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Forensic Engineering Evaluation and Testing of Horizontal Intrusion Protection Equipment for Stand-Up Forklifts

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Abstract

In 2004, a report issued by the National Institute of Occupational Health and Safety (NIOSH) evaluated a fatal stand-up forklift accident where a warehouse forklift operator was crushed against a rack beam after it intruded into the operator's compartment. One of the recommendations of the report was that "Manufacturers of stand-up reach forklifts should include vertical framing or posts at the rear corners of their machines, from the operator's console to the overhead guard, to protect the operator from horizontal components entering the operator's station[1]." Other published studies have also recognized the risk associated with the hazard of a horizontal rack beam entering the operator's compartment of a stand-up forklift. It has been previously reported that there have been at least 250 incidences of horizontal intrusion as of June 2008[2]. The ANSI B56.1 "Safety Standard for Low Lift and High Lift Trucks" has recognized such guarding as permissible since 1993, and almost all stand-up forklift manufacturers have made such guarding standard equipment. The evaluation that is the subject of this paper is related to the fatal horizontal intrusion incident involving a stand-up lift truck (forklift) operated by a 44-year-old male.

Keywords

Stand-up, forklift, horizontal intrusion, under-ride

Introduction

This paper evaluates the performance of the forklift manufacturer's horizontal intrusion* protection system, or posts, through a series of four low-speed collisions with a rack system. The four tests were conducted at increasing kinetic energy levels to first evaluate whether the posts were compliant with ANSI B56.1 and at higher speeds/loading to assure that the operator of the forklift in the subject incident would have been protected by the posts.

The stand-up lift truck in the subject incident is a universal or fore/aft stance truck available with optional horizontal intrusion protection that consists of steel posts connecting the tractor portion of the truck to the overhead guard at the rear corners of the tractor. During this testing, the performance of the horizontal intrusion protection was evaluated based on deflection of the guarding system after a collision at low speed with a typical racking system consistent with the test methodology outlined in ASME/ITSDF/ANSI B56.1[3,4].

Testing shows that the optional steel posts are compliant with the ANSI B56.1 testing requirements and that the forklift operator would not have been crushed in the low-speed collision in the subject incident, had the forklift been equipped with these posts.

Reportedly, the forklift operator was using the stand-up lift truck in a "forks trailing" manner (in reverse) with the operator compartment leading while transporting a pallet of boxed books in the warehouse. The forklift operator was driving the forklift facing in the direction of travel with his left hand on the multi-function controller and his right hand on the steering tiller. As the stand-up forklift approached a rack, the forklift apparently experienced a brake code/braking error immediately before a horizontal rack beam intruded into the operator compartment above the tractor portion and below the overhead guard of the forklift. A police officer with the local sheriff's office described the incident/scene in a supplemental report. The officer stated the following:

* Horizontal intrusion incidents are also referred to as "underride" incidents.

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"The forklift was driven into an orange in color metal support beam used to hold pallets of books. The forklift was of a design that required the operator to stand upright during operation; no seat was affixed to the forklift. The height of the support beam allowed the forklift body to travel underneath, exposing the operator to the beam as it traveled in reverse. The victim's upper torso impacted the support beam, causing it to become bent."

The bottom of the rack beam pinned the operator to the top of the operator's console in the operator's compartment of the forklift. The operator sustained multiple injuries, including broken/fractured ribs, a transection of the aorta, lacerations to the lungs, laceration of the left hemi-diaphragm with herniation of the stomach and large bowel into the chest cavity, hepatic lacerations, splenic lacerations, transection of the duodenum, lacerations/contusion to the pancreas, and internal bleeding/hemorrhaging. The operator reportedly survived the initial collision, and expired some time after the impact while pinned between the forklift and rack beam.

In conducting this investigation, the following were reviewed: documents related to the incident, the manufacturer's literature (including the parts manual, maintenance manuals, and optional equipment brochure), and the ASME/ITSDF B56.1 standard. This information was referenced in evaluating the incident and developing a testing protocol to analyze the effectiveness of the manufacturer's horizontal intrusion protection relative to the incident. The complete listing of the reviewed documents is provided in **Appendix A**.

An exemplar forklift with the optional horizontal intrusion protection equipment and additional posts were obtained. In addition, vertical uprights, rack beams, and wire decking were obtained.

The authors reviewed the provided documents, analyzed the incident, performed research relative to lift trucks, analyzed engineering standards and literature related to lift trucks and safety, and evaluated the design of the lift truck based on known mechanical engineering and safety engineering principles. As a result of the investigation and testing, this paper addresses the following areas:

- Findings from a review of the incident
- Test protocol developed to evaluate the performance of the manufacturer's horizontal intrusion protection equipment
- Testing results
- Findings and discussion of testing
- Summary of conclusions

Findings from a Review of the Incident

STAND-UP FORKLIFT: The forklift operator was using a narrow aisle, end-controlled forklift with a universal or fore/aft stance. The truck is equipped with a deep or double-reach pantograph (scissor) mechanism that can extend a pallet into a racking system either one or two slots deep. Nominal capacity of the forklift is 3,000 pounds; the manufacturer's truck identification plate indicates that the truck can lift 3,000 pounds to a height of 246 inches (20.5 feet), and its capacity is reduced to 2,800 at a height of 252 inches (21 feet). The forklift has a triple-stage telescoping mast. The top speed of the forklift is 7.5 mph, but this can be electronically limited to a lower speed. The serial number indicates that the forklift was manufactured in 2007. A photograph of the forklift is shown in **Figure 1**.

Figure 1
Stand-up narrow aisle forklift.

The stand-up truck is operated from a "universal" or fore/aft stance. The operator typically faces either directly toward (fore) or directly away from the forks (aft). When the operator faces away from the forks, the operator's left hand is on the multifunction control or joystick, and the right hand is on the steering knob or tiller. In the aft stance, the right foot is the closest to the deadman brake on the floor of the operator compartment. In the fore stance, the feet and hands switch positions. The left hand operates the steering tiller, the right hand operates the multifunction control, and the left foot operates the deadman brake. The incident scene photographs indicate that the forklift operator was using the forklift in the aft stance, facing away from the forks at the time of the incident and in the direction of travel.

The operator's compartment of the forklift, which is located near the right rear corner of the truck, is entered through an opening at the rear of the truck. However, it is protected at the left, front, and right with a steel wall that varies in height from 47 to 50 inches above the ground. Above the steel wall, the operator's compartment is open and unguarded, except at the front of the tractor portion where the mast extends vertically. There is an overhead guard extending from the mast above the operator's compartment intended to protect the operator from falling objects.

RACKING: The racking in the warehouse was labeled with the manufacturer's brand labeling. The vertical upright columns are roll-formed steel with slots for rack beam connections. The rack beams are 5-inch structural steel. The first rack beam was installed with the top of the rack beam at a height of approximately 60 inches above the floor. The manufacturer's brochures indicate that the 108-inch structural beams have a capacity of 8,830 pounds per pair. A photograph of the general configuration of the racking system is shown in **Figure 2**. The racking in **Figure 2** has been modified to lower the first beam in the first section of the racking to a height below 60 inches. The majority of the racking has a first beam height of 60 inches.

The horizontal beam that the forklift operator and the forklift collided with deformed approximately 2½ inches at a location about 80 inches from the left side of the beam and 28 inches from the right end of the beam. The rear beam, wire decking, and beam braces do not appear to have deformed in the collision. The vertical uprights did not deform or appear to sustain damage

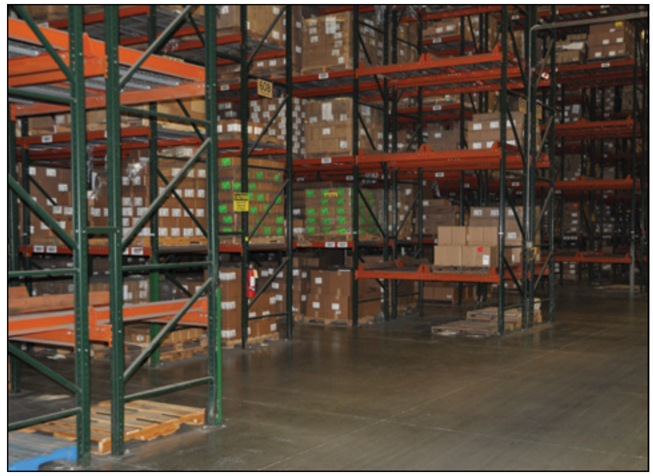


Figure 2
Warehouse rack (modified after the incident).

from the collision either. The forklift operator's body, the forklift, and the rack beam appear to have absorbed all of the kinetic energy associated with the truck and load at the time of the collision.

ENGINEERING STANDARDS: The American National Standards Institute (ANSI) published a standard in 1993 developed under the American Society of Mechanical Engineers (ASME) titled "Safety Standard for Low Lift and High Lift Trucks." In this 1993 revision of the standard, a new section was added, permitting the use of "guards or other means" to limit intrusions (into the operator's area) of horizontal members (e.g., rack beams) oriented generally transverse to the direction of travel. The standard also developed requirements for the performance and testing of the protection. The standard requires a collision between the forklift and a rigid barrier with a 3-inch vertical dimension performed at a speed of 1 mph with a truck carrying a full rated load. The performance of the horizontal intrusion protection is considered acceptable if there is no separation of parts or permanent deflection in excess of 4 inches in the horizontal plane.

