ISSN 1041-9489

SAFETY BRIEF

April, 2003 Volume 23, No. 2

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Bumpers / Fenders Used For Low Speed Runover Protection

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ABSTRACT

Because fenders, bumpers, and cowcatchers have been ubiquitous throughout our industrial history they are regularly proposed as safety intervention devices for runover accidents that occur with low speed industrial and construction vehicles. It has been alleged variously that they will protect pedestrians through the mechanisms of deflection, shielding, and tactile feedback. These notions are examined using straddle cranes, road grinders, and road wideners under low speed scenarios (4 mph). Anthropomorphic dummies and volunteers are used to simulate what actually happens to people when hit by various runover protection devices using different ground clearances. People think they are safe if a slow moving vehicle with a bumper, fender, or cowcatcher hits them because they expect to either bounce off of it or be moved out of the way. However, the tests in this paper show that these protection devices actually entrap people; and if the vehicle continues moving, the vehicle rolls right over them. Protection devices with only a few inches of clearance between the device and the ground may snare a person's shoe without entrapping his leg, but his hands and arms are not prevented from being entrapped and then run over.

INTRODUCTION

Industrial and construction vehicles that travel at speeds no greater than 4 mph, a brisk walking speed, will not lead to traumatic impact injuries. On the other hand, these vehicles are capable of running over pedestrians and in some cases, entrapping personnel beneath their bumpers and fenders. It is regularly proposed by safety specialists that the traditional application of fenders, bumpers, and cowcatchers will prevent runover and entrapment injuries by deflecting or moving pedestrians out of the path of the slow moving vehicle after impact. Three intervention systems are often proposed: deflection, shielding, and awareness barriers.

Deflection concepts envision mechanisms that will remove pedestrians from the trajectory of the wheels or tracks of moving vehicles. Shielding concepts provide barrier protection to the inrunning nips formed between the ground and wheels or track mechanisms. The idea is to preclude access of all body parts to the locomotion elements.

The notion of awareness barriers is to activate protective mechanisms of pedestrians to avoid runover or entrapment. Awareness barriers are not investigated in this study.

It has been hypothesized that tactile feedback provided by fenders or bumpers will stimulate an escape response in workers who are facing away from the moving vehicles. The tactile response mechanism will be considered in this paper.

This paper will be published in the Proceedings of the American Society of Mechanical Engineers' 2003 Design Engineering Technical Conferences in September of 2003.

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DEFLECTION DEVICES

Impact (By Forklift)

It is regularly proposed that properly configured bumpers and fenders will bounce pedestrians away from moving vehicles upon impact. Elastic impact theory leads to these bounce away scenarios which are chronicled in mechanics textbooks covering dynamics [1]. Observations, on the other hand, involving impacts with mammals such as dogs, deer, and human beings all indicate that impacts are plastic. That is, the coefficient of restitution is zero. Even bugs do not bounce off a windshield; they go splat. Automobile-pedestrian impacts with cadavers have been recorded in a study where it is noted that the impacting objects remain in contact after the impact [2].

To study vehicle-pedestrian impacts, investigators often employ anthropomorphic crash dummies such as the Hybrid II pedestrian test dummy which have been developed for automobile-pedestrian impact studies [3-6]. To demonstrate that impacts with anthropomorphic models are plastic impacts, a 175.3 cm (69 in.) tall Hybrid II pedestrian anthropomorphic test dummy weighing 172.4 kg (380 lb) was suspended by an eyebolt attached to its head which caused the feet to be raised above the ground by a small clearance. Weight was added to the test dummy to reflect the weight of an actual worker injured in a road widener accident. The suspended anthropomorphic dummy was impacted 15 ways using five different speeds (0.5 mph, 1 mph, 2 mph, 3 mph and 4 mph) and three different bumpers attached to a test rig propelled by a 6245 pound Allis Chalmers model ACE50 forklift. These three bumpers were constructed by another safety specialist to demonstrate the feasibility and efficacy of the bumper concept for protecting a road widener which is a heavy-duty self-propelled shoulder paving machine. The three bumpers are illustrated in Figure 1 which shows a 10.2 cm (4 in.) vertical contact surface with a 74.6 cm (29.375 in.) ground clearance, a 30.5 cm (12 in.) vertical contact surface with a 66.0 cm (26 in.) ground clearance, and a 40.6 cm (16 in.) vertical contact surface with a 43.2 cm (17 in.) ground clearance. In each of the fifteen impacts, the anthropomorphic dummy stayed in contact with the bumper at all times during and after impact. This plastic impact can be contrasted with the predominantly elastic impacts associated with hitting a ball with a baseball bat or a tennis racket. One of the plastic impacts is shown in Figure 2 where three consecutive frames from a video (1/30 of a second) illustrate the behavior at the time of impact.

