A New Energy-Absorbing High-Speed Safety Barrier

John D. Reid
University of Nebraska
N104 WSEC (0656)
Lincoln, NE 68588
Phone: (402) 472-3084
Fax: (402) 472-1465
jreid@unl.edu

Ronald K. Faller
University of Nebraska
1901 Y, Bldg C (0601)
Lincoln, NE 68588
Phone: (402) 472-6864
Fax: (402) 472-0506
rfaller1@unl.edu

Jim C. Holloway
University of Nebraska
1901 Y, Bldg C (0601)
Lincoln, NE 68588
Phone: (402) 472-9464
Fax: (402) 472-0506
jholloway@unl.edu

John R. Rohde
University of Nebraska
W348 NH (0531)
Lincoln, NE 68588
Phone: (402) 472-8807
Fax: (402) 472-2022
jrohde@unl.edu

Dean L. Sicking
University of Nebraska
W348 NH (0531)
Lincoln, NE 68588
Phone: (402) 472-9332
Fax: (402) 472-2022
dsicking@unl.edu

Transportation Research Board
82th Annual Meeting
January 12-16, 2003
Washington, D.C.

Duplication for publication or sale is strictly prohibited
without prior written permission
of the Transportation Research Board

November 13, 2002

Words = 4312, 2 Tables + 10 Figures = 3000          Total Equivalent = 7312
ABSTRACT

For many years, containment for errant racing vehicles traveling on oval speedways has been provided through the use of rigid, concrete containment walls placed around the exterior of the tracks. However, accident experience has shown that serious injuries, and even fatalities, may occur as a result of vehicular impacts into these non-deformable barriers. Because of these injuries, the Midwest Roadside Safety Facility at the University of Nebraska-Lincoln was sponsored by the Indy Racing League and Indianapolis Motor Speedway, and later joined by NASCAR, to develop a new barrier system that would improve the safety of drivers participating in auto racing events. Over the course of the project, several barrier prototypes were investigated and evaluated using both static and dynamic component testing, LS-DYNA computer simulation modeling, and a total of 20 full-scale vehicle crash tests. The full-scale crash testing program included bogie vehicles, small cars, a full-size sedan, as well as actual IRL open-wheeled cars and NASCAR Winston Cup cars. For the race car impact tests, typical impact speeds and angles ranged approximately between 190 to 245 km/h (120 to 150 mph) and 20 to 25.6 degrees, respectively. During this research effort, a combination steel tube skin and foam energy-absorbing barrier system, referred to as the SAFER barrier, was successfully developed. Subsequently, the SAFER barrier was installed at the Indianapolis Motor Speedway in advance of the running of the 2002 Indy 500 mile race. From the results of the laboratory testing program as well as from the accidents occurring into the SAFER barrier during practice, qualifying, and the race, the SAFER has been shown to provide improved safety for drivers impacting the outer walls. An overview of this research effort is contained herein. Additionally, several possible roadside or highway applications utilizing the new technology are identified.

Keywords: Racetrack Safety, Racetrack Barrier, Energy-Absorbing Barrier, High-Speed Crash Testing
INTRODUCTION

In recent years, automobile racing has arguably become one of the most popular sporting venues in the United States as well as internationally. This fact is evidenced by the number of weekend races, large fan-based support, corporate sponsorship, and the around-the-clock cable television coverage. Furthermore, this fact can be seen by the variety of race series available to both drivers and spectators, including the IRL, NASCAR, Formula 1, CART, and IROC to name a few.

For most of these race series, high-performance cars, and now even various truck classes, typically travel several hundred times around oval shaped tracks at very high speeds. For the larger ovals, which include banked corners, vehicle speeds for the open-wheeled type vehicles attain or exceed 370 km/h (230 mph).

Consequently, these higher speeds have increased the potential for more dramatic accidents, injuries, and occasional fatalities. As a result, the need for increased track safety for the drivers as well as the spectators has become more apparent. Historically, some of the early races were conducted without safety barriers around the raceways. This is still evidenced today on several smaller dirt tracks where steep banking is the only source of notable protection or containment. However, over time, track owners for most of the high-speed facilities have recognized the need for safety barriers. For drivers, this has resulted in the installation of rigid concrete walls on ovals and steel or tire barriers on other road courses. For spectators, tall chained-linked and cable combination barriers have been constructed above or adjacent to the rigid barriers in order to provide containment of the vehicle debris during an accident.