Test Protocol Developed to Evaluate the Performance of the Horizontal Intrusion Protection Equipment

The authors developed a testing protocol to determine whether the optional manufacturer's horizontal intrusion protection meets the ANSI B56.1 standard requirements and whether the guarding would have prevented or mitigated the fatal crushing injuries sustained by the operator. The test consisted of four collisions between a section of typical warehouse racking and an exemplar stand-up forklift equipped with the optional horizontal intrusion protection posts. The tests were conducted at increasing kinetic energy levels with impact speeds of approximately 1.4, 2.4, 2.8, and 3.4 mph. The acceleration distance required for speeds above 3.4 mph limited the top speed utilized in testing. Each test used a new post and new rack beam. Deflection in the post and racking were measured after each test. The forklift, racking, and testing are described below.

FORKLIFT: The forklift utilized for the testing was a narrow aisle, end-controlled, deep or double-reach forklift, with the same model number as the forklift involved in the incident. The serial number of the forklift indicated that the truck was manufactured in 2002 (approximately five years before the subject truck). The truck has a load capacity of 3,000 pounds at a 24-inch load center, and could lift to a height of 240 inches (20 feet). The truck in the incident had a lift height of 246 inches with a 3,000-pound load. **Figure 3** and **4** are photographs of the exemplar truck† (on the left) and the subject truck on the right.

The exemplar truck was equipped with the manufacturer's optional horizontal intrusion protection when it was purchased, and additional replacement posts were purchased through a forklift parts retailer. The retailer represented that the replacement posts were purchased from the forklift manufacturer and then repackaged as originating at the retailer‡. The chemistry and mechanical properties of a post from the retailer and a post from the manufacturer were tested. The chemistry and mechanical properties of the two samples were consistent, and, when combined with representations from the retailer, indicated that both sets of posts originated at the forklift manufacturer§.

Prior to the testing, maximum acceleration of the forklift as a result of maximum throttle input was measured using a SENSR GP1-programmable accelerometer. Maximum forklift acceleration was recorded to be approximately 0.06 g. Forklift acceleration appeared to remain relatively constant until top speed was achieved.

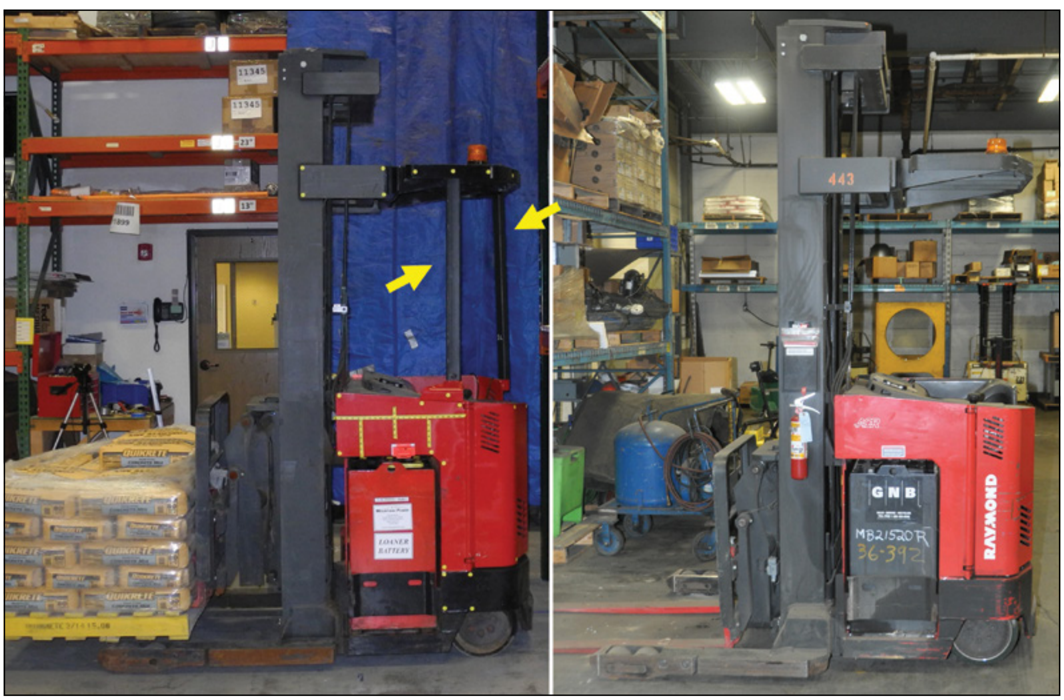


Figure 3
Exemplar truck with horizontal intrusion post protection (left) and subject truck without posts (right).

† The lift truck has been marked with round, yellow stickers and marking tape as a part of the testing.
‡ Despite ordering replacement posts based on the specific serial number associated with the forklift, the manufacturer supplied the retailer with posts longer than the posts on the truck. Because of the excess length, the authors cut the supplied posts to match the length of the post on the forklift, and a new mounting hole(s) was drilled. After the modification, the replacement posts matched the geometry of the original post. Additional posts were supplied that were obtained from the manufacturer's dealership using the serial number of the forklift. The posts supplied by the manufacturer's dealership were the same length as the posts supplied by the retailer.
§ Mechanical and Chemistry Testing Report prepared by Colorado Metallurgical Services, June 25, 2014.

Before the test, the multifunction controller of the forklift was removed from the operator compartment and extended outside of the operator compartment with an additional cable. The deadman brake pedal was disabled with weight to allow motion of the forklift without an operator present.

RACK: Vertical uprights, rack beams, and wire deck panels were used to conduct the collision testing. The vertical uprights were roll formed, slotted uprights (42 inches in depth and 12 feet in height). The uprights have a capacity of 22,100 pounds at a 48-inch lateral spacing. The rack beams were roll formed step beams (108.37 inches long and 4.65 inches tall). The beams have a manufacturer's rated capacity of 6,320 pounds per pair, with a factor of safety of 1.67 based on minimum yield strength of the steel. The decking was galvanized wire that was 42 inches deep and 52 inches wide with a capacity of 2,500 pounds.

The uprights were installed in a concrete floor using ½-inch x 5-inch wedge anchors. Two anchors were used per post leg (eight anchors total), utilizing all of the available mounting holes. Two rack beams and decking were installed at a height of 60 inches. A second pair of beams was installed at a height of 120 inches.

TESTING: During the first test, there was no load on the rack frame. In the second, third, and fourth tests, a nylon ratcheting strap was placed at each end of the rack and anchored to the floor using wedge anchors and angle iron brackets. The tension in each strap was approximately 1,000 lbf, simulating a 4,000-pound load on the rack system. Further, two sit-down forklifts were placed behind the rack system with masts raised and load carriages placed against the top of the rear of the rack system to increase the rigidity of the rack structure. **Figure 4** is a photograph of the forklift and rack configuration during the first test, and **Figure 5** shows the rack configuration for the subsequent tests. The simulated load and forklift placed behind the rack increased the rigidity or stiffness of the rack section.

Figure 4
Stand-up forklift and rack configuration during first test.

Figure 5
Rack configuration during second, third, and fourth test: Nylon ratcheting straps at each end of rack frame and sit-down forklifts. (Note that the 2x4 wood pieces in the foreground provide no structural support and are not part of the test equipment.)

Testing Results

The four tests of the manufacturer's posts were conducted at increasing speed and kinetic energy levels. The truck was accelerated for distances of 1, 3, 6, and 7 feet, respectively, to achieve the increase in speed prior to the collision. The tests are labeled sequentially 1-4 for the increasing distances. Tests labeled with an "L" denote a post supplied by the manufacturer through the retail parts distributor. The final test labeled "RL" denotes a post supplied by the manufacturer's dealer. **Table 1** summarizes the maximum impact speeds, peak kinetic energy levels, and peak accelerations (decelerations during the collision) achieved during testing. Impact speeds were obtained through numerical integration of the accelerometer data, and kinetic energy was calculated based on that impact speed and a mass of 11,178 pounds (truck weight of 8,178 pounds and load of 3,000 pounds). Kinetic energy levels are reported for comparison of the testing to other incidents, since the load on the forks during testing represents 25% of the overall mass involved in the test collisions, and other incidents may or may not include a load on the forks. Peak accelerations are reported based on both raw accelerometer data and on a peak acceleration based on a 20-point moving average of the data for noise reduction (representing an average acceleration over a 200 millisecond time span). The peak acceleration reported is related to the maximum collision force and the acceleration (deceleration) that the operator will be subjected to. However, the noise in the accelerometer data (apparent in the oscillation between positive and negative acceleration values) shows that vibration and/or noise is overstating the peak acceleration values. Therefore, the authors concluded that further noise reduction was necessary to report meaningful peak accelerations. The accelerometer acquires data at a rate of 100 samples per second (100 Hz). A 20 point moving average reports the average acceleration over the last 20 points of data (200 milliseconds), removing most of the noise associated with vibration in the accelerometer in the system. Acceleration, velocity, and distance traveled by the forklift during the tests are presented in **Appendix B**.