Deflection Behavior (By Road Widener)

In 2002, the authors investigated the behavior of bumper-pedestrian impacts associated with a 36,600 pound road widener. Using the three bumpers shown in Figure 1, 15 impacts on the 175.3 cm (69 in.) tall Hybrid II pedestrian test dummy weighing 172.4 kg (380 lb) were conducted with the dummy's weight supported primarily by the roadway surface. To stabilize the dummy, its head was held in a vertical position by a suspended cable attached to an eyebolt in the dummy's head. At the moment of impact, this stabilizing cable was released providing a force system made up entirely of gravity, reaction, friction, and impact forces that would normally be associated with pedestrian-vehicle impact. Using the same five speeds and the same three bumpers previously described for the suspended dummy forklift testing, 15 impacts were videotaped and consistently showed increasing vehicle contact with no bounceback during impact followed by leg entrapment and wheel rollover scenarios. Figure 3 displays a typical event sequence during a 4 mph impact of the anthropomorphic test dummy using the bumper illustrated in Figure 1A. It should be observed that the dummy's feet remain in place during the impact which allows the moving machine to eventually entrap the foot in the inrunning nip formed between the ground and the rubber construction wheel. After entrapment, the moving wheel inevitably rolls over the dummy. The phenomenon was

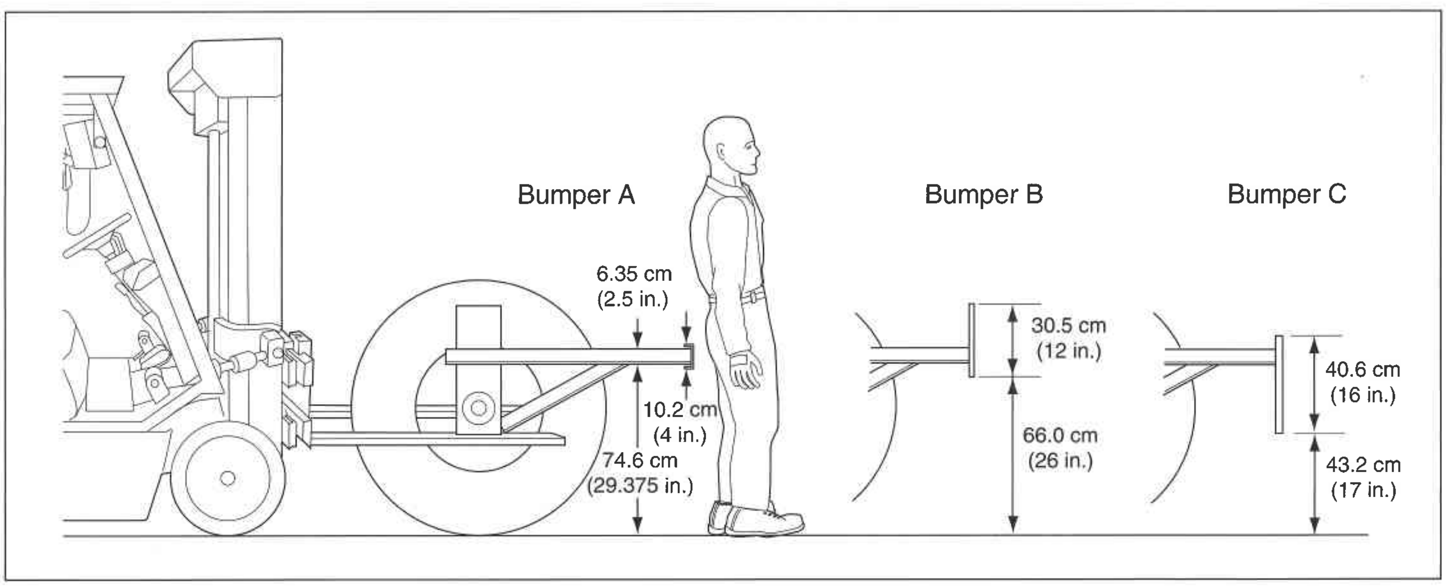

Figure 1 - Road Widener Steel Bumpers and Forklift Test Rig

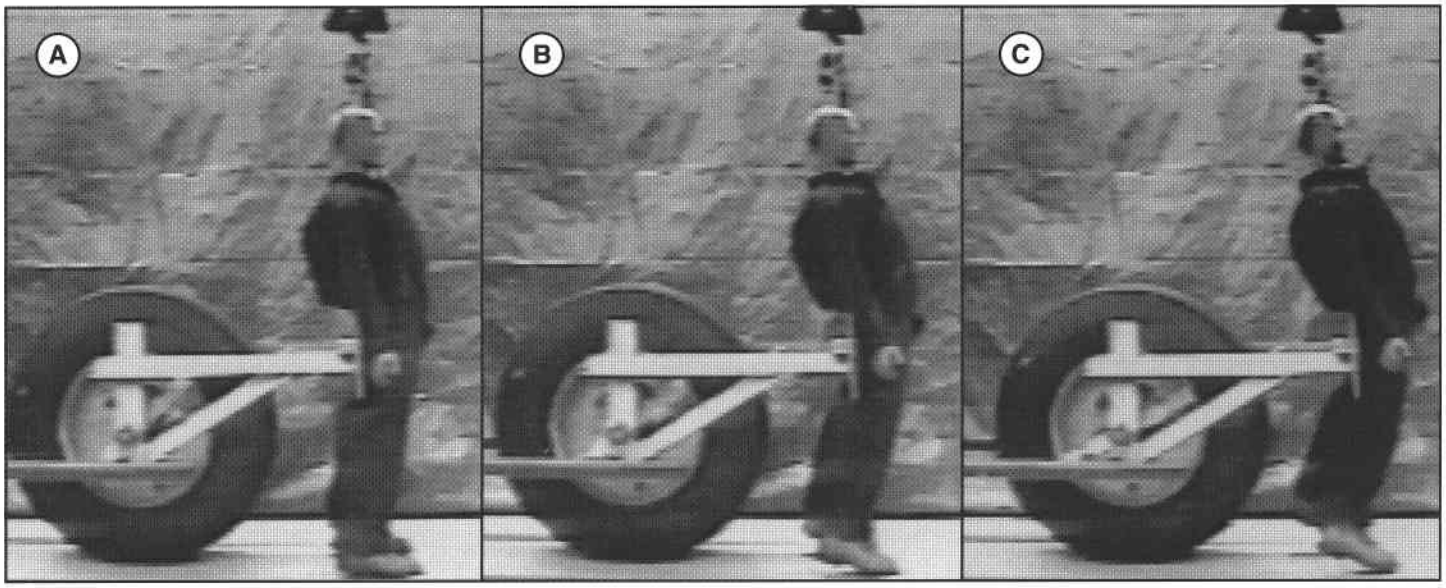

Figure 2 - Road Widener Suspended Dummy - Bumper Impact Sequence