For the most part, these safety features have provided considerable protection; however, serious injuries and fatalities to the drivers and fans are still occurring. Therefore, the need still exists to provide improved safety to those participating in the sport of auto racing.

Project Scope

The Midwest Roadside Safety Facility (MwRSF), sponsored by the Indy Racing League (IRL) and the Indianapolis Motor Speedway (IMS), and later joined by NASCAR, was asked to develop a new high-speed crash barrier system that would significantly improve crash performance over existing
systems. Additional design criteria for the new system included a self-restoring capability and modularity. After impacting a deformable barrier at high speeds, it is important that the system self-restore to a reasonable degree in order for the barrier to be left in-place during the remainder of the race. Modularity would allow the system to be somewhat easily constructed and for partially deformed sections, to be replaced in-between races. Under some extreme circumstances, a section of the barrier could be replaced during a race if the modular units were quickly and easily disconnected, replaced and reconnected. For example, if an energy-absorbing foam system was used, then cartridges could be quickly replaced during a brief race halt.

Reducing lateral impact loads is the critical major design goal of this project. At impact speeds between 160 and 350 km/h (100 and 220 mph) and impact angles in excess of 20 degrees, the lateral impact forces can be significant enough to cause severe structural damage to the vehicle and serious injury and/or fatalities to the driver. Barrier systems typically installed along highways are evaluated at impact speeds of 100 km/h (62 mph). These systems are designed to meet safety standards as specified in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* [1]. It is fairly obvious that barrier systems designed for 100 km/h (62 mph) impacts would not perform the same if impacted at the higher speeds obtained on race tracks.

As an example, during the first phase of the research project an 820-kg (1808-lb) small car was impacted into a concrete wall at 160 km/h (100 mph) at an angle of 20 degrees. During this crash test, the passenger side of the vehicle crushed considerably while the car was redirected to travel along the side of the concrete barrier. Using NCHRP 350 procedures, the lateral occupant ridedown acceleration and occupant impact velocity were calculated to be 26.5 g's and 10.0 m/s (32.8 ft/s), respectively. The recommended maximum allowable values for these measurements are 20.0 g's and 12.0 m/s (39.4 ft/s). However, it should be noted that the recommended values are for 100 km/h (62 mph) impacts and that NCHRP 350 does not address higher speed crash testing. Thus, the design goal of this high-speed barrier development project is to develop a deflecting wall that allows for a significant reduction in the lateral impact loads but without increasing longitudinal vehicle decelerations or the potential for vehicle snag, pocketing, or high-angle redirection away from the wall.
BACKGROUND

Over the years, former race car drivers, engineers, researchers, and speedway owners and employees have worked to advance the state-of-the-art with respect to safety barriers. Some of the simple solutions have consisted of loosely stacking foam blocks around the exterior walls of the tracks, thus reducing the impact between the errant vehicle and the rigid wall. Consequently, barrier debris for this option can be significant as well as costly due to an inefficient use of an energy-absorbing material. Other barrier concepts have consisted of placing banded tires around selected regions of road courses. However, these configurations can result in significant vehicle override or underride as well as produce hazards which may penetrate the vehicle and/or interfere with the driver.

More recently, several other advances in safety barriers have been identified and/or developed. First, a new compression barrier, consisting of large diameter, thick-walled resilient cylinders was developed for attachment to a rigid concrete racetrack wall [2]. For this system, now known as the FLAG barrier, the cylinders were placed adjacent to one another, thus forming a longitudinal row with the cylinder openings positioned parallel to the vertical axis. Smaller diameter cylinders, placed on the traffic-side face of the longitudinal barrier, were attached between the recessed regions where the larger cylinders were no longer in contact, thus reducing the potential for vehicle pocketing. In 1998, researchers at the Department of Aerospace Engineering of Politecnico di Milano, Italy published the results of a computer simulation effort which investigated and evaluated several racing barrier options using both moving sled testing and computer simulation modeling with VEDYAC [3]. Following the research study, researchers provided several conclusions with regards to a new barrier concept, known as the GrandPrix, as well as its use in combination with other safety barriers, such as tires and water-filled modules.