The four tests produced increasing deflection in the rack beam and rack system but little or no deflection in the horizontal intrusion post. Post deflections are shown in **Table 2**. Post deflection or deformation was measured while the post was still installed on the forklift, and then again after removal from the forklift. Values of maximum deflection differ between the two methods because the first method reflects slight shifting of the post during the test relative to the weldment mounts, while the latter method documents only deformation in the post. **Figure 6** is a photograph of the posts after testing with little visible deflection.

Test	d (ft)	V (mph)	KE (ft *lbf)	Peak Acc. (g)	Peak Acc. 20 pt. (g)
1L	1	1.37	701	.87	.34
2L	3	2.42	2187	1.5	.52
3L	6	2.80	2927	1.2	.73
4RL	7	3.40	4316	1.37	.74

Table 1
Impact speeds, kinetic energy and accelerations. “L” denotes a post supplied by the manufacturer through the retail parts distributor. “RL” denotes a post supplied by a manufacturer’s dealer.

	Maximum Deformation On Truck (in.)	Height at Max. (in.)	Maximum Deformation of Post (in.)	Distance From Top of Post (in.)
1L	0.028	39	0	20
2L	0.052	29	0.063	20
3L	0.229	27	0.188	20
4RL	0.112	32	0.125	20

Table 2
Post deformation.

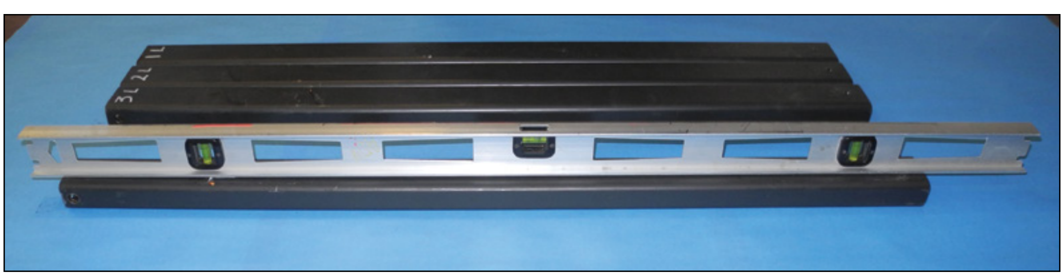


Figure 6
Posts after collision testing – little visible deflection.

Rack beam deformation is shown in **Table 3**. The deformation distance reported is the maximum deformation of the rack beam relative to the two ends of the beam. The test attempted to replicate the distance from the vertical upright during the subject incident of 28 inches; however, the forklift was driven into the rack, and the impact location varied slightly. The distance from the vertical upright is reported in **Table 3**. Static deformation of the rack system was also documented by the total distance that the forklift traveled after contact with the rack beam and consists of both rack beam deflection and the deformation of the rack system. While the forklift remained in close proximity to the area of contact in the first, second, and third test, it rebounded several inches in the fourth test. Therefore, forklift travel measured at rest after contact under-reports total rack deformation in the fourth test. In the first test, the vertical uprights deformed significantly while the rack beam did not. In the second and third tests (with the added reinforcement), the deformation occurred primarily in the rack beams, while the vertical uprights remained undeformed. In the fourth and final test, the rack beams and vertical uprights both deformed. **Figure 7** displays the deformed end of the rack beams after testing.

	Maximum Deformation of Rack Beam (in.)	Distance from Left End (in.)	Forklift Travel After Contact (in.)
1L	0.56	29	5.3
2L	6.13	25	6.6
3L	6.0	22.5	6.5
4RL	9.5	15	9.25

Table 3
Rack beam deformation and forklift travel after contact.

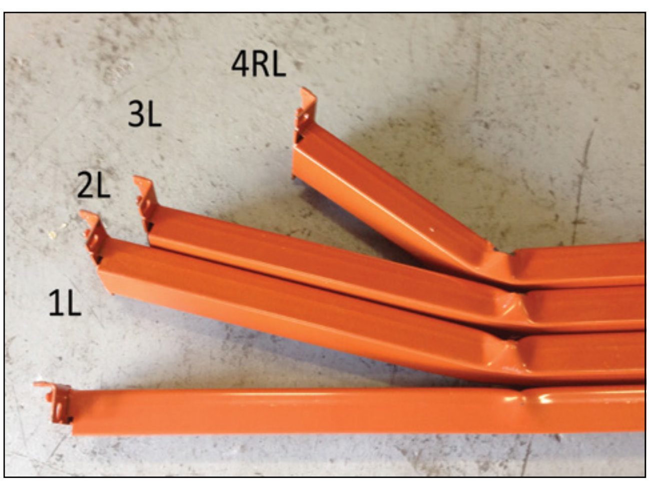


Figure 7
Deformed rack beams after testing.

Findings and Discussion of Testing

COMPLIANCE OF HORIZONTAL INTRUSION PROTECTION WITH ANSI B56.1: The primary requirements of the ANSI B56.1 test are an impact transverse to the direction of travel, an impact speed of 1 mph, and a rigid barrier simulating a rack beam with a 3-inch vertical dimension. Each test described in this paper exceeds the speed requirements of ANSI B56.1. The rigidity of the barrier requirement within the ANSI standard is not well defined; however, the racking used in the testing is prevalent throughout warehouses and distribution centers. The 4.65-inch vertical dimension of the rack beams exceed the height requirement in the B56.1 standard, which results in a higher moment of inertia in resistance to loading and bending. The first and fourth test dissipated energy in the rack beam and vertical uprights, while the vertical uprights remained undamaged in the second and third tests. The performance requirements of ANSI B56.1 specify no separation of parts or permanent deflection in excess of 100 mm (3.9 inches) in the horizontal plane. The manufacturer's horizontal intrusion posts and forklift tested met this requirement after four successive tests of increasing impact speed and energy levels. Based on the testing performed as a part of this research, the horizontal intrusion protection system of posts offered by the manufacturer met or exceeded the test requirements of B56.1.

The majority of the stand-up forklifts currently available on the market have some form of horizontal intrusion protection. The subject manufacturer's counter-balance stand-up trucks and sit/stand model of a reach truck also incorporate some horizontal intrusion protection. Given that the majority of forklift manufacturers have adopted standard horizontal intrusion protection, the benefits or utility of the protection clearly outweigh any trade-offs associated with the horizontal intrusion protection. Therefore, it is the authors' recommendation that the permissive language within the ANSI B56.1 standard should be modified to "require horizontal intrusion protection."**

The authors also recommend that the performance requirements of the ANSI B56.1 standard be strengthened in regard to horizontal intrusion protection. The

** It is the authors' further recommendation that the horizontal intrusion protection should not require modification of the end user's facility to make the horizontal intrusion protection effective. Vertical posts connecting the tractor to the overhead guard and extended backrests have proven effective in testing without significant modification.

maximum speed of stand-up forklifts is significantly higher than the performance requirement within the standard. The section within the standard regarding horizontal intrusion protection is also more than 20 years old. Manufacturers, including the subject manufacturer, have had more than sufficient time to develop robust horizontal intrusion protection equipment that can meet more stringent requirements than the current standard has.

ANALYSIS OF THE TESTING IN REGARD TO THE SUBJECT INCIDENT: While the subject incident apparently occurred as a result of a braking (plugging)†† failure with the forklift, other horizontal intrusion incidents also appear to have occurred through operator error or foreseeable misuse of the forklift. Regardless of the cause of the horizontal intrusion incident, the need for effective, standard operator protection is clear. The amount of deflection of the protective structure is the primary method of assessing the effectiveness of the horizontal intrusion protection because it determines how much intrusion will occur into the operator compartment. The subject incident produced a maximum deflection of 2½ inches of deformation in the rack beam that the operator and forklift collided with. The other components within the rack system appear undamaged, indicating that all of the kinetic energy of the forklift was absorbed, crushing the operator and damaging the rack beam. The testing performed in this research all produced more deformation (either in the vertical uprights or the rack beams) than the subject incident did. While the test performed at 1 mph produced less deformation in the beam than the subject incident, the vertical uprights were deformed at both ends of the rack. Further, the collision at approximately 2 mph produced 2.5 times as much deformation in the beam. While considering the difference between the testing and the incident (a rigid vertical beam colliding with the rack compared to the operator involved in the incident), the testing in this research shows that the subject incident occurred at a speed on the order of 1 mph, given the greater deflection in the 1 and 2 mph tests.

The authors consulted with another retained expert who analyzed the collision force and speed using a finite element analysis (FEA) of the rack system. The FEA indicated that the collision occurred at a speed between 1.9 mph and 3.0 mph. The FEA utilized assumptions that would produce maximum speeds rather than minimum speeds to consider the upper boundaries of the impact forces and speed. The FEA model was limited to the rack beams and end connections, and did not reproduce the whole system. Considering the FEA and the testing using similar (but not identical) rack components, the authors concluded (using this alternate analysis) that the collision occurred at a speed on the order of 2 mph. Both the testing and FEA analysis show that the collision took place at a low speed/energy level in comparison to a lift truck moving at full speed with a maximum capacity load.