independent of vehicle speed between 0.5 mph and 4 mph and independent of the bumper configuration.

ENTRAPMENT/ROLLOVER

Entrapment Experiments (By Crane and Snowplow)

Straddle Crane. In 1992, a standard 200,000 pound four post straddle crane was used by Dr. James Wingfield at Triodyne Inc. to investigate the efficacy of a standard metal fender which is shown in Figure 4A. This fender was mounted on the straddle crane with a ground clearance of 15.2 cm (6 in.). It was also suspended on a laboratory test rig with the same ground clearance. Pedestrian-vehicle impact scenarios were studied in the field and in the laboratory using an impact speed of 3.4 mph. In those tests which used an anthropomorphic model, the dummy was supplied by First Technologies Systems and represented a male workman weighing 72.6 kg (160 lb) at a height of 177.8 cm (70 in.). Figure 4 illustrates a typical pedestrian-fender impact sequence where it is observed in Figure 4B that the ankle is entrapped between the bottom of the fender and the ground. It should be observed that the torso has not bounced forward off the fender. Figure 4C indicates that the 15.2 cm (6 in.) ground clearance enables the crane to roll over the crash dummy.

A laboratory test rig supported the standard fender on pneumatic cylinders with a 61.0 cm (24 in.) horizontal stroke. Using the 15.2 cm (6 in.) ground clearance and a 3.4 mph impact velocity with both an anthropomorphic dummy and human subjects, the laboratory rig produced the same entrapment mode experienced in the field tests illustrated in Figure 4. When the test rig was outfitted with a slant back guard under the same field and laboratory test conditions as previously described, the entrapment mode was identical to