Finally, John Pierce of Kestrel Advisors, Inc. and Kevin Forbes of the IMS, in conjunction with the IRL, developed a polyethylene energy-dissipating system or PEDS barrier for use on oval racetracks in early 1998. The new barrier system was configured using high-density, polyethylene (HDPE) cylinders which were covered by a thin HDPE cover skin on the front and upper surfaces. In order to expedite construction and repair, the barrier system was designed and fabricated into modular units which were then attached to the concrete wall using a cable restraint system. The cover skin was used to reduce the potential for vehicle pocketing in the front face as well as to
eliminate the potential for driver limbs becoming caught in the cylinder openings on the upper surface.

During the IROC race at IMS in August 1998, race car driver Arie Luyendyk was involved in a crash which resulted in his car impacting rearward on the PEDS barrier installed downstream from the inside corner of turn 4. The estimated impact condition for this event consisted of a 1,633-kg (3,600-lb) car striking at a speed of 209 km/h (130 mph) and at an angle of 32 degrees. Following this severe impact event, the driver remarkably did not sustain any serious injury, very likely due to the existence of the PEDS barrier, the rearward impact orientation, as well as other improvements in vehicle safety. Although this barrier system mitigated the severity of the impact, modifications to the PEDS barrier were warranted since several modular units became detached and scattered across the track, thereby causing potentially hazardous debris for oncoming cars. Several modifications were then made to the PEDS in order to increase its energy-absorbing capabilities as well as to prevent the units from becoming dislodged. This second generation of the PEDS system was termed the PEDS-2.

ENERGY ABSORBING TECHNIQUES

Although many energy-absorbing techniques exist, two specific types were concentrated on: (1) HDPE plates and (2) crushable foam. HDPE plates of various shapes and sizes can be designed to absorb significant energy through buckling and subsequent bending of the buckled plate. In many instances, HDPE plates can be designed so that they recover their shape and energy-absorbing capability relatively quickly and thus, might be reusable during a race. Energy-absorbing foams can be designed to provide uniform crushing loads. Polystyrene foams and recoverable polyurethane foams can recover their shape considerably, but their effectiveness upon reloading is generally unknown.

Several different variations of these concepts were analyzed during the project. This analysis included analytical calculations, computer simulation, static components and material testing, dynamic “bogie” testing of components and subsystems, and full-scale vehicle crash testing of complete systems. Two of the initial barrier prototypes investigated, shown in Figure 1, utilized HDPE material as a spin-off of the PEDS-2 system.
In Figure 1(a), a primary HDPE system is shown, consisting of energy-absorbing panel members and a 50 mm (2 in.) thick HDPE front skin. The cables shown are used to provide tension to the system during an impact. In Figure 1(b), a foam based system is depicted which utilizes a thin steel plate skin and Z-shaped HDPE plates used between foam cartridges. Although both of these types of systems showed promise in regards to absorbing energy, they lacked desired attributes such as preventing pocketing, low friction between the vehicle and the outer skin, puncture strength, bending strength and ability to transfer loads to a large number of cartridges at the same time.

FULL-SCALE TESTING

After examining available literature and documentation of previous real-world crashes provided by IRL, and a few initial full-scale crash tests, researchers narrowed the impact conditions down to two impact angles and two impact speeds. Impact angles of 20 and 25 degrees and impact speeds of 190 to 245 km/h (120 to 150 mph) were chosen for design. It was believed that if safety improvements at these speeds and angles could be demonstrated, then similar safety improvements would be available for actual race track applications. Typical test impact conditions for both IRL and NASCAR vehicles are shown in Figure 2. A total of 20 full-scale crash tests were run in order to develop the system discussed within this paper. A listing of those tests is given in Table 1.

Crash testing procedures, and recording and documentation of data at these unprecedented impact conditions proved to be very difficult, challenging and dangerous. Therefore, details of these enormous tasks, problems and solutions will be documented in a separate research paper focusing on high-speed crash testing.
SIMULATION

Computer simulation using LS-DYNA [4], a nonlinear finite element analysis code, was used throughout the project. A paper detailing the initial simulation efforts was presented at the 2000 ASME Congress and published in reference [5]. In brief, that paper showed that both energy absorbing methods (buckling/folding of HDPE plates and crushing of foam blocks) indicated significant reduction of the pulse during high-speed impacts was attainable. The systems presented showed great promise in improved high-speed barrier designs.