Of foremost importance, the testing performed as a part of this research further shows that the manufacturer's horizontal intrusion protection was effective at a speed of 3.4 mph with a full load. The protection would therefore be effective at higher speeds as well. Since the subject forklift involved in the incident was reportedly operating with a load of approximately 972 pounds, the load used in this testing exceeded the load in the incident. Further, the incident occurred at a speed lower than the maximum test speeds — and at a significantly lower amount of kinetic energy. Even at a higher load, higher impact speed, and higher kinetic energy, the rack beam was held outside of the operator compartment by the post guarding system. Since the rack beam did not significantly intrude in the operator compartment, the volume or space required by the operator was not compromised. **Figures 8** and **9** show that the operator compartment space was maintained during the fourth test at 3.4 mph. Therefore, it is clear that the manufacturer's horizontal intrusion protection system would have prevented the crushing injuries sustained by the operator.

†† Plugging is the process of reversing the directional control (joystick) and using the electric motors to decelerate the forklift.

Figure 8
Operator able to stand inside compartment after fourth test.

Figure 9
Deformed rack beams outside of operator compartment after the fourth 3.4-mph test.

Conclusions

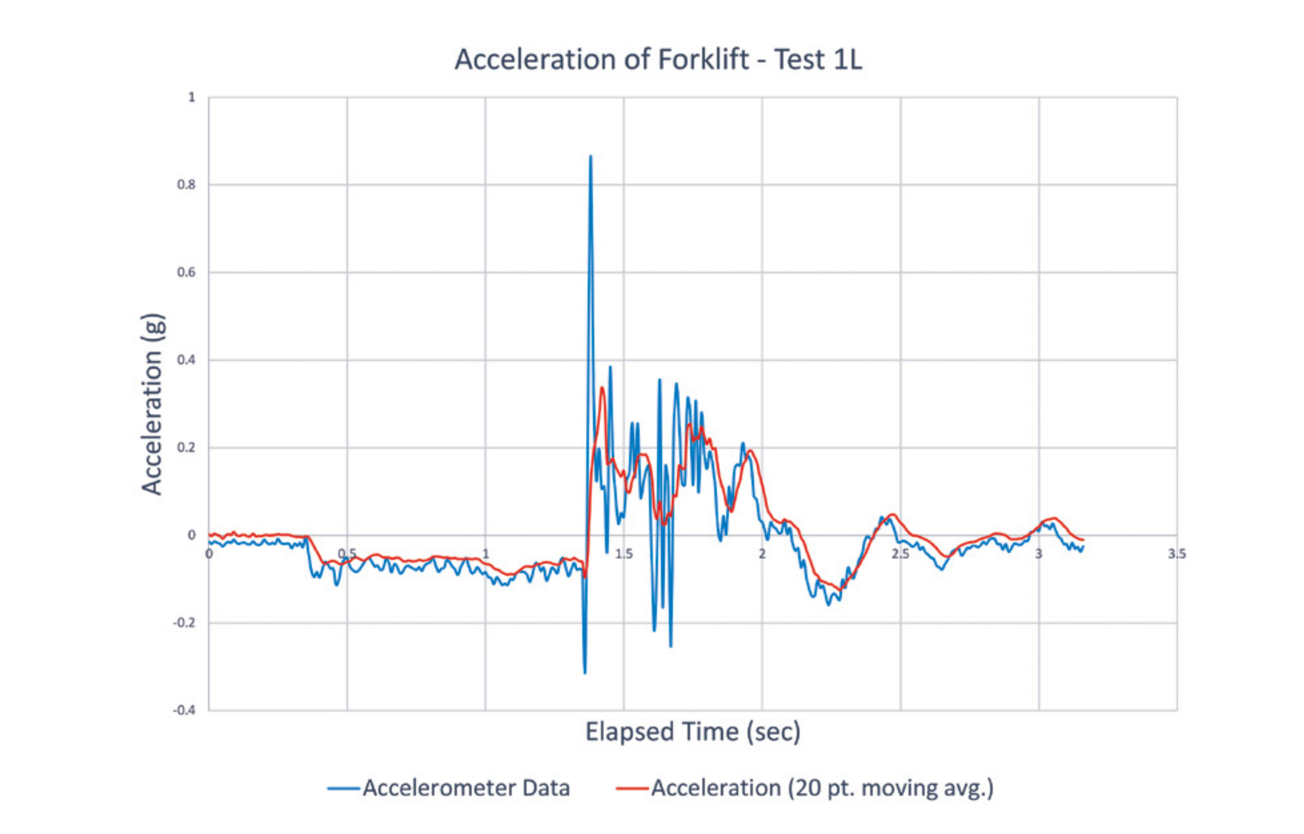
This study evaluated the effectiveness of a horizontal intrusion protection system. The system was found to be effective at preventing intrusion into the operator compartment on a fully loaded forklift at a speed of 3.4 mph — well in excess of the requirements of the ANSI B56.1 standard. The minimal deflection that occurred in the system at a collision speed of 3.4 mph shows that the system would be effective at higher speeds as well. The optional equipment provided by the manufacturer meets and exceeds the B56.1 standard, and provides protection in the event of a horizontal intrusion incident.

The subject incident occurred on a narrow aisle stand-up forklift at a speed on the order of 2 mph with a less-than-maximum load at less than the maximum speed of the forklift. While the optional horizontal intrusion protection offered by the manufacturer for the forklift would not have prevented the subject collision, it would have prevented the operator from being crushed between the rack beam and the forklift.

Appendix A

- Forklift arrival inspection checklist
- Autopsy report
- Sheriff's office news release
- Patient care report
- Sheriff's investigation report
- OSHA investigation
- News article
- Obituary
- Forklift photo index
- Forklift schematics
- Forklift incident news articles
- Incident site photographs

Appendix B



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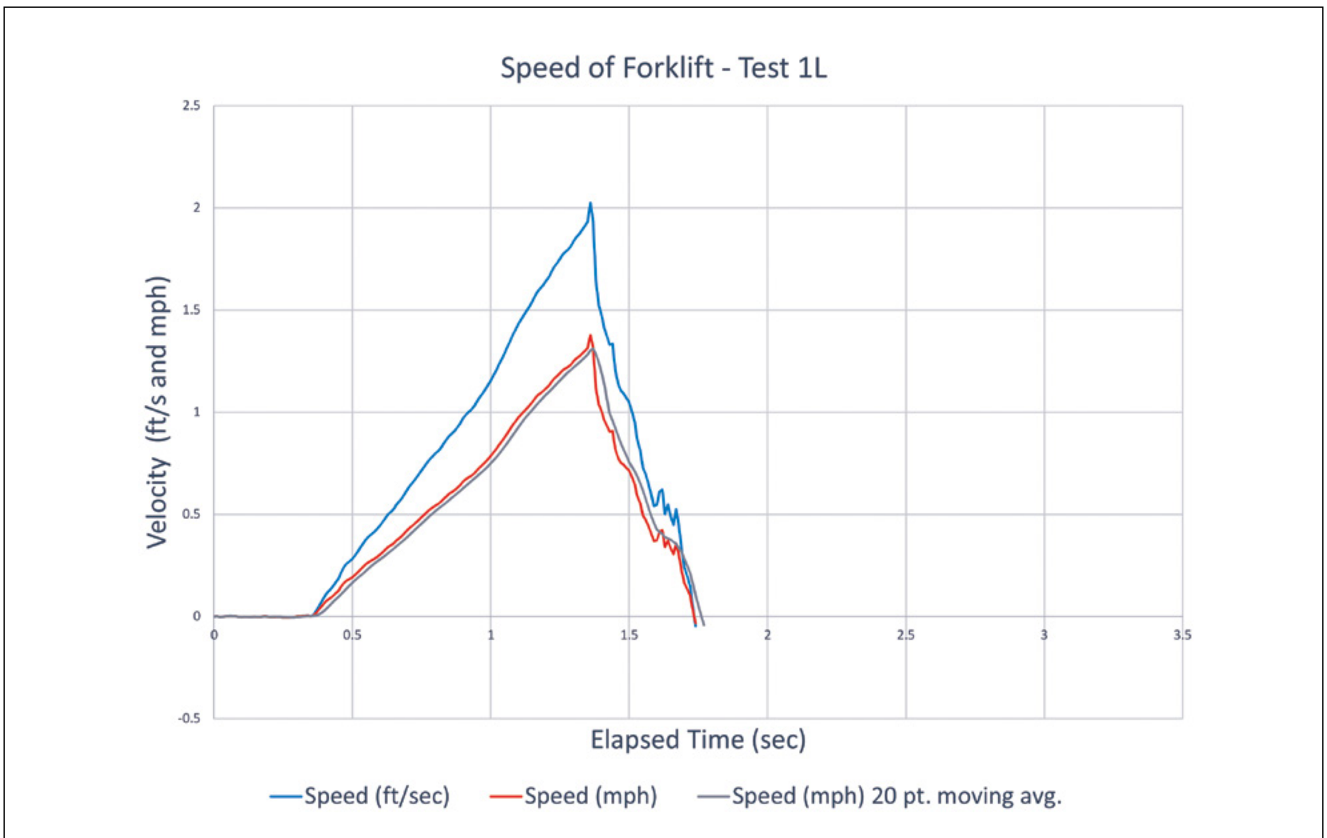