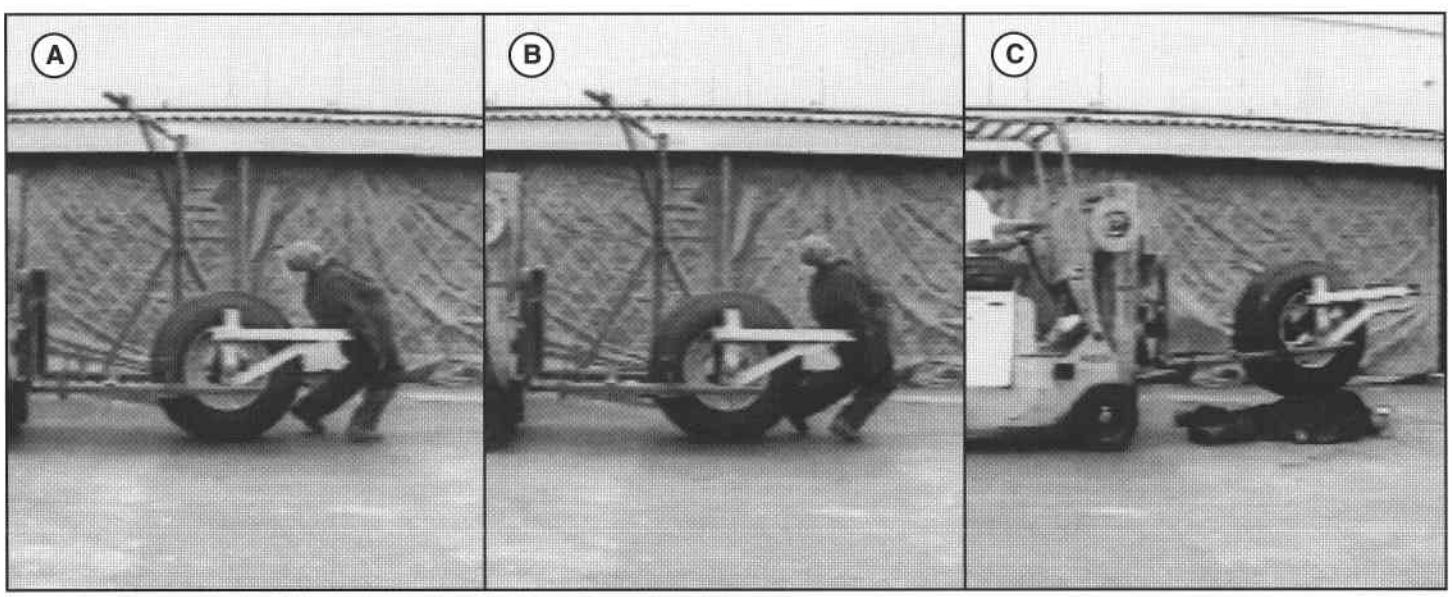

Figure 3 - Road Widener Released Dummy - Bumper Impact Sequence

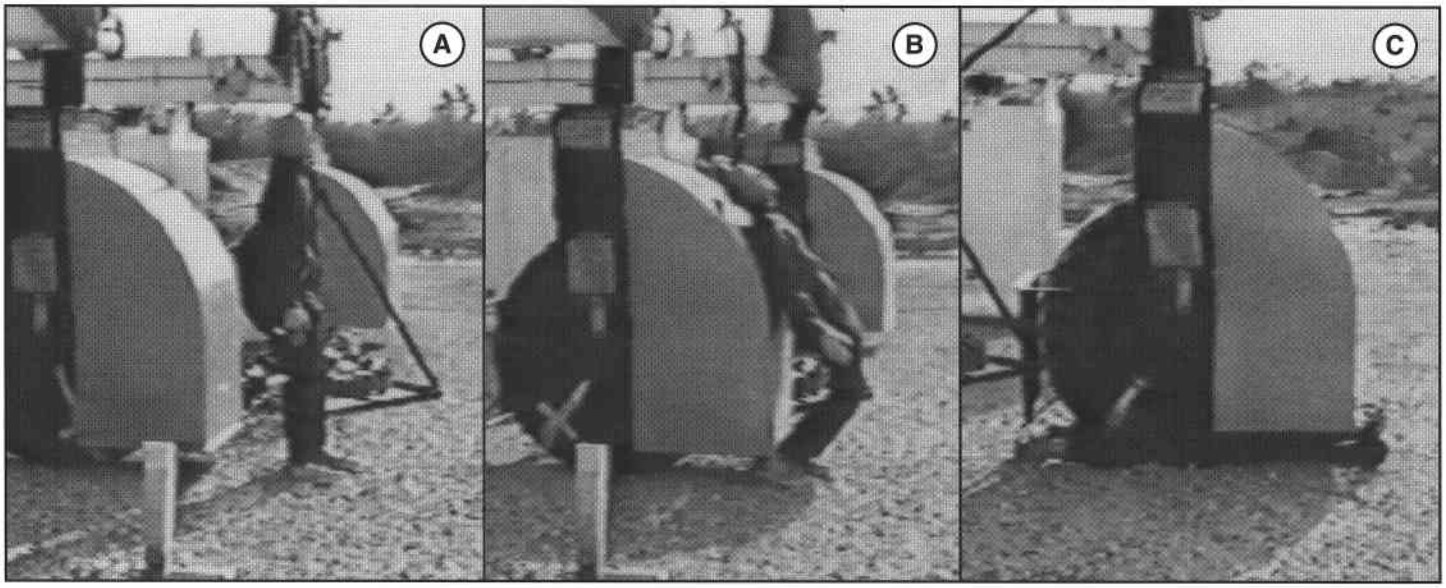

Figure 4 - Straddle Crane Pedestrian - Fender Rollover Sequence

the standard guard as illustrated in Figure 5. With a 15.2 cm (6 in.) ground clearance, the standard guard and the slant back guard fail decisively.

The slant back guard tests were repeated with a triangular bumper with a cowcatcher type leading edge in order to examine the hypothesis that a snowplow type action would occur, moving pedestrians sideways out of the vehicle path. Under rear central impact conditions, the inboard leg was first contacted and trapped beneath the slanted leading edge of the cowcatcher. This caused the human subject to fall further into the vehicle path with exactly the opposite effect than was desired.

Road Grinding Machine. In 1999, an 80,000 pound road grinding machine propelled on tracks was studied by Michael Dilich at Triodyne Inc. in a pedestrian-fender impact investigation. A wooden fender was constructed as illustrated in Figure 6A. This fender was mounted on a 6245 pound forklift with ground clearances of 5.1 cm (2 in.), 20.3 cm (8 in.), and 30.5 cm (12 in.). This test rig was utilized to impact a Hybrid II 50th percentile pedestrian anthropomorphic test dummy and a human subject at 1.4 mph and 3.4 mph. The anthropomorphic dummy was impacted centrally where both legs were simultaneously contacted and also in an offset condition where only one leg was impacted. The human subject was only used in the central impact testing. At the moment of impact, the dummy was supported with its full weight on an asphalt pad and it was hand stabilized from lateral movement by a technician who released the dummy upon impact. In every case, the 20.3 cm (8 in.) and 30.5 cm (12 in.) ground clearance tests exhibited the same entrapment mode experienced by the road widener bumpers and the straddle crane fender. As shown in Figure 6, with a 5.1 cm