Simulation results of a NASCAR Winston Cup car into a steel tube and foam barrier design are shown in Figure 3. The Winston Cup car model was provided by NASCAR and originally developed by Altair Engineering. One of the difficulties encountered with simulation was contact penetrations leading to code instabilities, which subsequently caused LS-DYNA to abort. This was due to the high speed of the impact. Modifications to improve simulation stability included refining the mesh size of both the vehicle and the barrier, lowering the overall time step and modifying the contact penalty scale factors.

The primary benefit of simulation turned out to be the evaluation of the various foam alternatives and the determination of the amount of energy-absorbing foam to be used in the final barrier system.

THE DESIGN

After analysis of all the research completed on this project, a final design was recommended to IRL for construction at the Indianapolis Motor Speedway (IMS), known as The Brickyard. This section provides some of the details of that design. Details of the development process which led to the recommended system for the Brickyard is intended for a separate paper. However, the system described herein is very similar to several of the final full-scale crash tested systems.

A schematic of the recommended design is shown in Figure 4. The barrier is 521 mm (20.4 in) thick and consists of 508 m (20 ft) long modules composed of four welded rectangular structural steel tubes. The steel tubing impact plate is 978 mm tall (38.5 in.) but most likely could accommodate barrier heights ranging between 914 and 1067 mm (36 and 42 in.) without further testing. Four internal stiffened steel splices connect each of the modules together with bolted
fasteners. Bundles, or cartridges, of 51 mm (2 in.) thick sheets of extruded polystyrene foam are placed between the existing concrete wall and the steel tubing every 3 m (10 ft). Six or seven sheets of polystyrene compose each cartridge depending on the location of the module. Additionally, 9.53 mm (3/8 in.) diameter cables are used to anchor the steel tubing to the concrete wall and are spaced on 3 m (10 ft) centers.

SYSTEM PERFORMANCE

Results from the crash testing program clearly indicated that high-speed crashes into the new barrier design resulted in an improvement over high speed crashes into rigid concrete walls. This is not trivial since concrete walls exhibit some very desirable features not easily reproduced with deformable barriers, including no risk of snagging or pocketing, and low sliding friction between the vehicle and the wall.

Tests IRL-17 and IRL-15 were Winston Cup vehicle tests impacting at 25 degrees without and with the new barrier design, respectively. The concrete wall test (IRL-17) impacted at 225 km/h (140 mph) while the new barrier test (IRL-15) impacted at 238 km/h (148 mph), a significant increase in initial impact severity. A reduction in vehicle damage due to the new barrier was evident, as shown in Figure 5.

Tests IRL-9 and IRL-16 were IRL open-wheeled vehicle tests impacting at 21 degrees without and with the new barrier design, respectively. Both tests were performed at approximately the same speed, 230 km/h (143 mph). A reduction in lateral decelerations between the two tests was significant, as shown in Figure 6.

Although space limitations prevent a complete record of crash testing results, Table 2 is provided to show some of the full-scale results associated with the IRL open wheel vehicles and the NASCAR Winston Cup vehicles. Relatively high peak lateral deceleration anomalies for test number IRL-14 and IRL-15 were attributed to the barrier system bottoming-out at 315 mm. Note, however, that these were also the highest severity impact conditions tested. By proper selection of the energy absorbing foam, the system can be optimized to limit the system from bottoming-out for a given impact severity test condition.

The energy reduction and management occurs in stages beginning when a vehicle hits the barrier at a high speed. The extreme force of the impact causes local deformation of the steel tubing.
This almost instantaneous local deformation allows for a reduction of extreme peaks due to the initial impact. However, the tubing is thick enough to prevent significant gouging or snagging of the vehicle. As a tube deforms locally, the welds in the vicinity of the impact, which connect surrounding tubes, may also begin to stretch and deform, absorbing more of the high-speed impact energy. As the heavy steel tubing begins to be pushed back, energy is then absorbed due to the inertia required to move those system components. Finally, the foam cartridges in the area of the impact begin to compress and absorb additional energy, providing a sustained cushion for the impacting vehicle. Because of the large structural tube modules (i.e., those with high bending strength), the steel tubes transfer the load upstream and downstream of the impact to several foam cartridges at relatively the same time. As the steel tubes bend towards the concrete wall (primarily elastically), the far upstream and downstream ends of the tubes are prevented from pulling out away from the concrete wall by the steel cable anchors.