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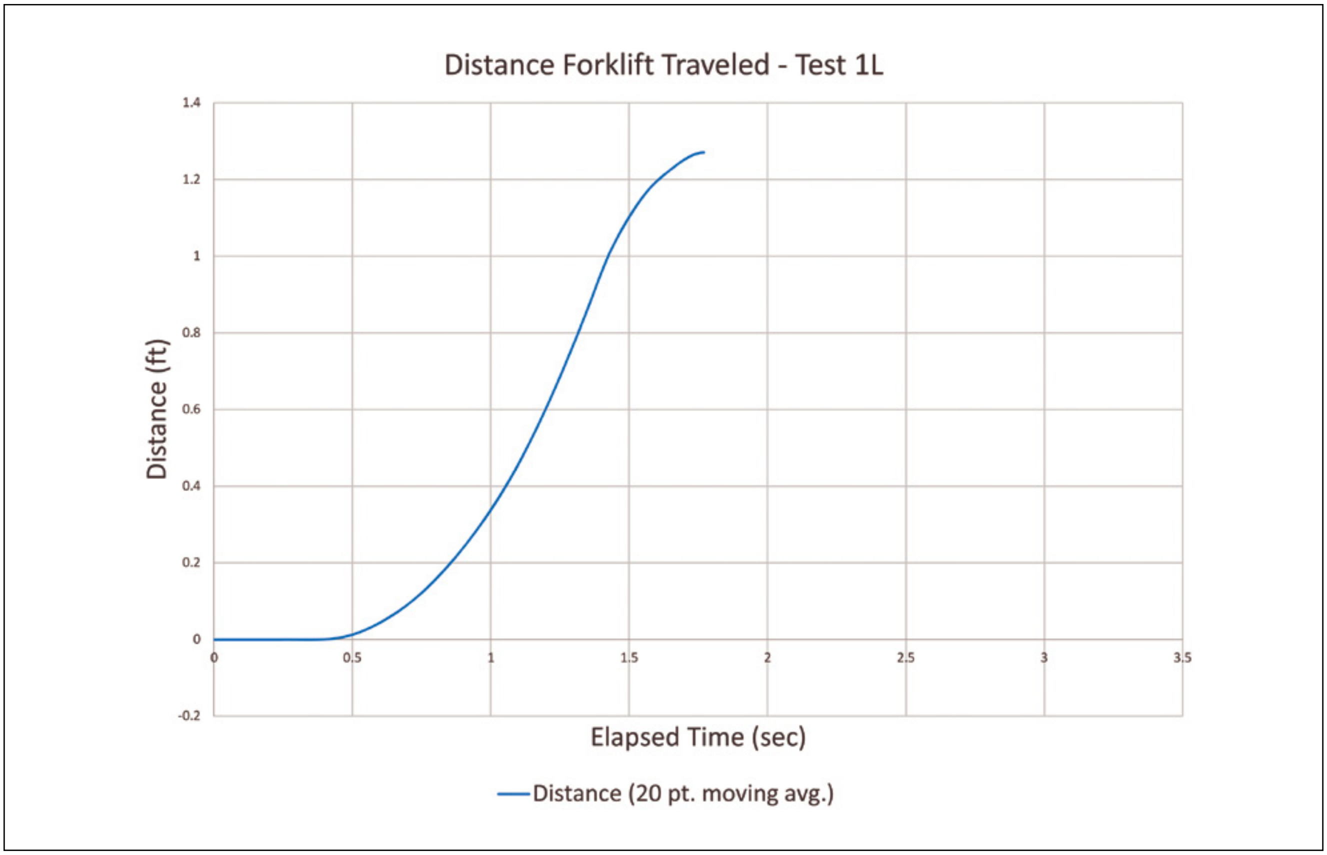

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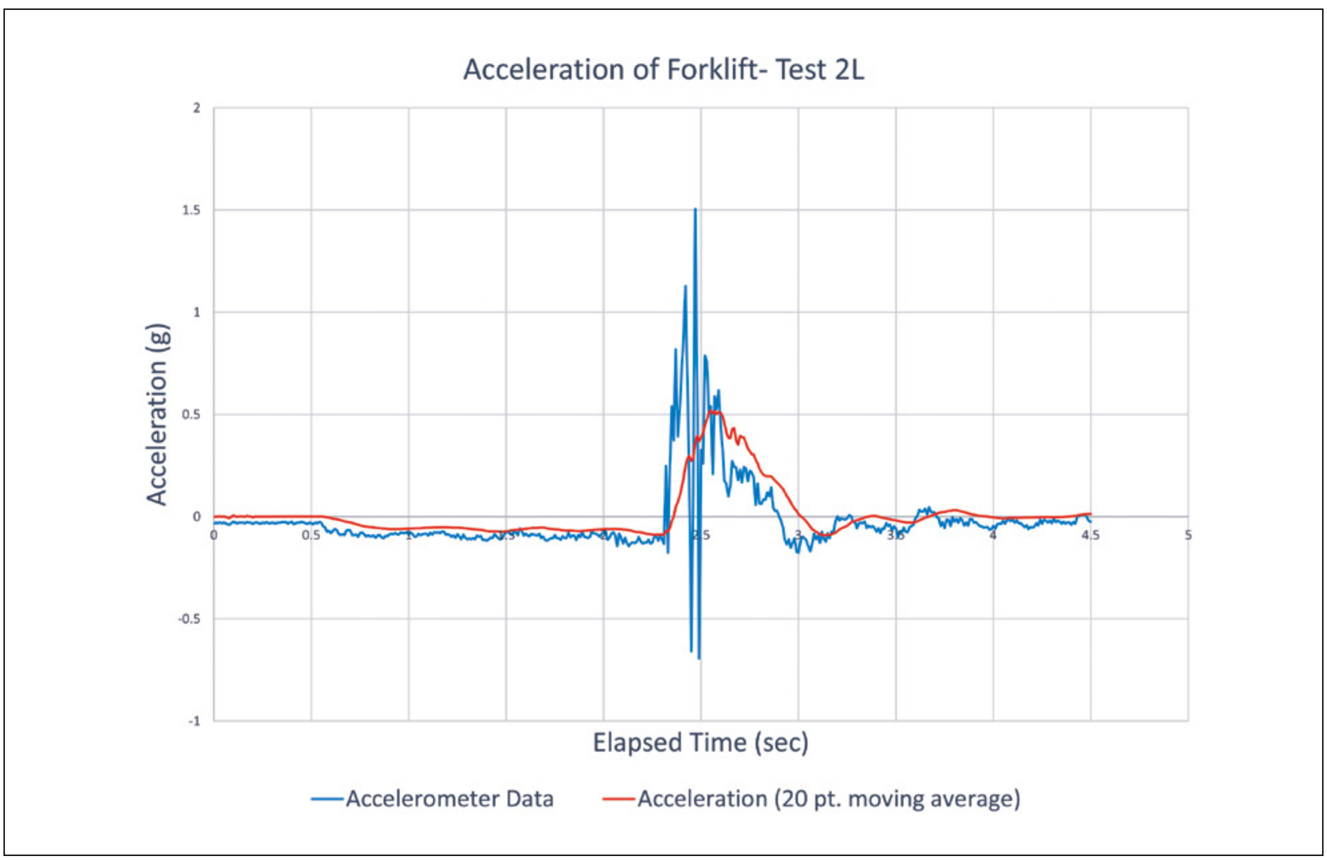

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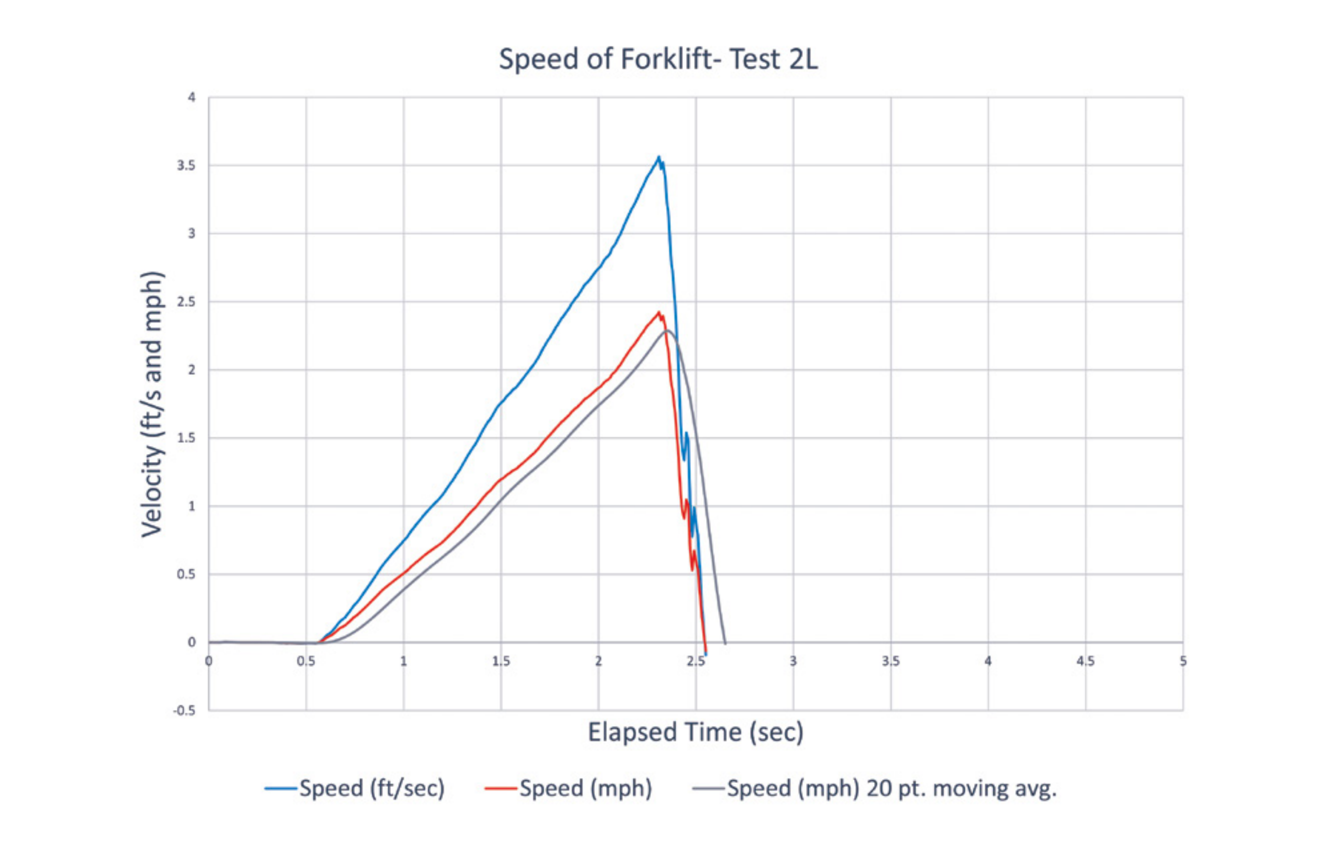