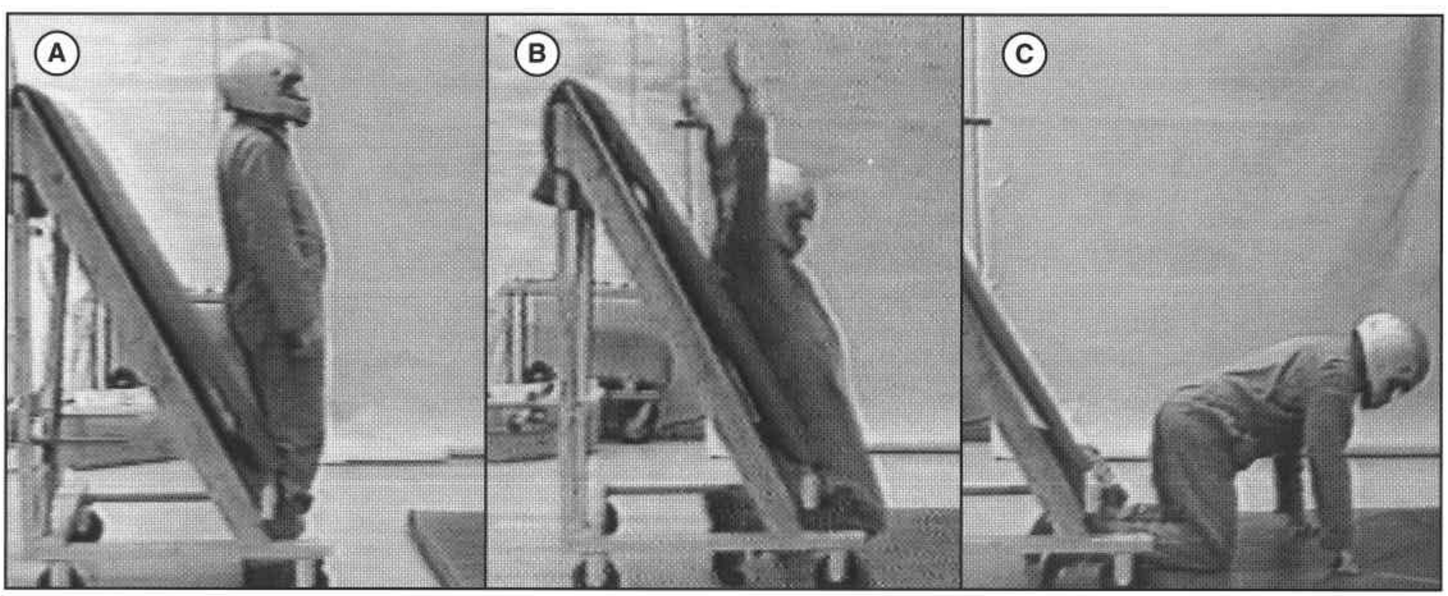

Figure 5 - Slant Back Guard - Human Subject Entrapment Sequence

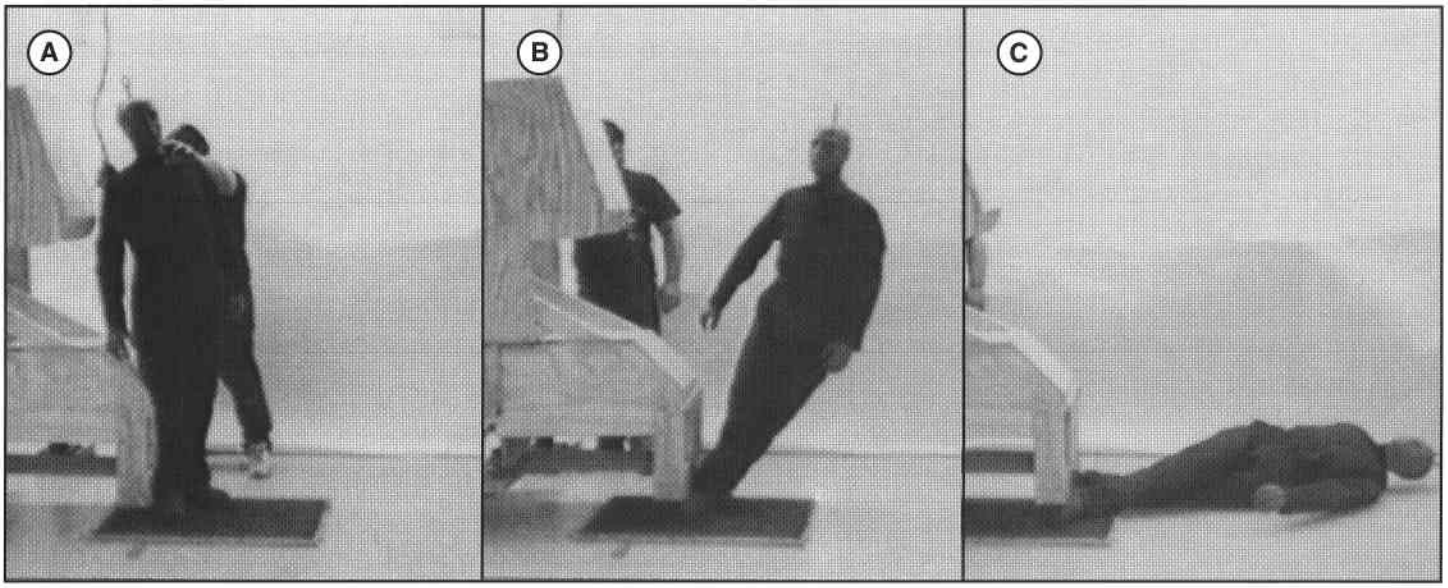

Figure 6 - Road Grinder Fender - Dummy Entrapment Sequence

(2 in.) ground clearance and a 1.4 mph impact speed, the fender entraps the dummy's shoe and slides it along the ground. This action causes the dummy to fall in front of the fender. The total entrapment of one or both of the dummy's shoes occurred during rear central impact, side central impact (facing perpendicular to the line of travel), and offset impact (where only one leg was struck). The experiments were terminated immediately after the anthropomorphic dummy fell to the ground.

Shielding (Inrunning Nip Tests)