Because of the interaction of all the energy-absorbing components, as described above, for many of the impacts the final plastic system deformation is minimal and the race can continue without the need for repairs or replacement of the system. As an example, barrier damage for IRL-15 test (238 km/h [148 mph] at 25 degrees) is shown in Figure 7. In some cases, severe local deformation on steel tubes may take place which warrant immediate attention. These can be quickly repaired by welding a steel plate over the damaged area. Additionally, if a few foam cartridges are significantly damaged, they can be easily replaced in only a few minutes. In the predicted rare event of severe damage to the barrier, complete modules of the system can be removed and replaced in approximately 30 to 45 minutes.

BRICKYARD INSTALLATION AND REAL-WORLD RESULTS

Upon receiving design plans, the IMS built the first installation of the new barrier at the Brickyard, as shown in Figure 8. This racetrack barrier system was named the SAFER Barrier; SAFER is an abbreviation for Steel and Foam Energy Reduction. Installation of the barrier began in late April of 2002, just in time for use in the month of May’s practice and qualifying laps, as well as for the 2002 Indianapolis 500 race. The Indy 500 is thought by many as the worldwide premier event in motor racing.
During the first weekend of practice with the SAFER installed, Robbie McGehee lost control of his vehicle and experienced a high-speed impact into the new barrier. Just a few weeks earlier at the Brickyard, Eliseo Salazar experienced what was deemed to be nearly identical impact conditions as experienced by McGehee, but into the unprotected concrete wall. Estimated speeds of both impacts were estimated to be 290 km/h (180 mph). In the first crash, Salazar went to the hospital in serious condition after experiencing a peak crash deceleration of 115 G’s. Emergency surgery was required to repair a torn vertebral artery in his chest. In the second crash, McGehee walked away from the crash after experiencing a peak crash deceleration of 43 G’s from the first contact with the SAFER barrier. A comparison of the two acceleration crash pulses for the initial impact event is shown in Figure 9.

During lap 30 of the actual Indy 500 race, Greg Ray, 1999 IRL Champion, did a half-spin in turn 1 and hit the SAFER Barrier with the rear of his car at nearly 354 km/h (220 mph), as shown in Figure 10. Heavy damage occurred to his racecar, but Ray was checked and released without injury. Ray was subsequently cleared to drive.

CONCLUSIONS

A new barrier system was designed to mitigate the severity of high-energy vehicular impacts into rigid containment walls. The new energy-absorbing barrier system, or SAFER barrier, was successfully developed, tested, and evaluated for high-speed oval racetrack applications using LS-DYNA computer simulation modeling and full-scale vehicle crash testing. This SAFER barrier system, which attaches to concrete walls, has been shown to reduce both peak vehicle and occupant decelerations when compared to those observed during impacts with concrete walls, thus decreasing the potential for serious and fatal injuries which can occur in high-speed racing accidents.

This new barrier system has been designed primarily for use as protection for errant vehicles at high-risk locations and for oblique-angle vehicular impacts, such as on the outside of curves on race tracks. However, since this barrier is primarily, but not exclusively, a longitudinal barrier, the technology has potential application as a roadside barrier in high accident locations such as curves in tunnels and congested roadways. This technology also has application in retrofitting rigid bridge railings and other permanent or temporary traffic barriers. Finally, this barrier technology potentially may be applied to severe, high-speed events where perpendicular impacts to the system
are anticipated. Examples of these high-severity events include situations where crash cushions, end terminals, and truck-mounted or trailer-mounted attenuators are required. However, all future developments of this technology for use in roadside applications would require an economical review, design modifications and/or reductions, and evaluation through the use of full-scale vehicle crash testing according to the guidelines provided in NCHRP Report No. 350.