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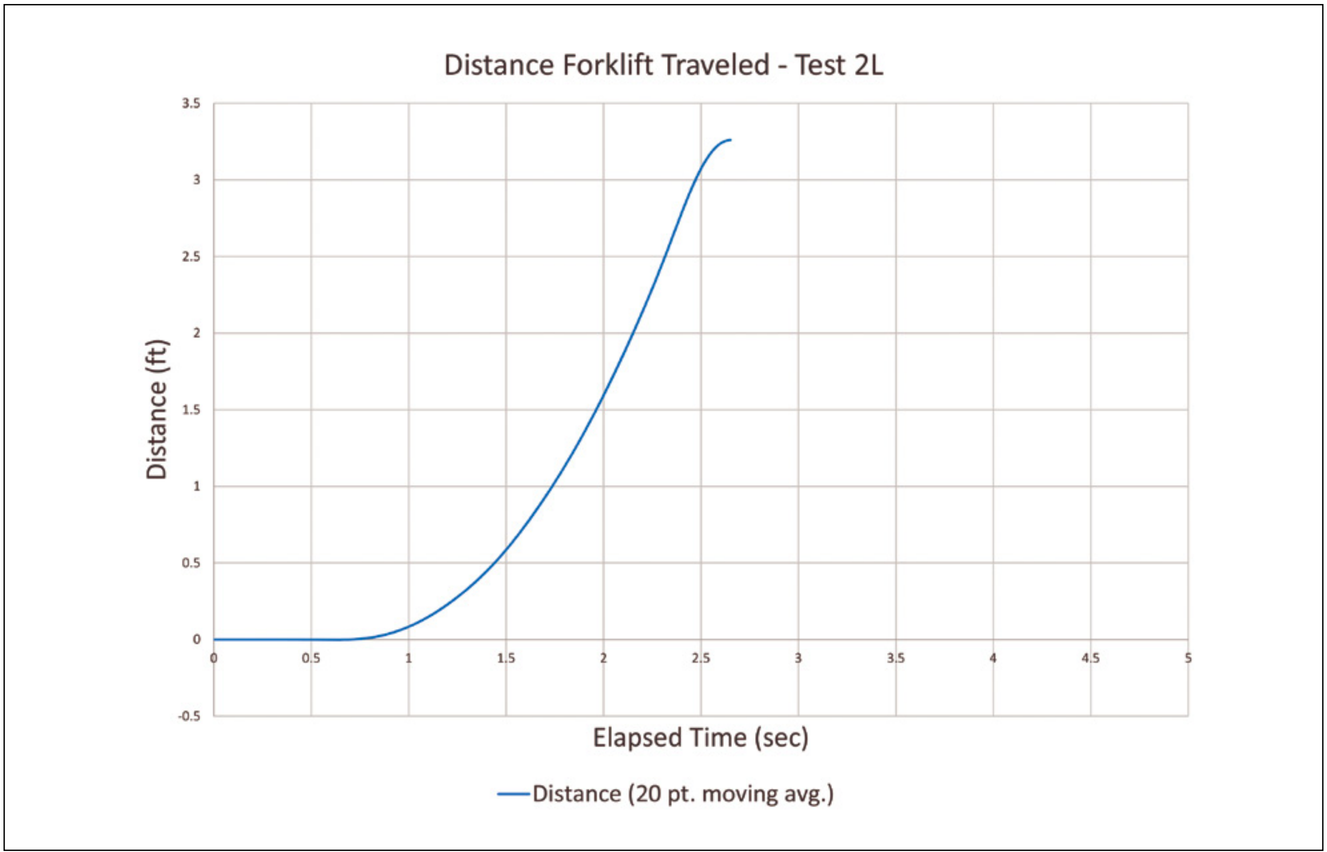

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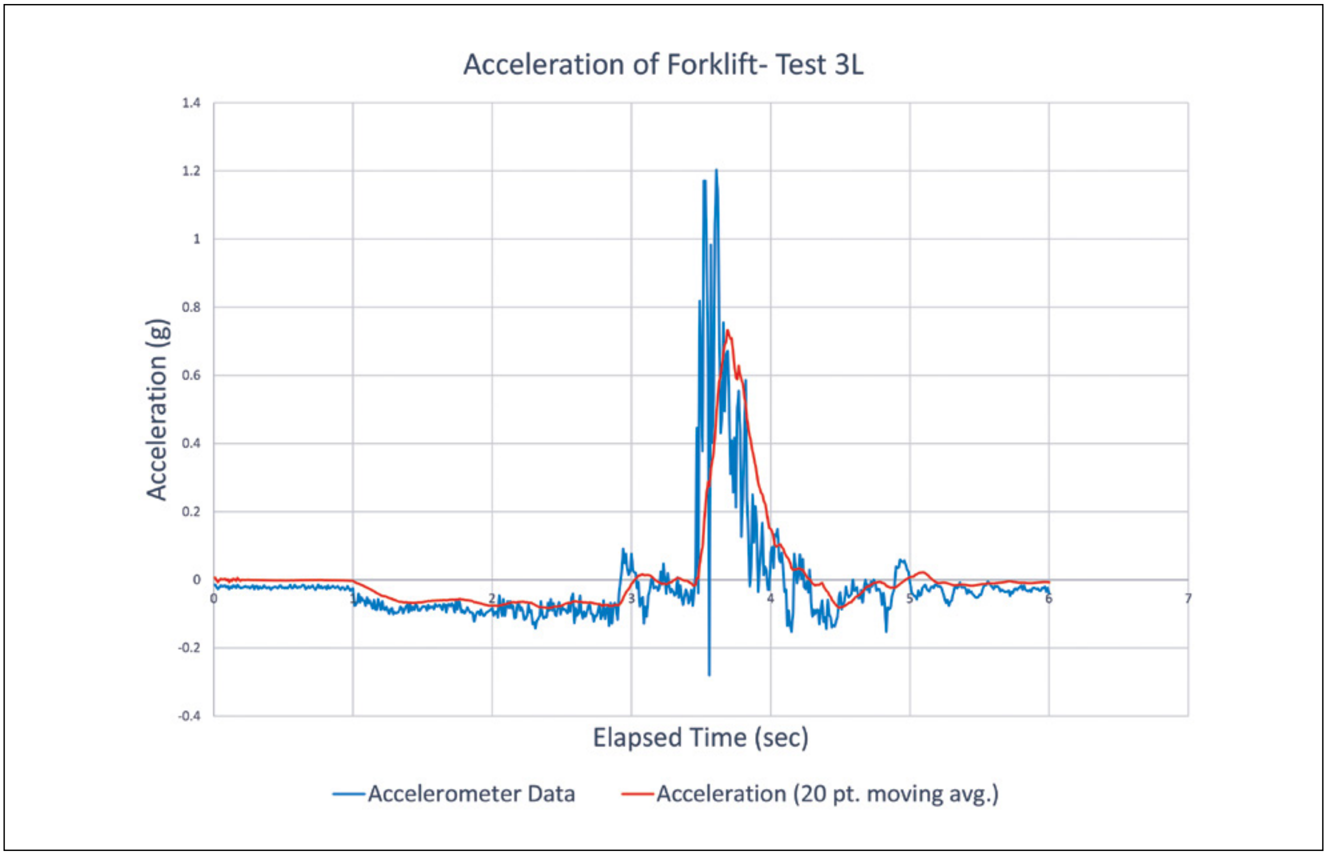

