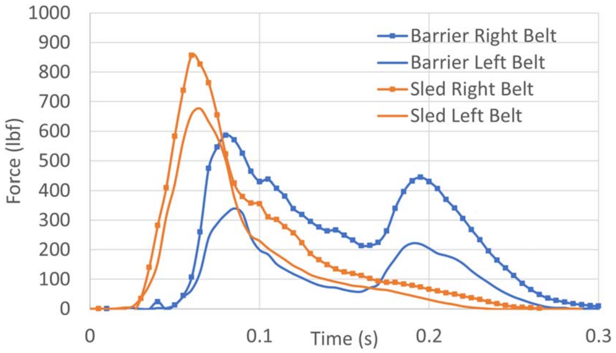

Fig. 7 Comparison of belt load in barrier test versus sled test

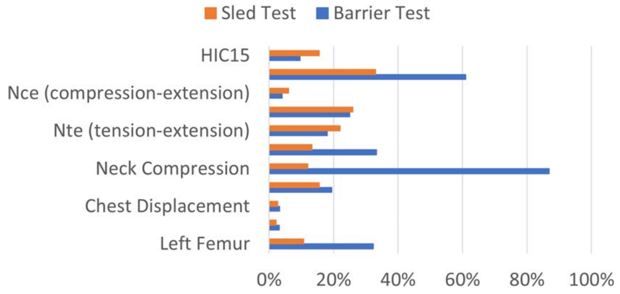

Fig. 8 Percentage of injury assessment reference values (IARVs) reached in barrier and sled tests

resulting seat movement. The barrier test showed two smaller loading events, whereas the sled test showed one large event. The difference in kinematics led to higher loads on the ATD neck and left femur on the barrier test. Comparing the ATD injury criteria results to FMVSS 208 injury assessment values showed that despite the seat actuation in the barrier test and head contact to the steering wheel in the sled test, the lap seat belt provided reasonable occupant protection in a high acceleration frontal impact. Figure 8 shows the percentage of each IARV attained in both tests. In the barrier test neck compression and the related N_{cf}, N_{ij} values were 87% and 61% of their respective IARVs with all other values less than 40% of the IARV. The average IARV percentages were 27 for the barrier test and 15 for the sled test. All IARVs in both tests were within the FMVSS 208 Standard.

3.4 Limitations. One limitation of this study is that only two tests were performed. This research analyzed the feasibility of such testing, as well as the performance of the restraint system in a potential crash scenario. Future testing could include repeated testing, as well as testing in different crash configurations with different ATDs. Another limitation of this study is the limited nature of the data on lift truck collisions. The percentage of lift truck accidents that involve frontal collisions with significant acceleration is unknown. Though this is the most common collision scenario in automotive accidents, lift trucks are operated differently from passenger vehicles and in a different environment. The testing described in this work was performed with a Class V sit-down lift truck, which has a seatbelt restraint system designed to retain the operator in the event of an overturn. Other types of lift trucks do not have seats or belts and are designed for rapid operator egress in the event of an overturn. The testing involved a single barrier impact and a single sled test of a Class V lift truck and is not representative of lift trucks with different operator configurations.

4 Conclusion

This study described frontal impact testing of a Class V lift truck and the resulting injury measurements on an instrumented ATD placed in the operator's position and utilizing the available restraint system. The acceleration in this testing was significantly and intentionally higher than that expected for the majority of field accidents involving Class V lift trucks. The results showed that the lift truck restraint system, designed to protect the occupant in a tip-over, also performed well in a frontal collision with all injury metrics below serious injury threshold standards in the automotive FMVSS 208 Standard.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human and animal participants were involved. Informed consent is not applicable.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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