In the future, it is recommended that the in-service safety performance of the SAFER barrier system be continuously monitored. If actual in-service performance shows a need for potential modifications based on "real-world" accident experience, then those barrier modifications would be studied and evaluated using a combination of computer simulation modeling and full-scale vehicle crash testing. Finally, the SAFER barrier system was developed on level terrain, configured with a barrier system installed parallel to the roadway (i.e., representing a large radius corner), and included oblique-angle impacts with vehicles tracking forward into the barrier system. However, it is widely known that many of the oval speedways have high banking, smaller radius corners, or combinations thereof. In addition, many of the race car accidents occur with impact conditions that are rearward tracking or non-tracking events. Therefore, future research is recommended in order to allow engineers to better understand the dynamic behavior of the SAFER barrier when installed on high banking, tight radius corners, and/or when subjected to rearward or non-tracking impact events.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Indy Racing League, the Indianapolis Motor Speedway, and NASCAR for sponsoring the project; John Pierce of Kestrel Advisors; IRL and NASCAR race teams and Ford Motor Sports for donating vehicles; Wayne State University and Delphi Automotive Systems for providing dummies and various crash test sensors, and the Midwest Roadside Safety Facility personnel. Additionally, the authors thank Livermore Software Technology Corporation for their continued support of LS-DYNA.
REFERENCES


List of Tables

TABLE 1 Summary of Full-Scale Testing
TABLE 2 Full-Scale Testing Results

List of Figures

FIGURE 1 Initial Barrier Prototypes.
FIGURE 2 Test Vehicles and Impact Conditions.
FIGURE 3 Simulation of Winston Cup Car into Barrier.
FIGURE 4 Design Schematic.
FIGURE 5 NASCAR Winston Cup Car Test Results.
FIGURE 6 IRL Open-Wheeled Vehicle Test Results.
FIGURE 7 Barrier Damage – IRL-15 Test.
FIGURE 8 Brickyard Installation.
FIGURE 9 McGehee vs Salazar.
FIGURE 10 Ray Impact During Indy 500.


<table>
<thead>
<tr>
<th>Test Type</th>
<th>Barrier Description</th>
<th>Test Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogie Vehicle</td>
<td>HDPE Skin with HDPE Panel Absorbers</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Steel Tube Skin and Spaced Foam Absorbers (Rearward)</td>
<td>1</td>
</tr>
<tr>
<td>Small Car</td>
<td>Concrete Wall</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>HDPE Skin with Continuous Foam Absorbers</td>
<td>2</td>
</tr>
<tr>
<td>Large Sedan</td>
<td>HDPE Skin with HDPE Z-Plates</td>
<td>1</td>
</tr>
<tr>
<td>IRL Open-Wheeled</td>
<td>Concrete Wall</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>HDPE Skin with Continuous Foam Absorbers</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Steel Tube Skin with Spaced Foam Absorbers</td>
<td>3</td>
</tr>
<tr>
<td>NASCAR Winston Cup</td>
<td>Concrete Wall</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>HDPE Skin with Continuous Foam Absorbers</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Steel Plate Skin with Continuous Foam Absorbers</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Steel Tube Skin with Continuous Foam Absorbers</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Steel Tube Skin with Spaced Foam Absorbers</td>
<td>3</td>
</tr>
</tbody>
</table>
### TABLE 2  Full-Scale Testing Results