In the vehicle scenario, a fallen pedestrian has a stationary hand which is approached by the inrunning nip. In machine guarding, one normally visualizes a roller or conveyor element carrying the hand into an inrunning nip. The relative motion is identical. If the vehicle operating surface is flat, the openings recommended by the available formulas will allow a fixed penetration beneath the fender and the arm and torso will be pushed along in front of the vehicle. The available formulas which address the geometry of the hand and arm will clearly preclude the penetration of the human foot, especially with footwear. Indeed, even larger clearances between the operating surfaces and the bottom surface of the bumper or fender will effectively prevent entrance and entrapment of the foot. An impact using an 80,000 pound road grinding machine whose track has been retrofitted with a deployable steel fender is depicted in Figure 7. The leading edge ground clearance was set at 1.9 cm (0.75 in.) and in every trial the anthropomorphic dummy was pushed in a sliding fashion in front of the moving vehicle. Unfortunately, the terrains encountered by construction equipment are highly irregular which precludes small ground clearances such as 1.9 cm (0.75 in.). It should be recalled from the laboratory studies of the road grinder that a 5.1 cm (2 in.) ground clearance entraps the ankle, throws the dummy to the ground, and pushes the dummy in front of the vehicle. Hence, a 5.1 cm (2 in.) ground clearance will prevent wheel rollover if the operator's feet are contacted, but will engulf a hand and an arm consistent with the predictions of the guard opening formula.

Barrier Guard Openings - Theoretical

Barrier guards which are used to protect people from rotary machinery often incorporate openings which allow workpieces to be inserted into the points of operation. These openings also allow an operator's hand to reach a fixed distance inside of the guard before the hand is restrained by the opening. The relationship between the guard opening and the safe distance that the hand can be inserted was reported in 1943 by the Royal Society for the Prevention of Accidents in London by using the following formula [7]:

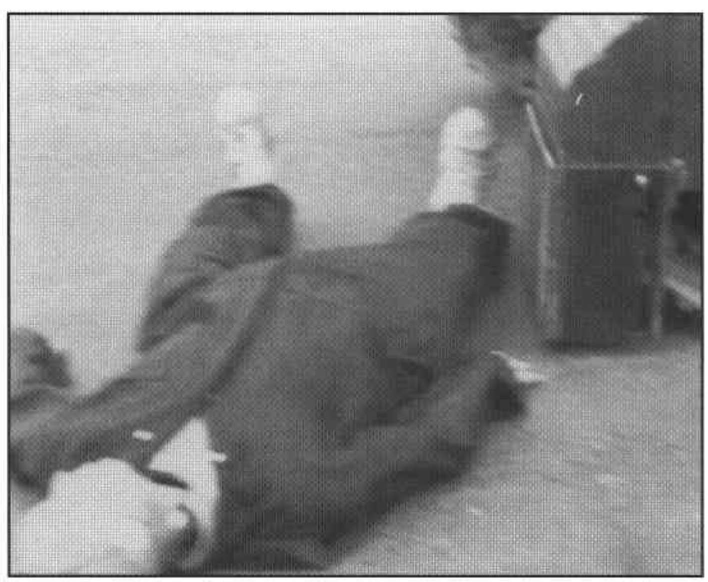

Figure 7 - Road Grinder Steel Fender
(0.75 in. ground clearance)

Maximum Safe Opening =

$$1/4 \text{ in.} + \frac{\text{Distance of Guard from Danger Zone}}{8}$$

This relationship was revisited by the National Association of Mutual Casualty Companies in 1949 as reported by the American Mutual Insurance Alliance in Technical Guide No. 2 in May of 1966 [7]. After a considerable amount of anthropometric testing, this technical guide developed a safe opening-distance away from hazard relationship that was based on a woman's hand of a 6-1/2 glove size. The relationship is normally reported graphically and has been adopted by most of the consensus standards and regulatory standards in the United States.

TACTILE FEEDBACK

It is theoretically possible for a pedestrian who is contacted in the rear by a bumper system to respond to the tactile feedback in such a way that running before the slow-moving vehicle provides an escape strategy. Indeed, this hypothesis is always viable if the vehicle moves at a sufficiently slow speed. On the other hand, it is necessary to investigate the tactile feedback/escape strategy under walking speed impacts.

Another safety specialist hypothesized the viability of the tactile system and attempted to demonstrate its effectiveness by constructing a wooden test rig with the same bumper configurations illustrated in Figure 1. The rig incorporated a rear wheel from a road widener into a wheelbarrow-type vehicle manually propelled by a technician. The bumper was propelled symmetrically into the rear of three volunteers whose incentive was to move rapidly forward away from the rig upon impact. The scenario was videotaped with frames every 1/30 of a second which allowed the determination of the impact speed immediately before impact and the escape speed immediately after impact. A typical sequence is illustrated in Figure 8. In all 10 cases, the pedestrians would not have escaped the bumper had the test rig continued at a constant speed. Because the masses of the pedestrians and the rig were the same order of magnitude, the test rig slowed down significantly upon impact, allowing a gap to form between the bumper and the pedestrian as shown in Figure 8C. Real construction vehicles are massive and will undergo nearly no speed change during pedestrian impact.