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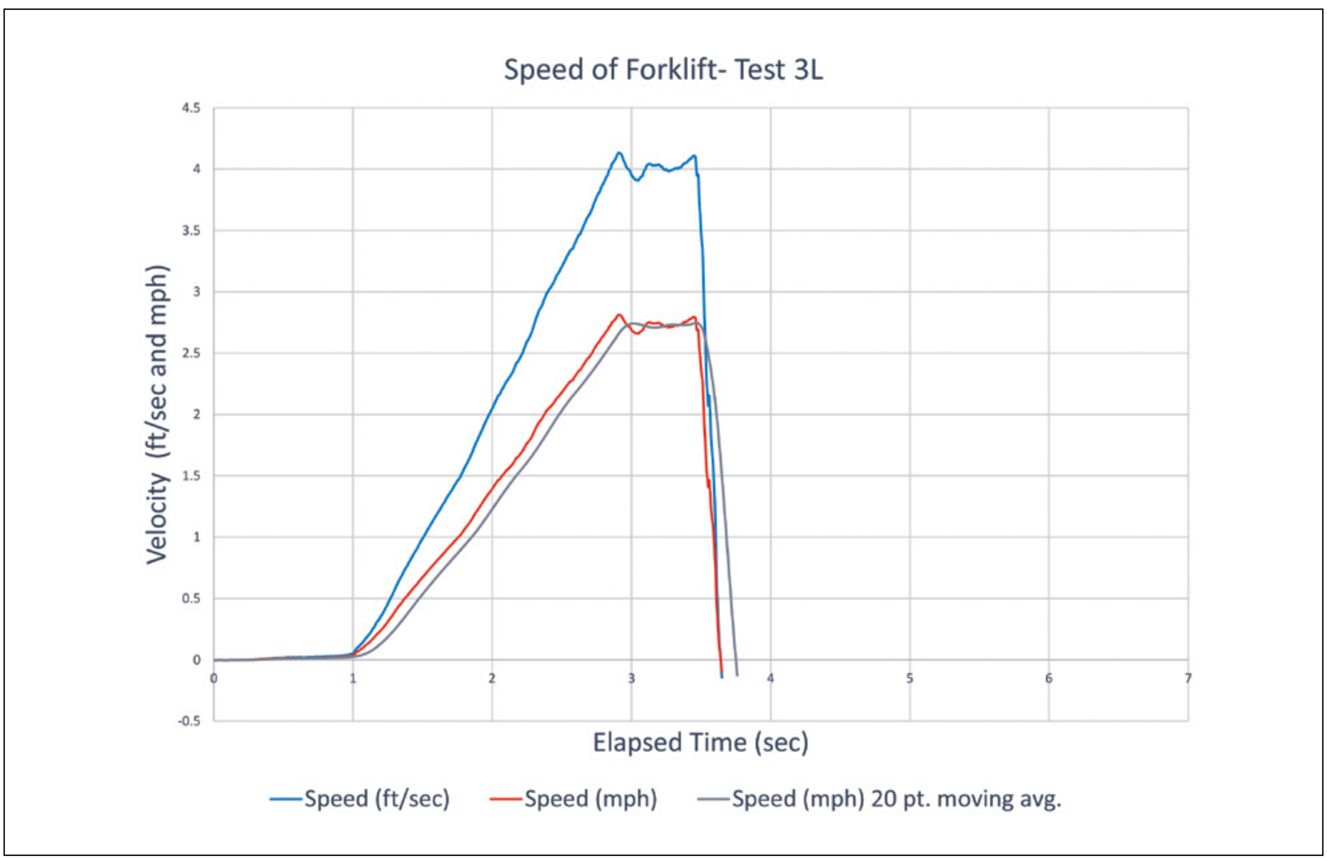

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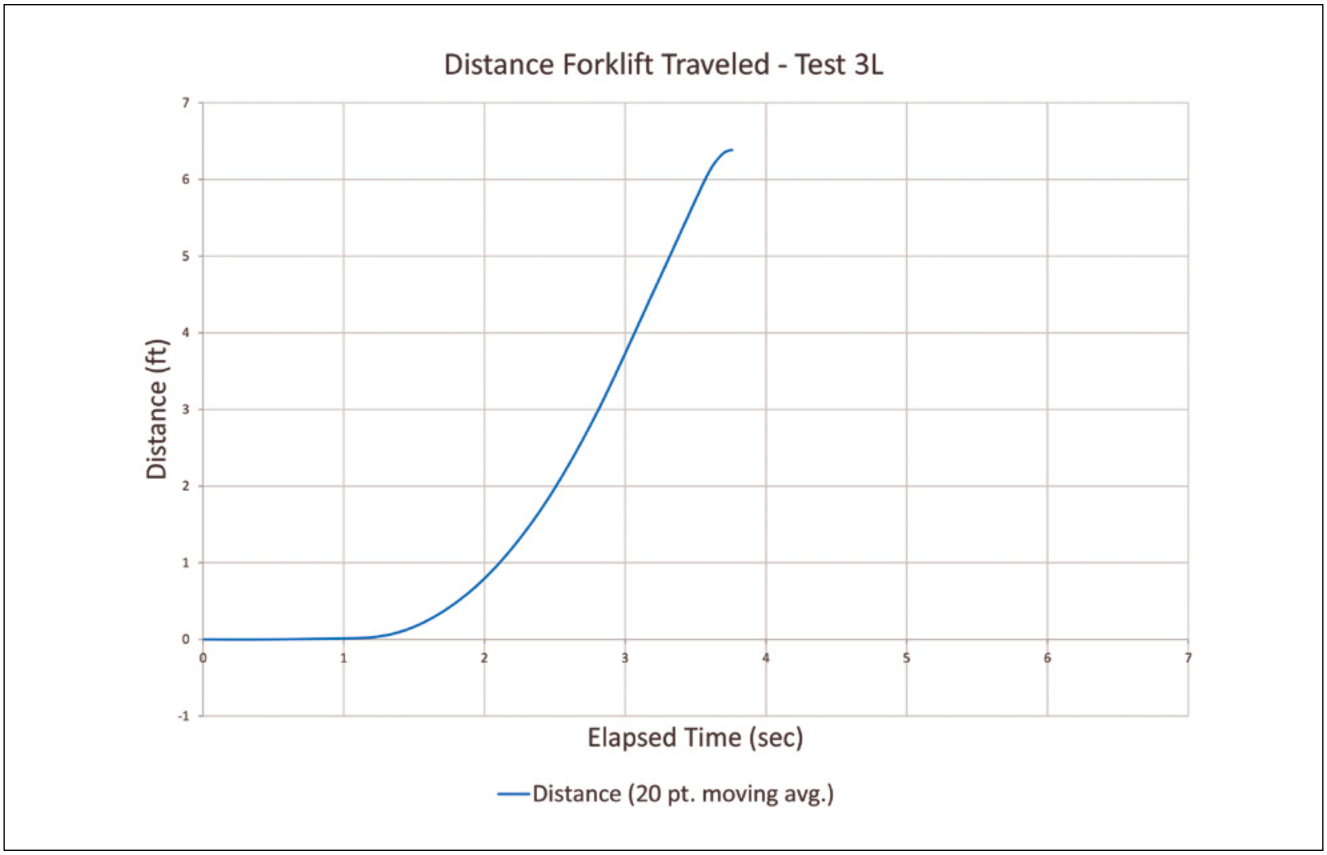