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Vehicle Style</th>
<th>Test Description</th>
<th>Vehicle Weight (kg)</th>
<th>Impact Speed (km/h)</th>
<th>Impact Angle (degrees)</th>
<th>Impact Severity (kN-m)</th>
<th>Exit Trajectory Angle (degrees)</th>
<th>Peak Longitudinal Deceleration (G's)</th>
<th>Peak Lateral Deceleration (G's)</th>
<th>Dynamic Wall Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRL-6</td>
<td>IRL</td>
<td>HDPE Skin and Continuous Foam</td>
<td>879</td>
<td>136</td>
<td>23.7</td>
<td>101</td>
<td>small</td>
<td>NA</td>
<td>NA</td>
<td>102.0</td>
</tr>
<tr>
<td>IRL-9</td>
<td>IRL</td>
<td>Concrete Wall</td>
<td>926</td>
<td>229</td>
<td>20.7</td>
<td>234</td>
<td>11.5</td>
<td>26.52</td>
<td>137.04</td>
<td>NA</td>
</tr>
<tr>
<td>IRL-11</td>
<td>IRL</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>886</td>
<td>225</td>
<td>21.3</td>
<td>228</td>
<td>8.0</td>
<td>14.21</td>
<td>49.20</td>
<td>224</td>
</tr>
<tr>
<td>IRL-14</td>
<td>IRL</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>904</td>
<td>241</td>
<td>25.3</td>
<td>370</td>
<td>5.3</td>
<td>17.73</td>
<td>177.22</td>
<td>315</td>
</tr>
<tr>
<td>IRL-16</td>
<td>IRL</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>923</td>
<td>229</td>
<td>20.7</td>
<td>233</td>
<td>4.5</td>
<td>22.63</td>
<td>69.97</td>
<td>188</td>
</tr>
<tr>
<td>IRL-7</td>
<td>NASCAR</td>
<td>HDPE Skin and Continuous Foam</td>
<td>1,632</td>
<td>199</td>
<td>20.0</td>
<td>292</td>
<td>11.5</td>
<td>41.83</td>
<td>47.53</td>
<td>251</td>
</tr>
<tr>
<td>IRL-8</td>
<td>NASCAR</td>
<td>Concrete Wall</td>
<td>1,632</td>
<td>191</td>
<td>20.5</td>
<td>282</td>
<td>3.9</td>
<td>20.69</td>
<td>52.18</td>
<td>NA</td>
</tr>
<tr>
<td>IRL-10</td>
<td>NASCAR</td>
<td>Steel Plate Skin and Continuous Foam</td>
<td>1,630</td>
<td>140</td>
<td>19.3</td>
<td>135</td>
<td>13.6</td>
<td>13.33</td>
<td>29.32</td>
<td>69</td>
</tr>
<tr>
<td>IRL-12</td>
<td>NASCAR</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>1,632</td>
<td>203</td>
<td>21.7</td>
<td>355</td>
<td>10.7</td>
<td>19.24</td>
<td>50.77</td>
<td>277</td>
</tr>
<tr>
<td>IRL-13</td>
<td>NASCAR</td>
<td>Steel Tube Skin and Continuous Foam</td>
<td>1,632</td>
<td>237</td>
<td>25.6</td>
<td>660</td>
<td>5.9</td>
<td>62.75</td>
<td>94.41</td>
<td>79</td>
</tr>
<tr>
<td>IRL-15</td>
<td>NASCAR</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>1,619</td>
<td>238</td>
<td>25.6</td>
<td>661</td>
<td>9.3</td>
<td>47.51</td>
<td>109.65</td>
<td>315</td>
</tr>
<tr>
<td>IRL-17</td>
<td>NASCAR</td>
<td>Concrete Wall</td>
<td>1,640</td>
<td>225</td>
<td>24.9</td>
<td>568</td>
<td>5.5</td>
<td>66.95</td>
<td>87.81</td>
<td>NA</td>
</tr>
<tr>
<td>IRL-18</td>
<td>NASCAR</td>
<td>Steel Tube Skin and Spaced Foam</td>
<td>1,630</td>
<td>196</td>
<td>21.5</td>
<td>325</td>
<td>8.9</td>
<td>25.79</td>
<td>46.72</td>
<td>208</td>
</tr>
</tbody>
</table>

NA - Not available or not applicable.

Note: Peak decelerations are just one data point and should not be used to evaluate the overall effectiveness of a system.
FIGURE 1 Initial Barrier Prototypes.
FIGURE 2 Test Vehicles and Impact Conditions.
FIGURE 3  Simulation of Winston Cup Car into Barrier.
FIGURE 4 Design Schematic.
IRL-17 Concrete Wall Test

IRL-15 New Barrier Test

FIGURE 5 NASCAR Winston Cup Car Test Results.
FIGURE 6  IRL Open-Wheeled Vehicle Test Results.
FIGURE 7  Barrier Damage – IRL-15 Test.
FIGURE 8  Brickyard Installation.
FIGURE 9  McGehee vs Salazar.
FIGURE 10  Ray Impact During Indy 500.