CONCLUSIONS

1. All of the low speed impact scenarios led to plastic impact behavior among the wood and steel bumpers and fenders, crash dummies and human subjects, and test rigs and actual machines in investigations involving road wideners, straddle cranes, and road grinders. For machine speeds that mimic normal walking, tactile impact does not provide sufficient warning time for pedestrians to safely clear the trajectory of the vehicle. This is especially true for workmen involved in multi-tasking which increases their response time over those measured in the reported study which involved a single stimulus [8].

2. At ground clearances above 5.1 cm (2 in.), the legs of anthropomorphic dummies and test subjects were trapped between the ground and leading edges of bumpers and fenders mounted on both test rigs and actual machines employed in the reported investigations of road wideners, straddle cranes, and road grinders. If the leg is entrapped and the vehicle continues moving, the vehicle will run over the person's leg.

3. Using a 5.1 cm (2 in.) ground clearance, an operator's leg will not be entrapped, but a hand or arm could be entrapped and then run over.

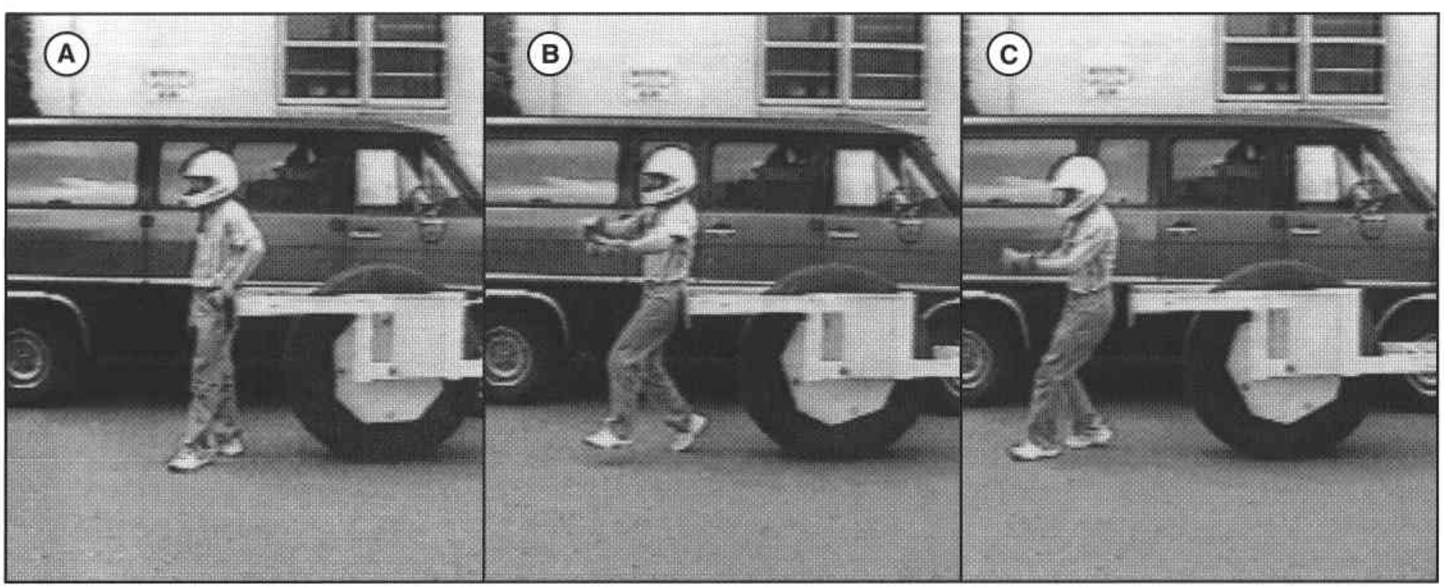

Figure 8 - Tactile Feedback Bumper - Pedestrian Impact Sequence

4. Designers must be constantly aware of potential downsides associated with bumpers and fenders. According to the Dependency Hypothesis [9 – 10], ineffective bumpers and fenders give rise to a false sense of security which causes workers to relax their personal vigilance in the vicinity of wheeled and tracked locomotion elements.

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ACKNOWLEDGMENT

Dr. James Wingfield is a Senior Reliability and Safety Engineer at Triodyne Inc. and has investigated the efficacy of fenders on a straddle crane. Mr. Michael Dilich is a Principal Scientist at Triodyne Inc. and has studied pedestrian-fender impacts on a road grinding machine. The authors would like to acknowledge the technical contributions of Dr. Wingfield and Mr. Dilich on this project.

SAFETY BRIEF

April, 2003 – Volume 23, No. 2

Editor: Paula L. Barnett

Illustrated and Produced by

Triodyne Graphic Communication