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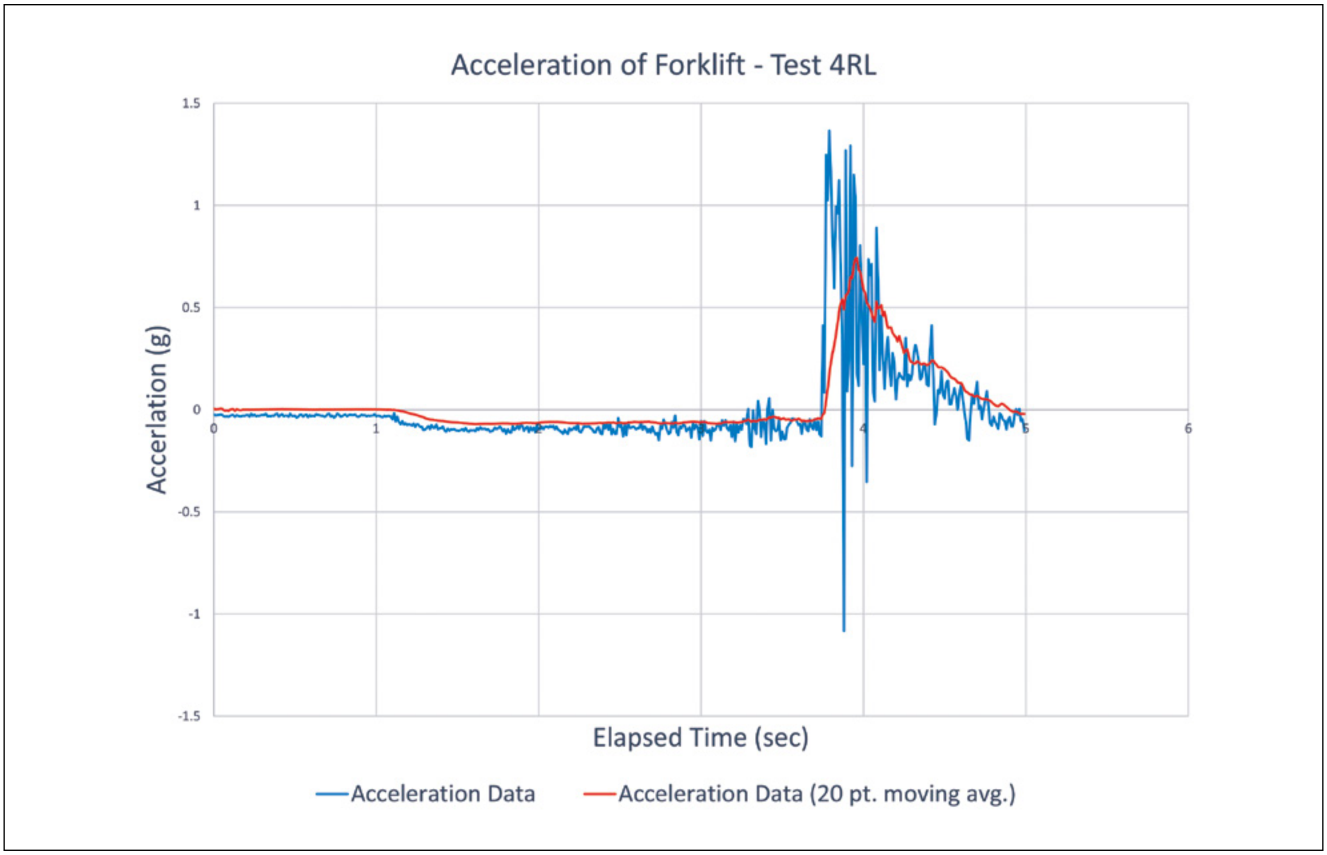
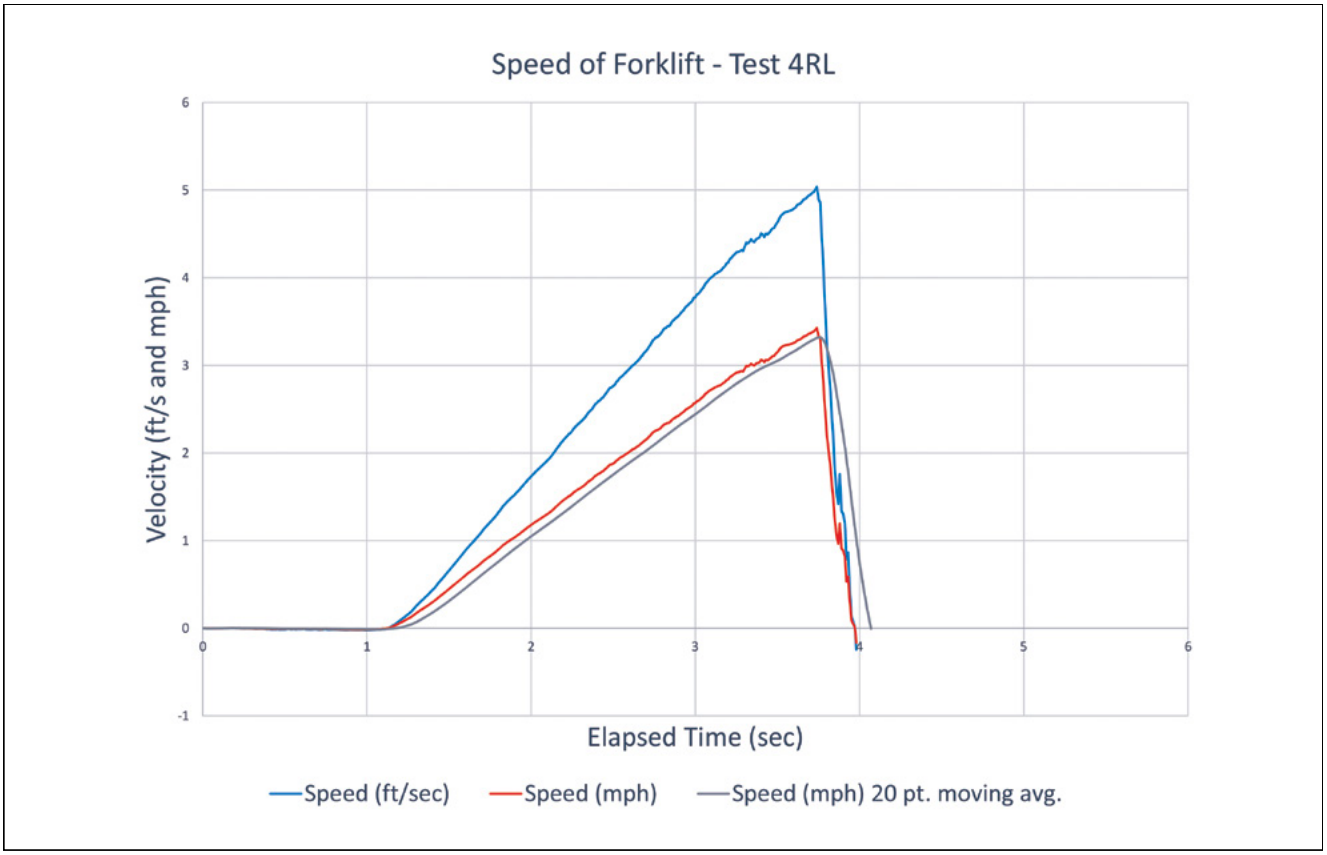
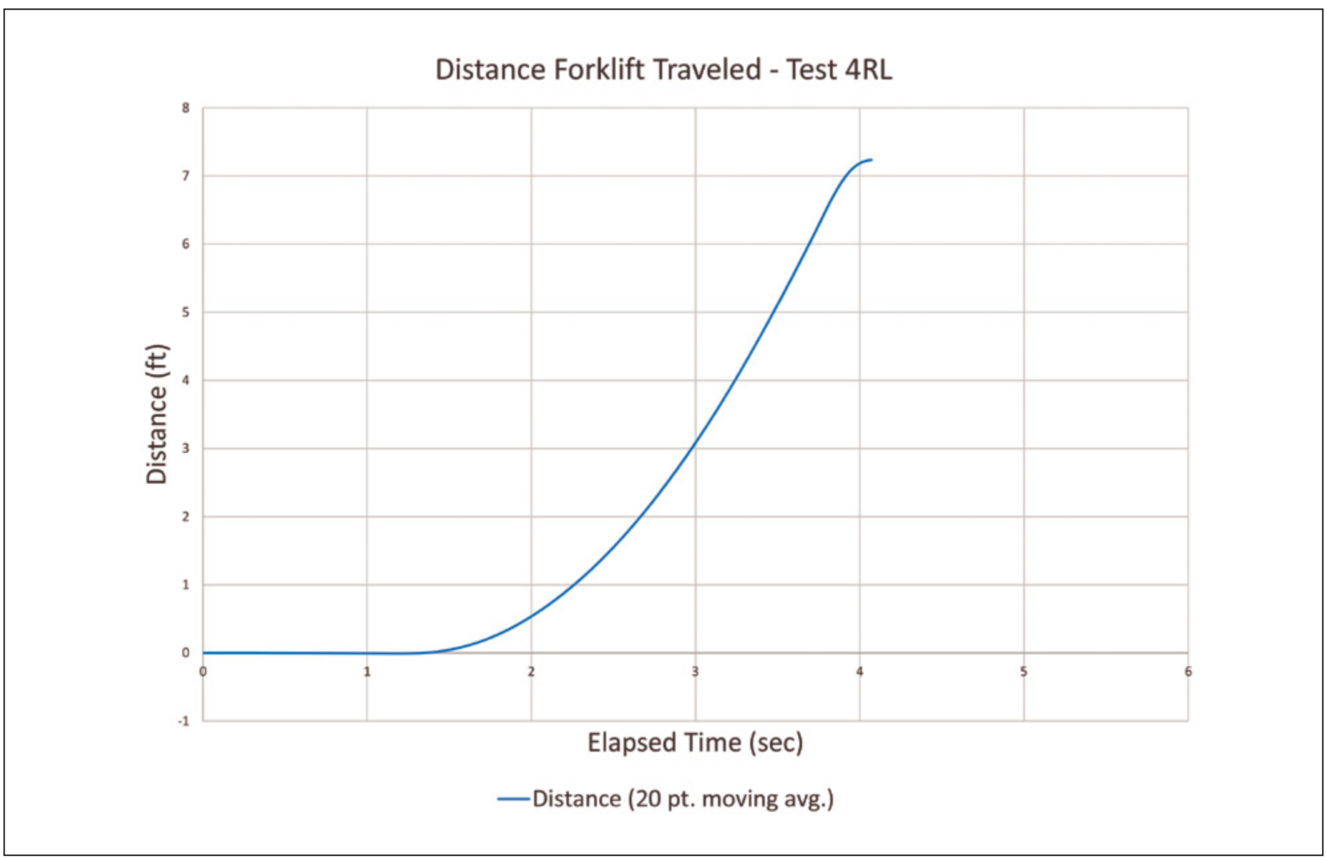


Appendix B-10



Appendix B-11



Appendix B-12

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