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NCHRP IDEA Program

SaferCushion

Final Report for
NCHRP IDEA Project 203

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The National Academies

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DISCLAIMER

The authors of this publication hold patents on this device and other similar devices. This protected intellectual property has the potential for generating financial remuneration for the authors. However, all safety performance evaluations are conducted by a third-party, independent, accredited testing facility. Therefore, the results of this research and the ultimate determination of crashworthiness cannot be influenced by the author's financial interests.

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EXECUTIVE SUMMARY

This project encapsulates portions of the development of a new crash cushion. It utilizes a rotating drum with band brakes to apply a braking force, via friction, to the vehicle. Then, the band brakes will be released, and a motor will reverse the rotation of the drum to pull the system back into its original position. This resetting will be automated and controlled by a programmable logic controller. It will include communication technology to potentially alert emergency responders about the crash. In addition, it will be able to communicate to the owners of the system and the manufacturer that there has been a crash, and that information can be used in concert with crash records to build a database of performance and permit a true evaluation of its in-service performance (including unreported crashes). Crash testing using a bogey vehicle has been done, as well. This testing demonstrated the proper functionality of the compression and sliding of the crash cushion. It also demonstrated minimal damage to the track, which was a primary design objective. Any damage that was caused by this testing will be designed out of the system in subsequent iterations.

1. BACKGROUND

Crash cushions are intended to shield the motoring public from a stiff, hazardous fixed object that cannot be removed and where space is limited leading up to the hazard. Most crash cushions are designed to stop a pickup truck in under 20 feet, from a speed in excess of 60 mph. Due in large part to the distance constraint, crash cushions are expensive devices, compared to guardrail terminals, for example. As such, crash cushion implementation is generally limited to areas of specific need, especially low-maintenance crash cushions, which cost more upfront, and with enough crash frequency, become cost effective over time. Work crews are expected to operate on the side of the road to repair or replace any safety hardware that has been damaged, but low-maintenance crash cushions need more work than most devices, in terms of work zone setup, given that they are generally reserved for high crash frequency locations. Work zones must be set up, delaying traffic and, more importantly, risking the lives of the workers themselves. On average, over 100 crew members are killed in work zones every year (*1*).

The SaferCushion was proposed to help eliminate work zone casualties and to provide a plurality of other benefits to the States and to the motoring public. It operates using a spinning drum with band brakes as the energy absorbing mechanism. A large nylon strap wraps around the drum axel, and as the system is struck and compressed by a vehicle, this strap is pulled off the drum, causing the drum to rotate. That rotation is inhibited by large band brakes, which absorb the energy of the vehicle via friction. To allow for compression, the SaferCushion is built with modular diaphragms and panels, with these panels being able to telescope back on themselves. The diaphragms are attached to a track using steel "feet", which are claw-like steel hooks that grip the flange of the track while still being able to slide down its length.

The SaferCushion concept stands apart from other low-maintenance crash cushions in that it is a truly self-restoring design. It will be outfitted with a motor and winch that release the brake and pull the lead sled back to its home position. This will be done with a series of sensors that will detect when the crashed vehicle has been removed and when the sled has returned home. Essentially, a pressure sensor will be able to detect the presence of the crashed vehicle, and a given time, say three hours, after that pressure has been removed, the resetting algorithm will begin.

Two other features are planned that will greatly improve the in-field performance of the SaferCushion and may help to improve in-field evaluations in the industry as a whole. Proper tension in the strap and the home position of the sled will ensure that the system will function as intended. It is possible, over time or with unnoticed nuisance hits, for crash cushions to be out of position prior to a crash. In this scenario, it is unlikely that the device would be able to operate as intended, potentially exposing the motorist to a higher risk of fatality. The controller of the band brake and motor will be able to send a message to the owner of the device if it is not capable of fixing the problem on its own (e.g., the feet are too damaged to slide back into place). This message might contain information about the service life of the subject SaferCushion along with the most recent crash data, including date, location, and time of day. This information would be useful in collecting in-field performance data by matching police reports and by determining a real value for unreported crash rate. This practice would certainly help to improve the design (if needed) of the SaferCushion, but it would also provide a real-world example of the application of real-time in-service performance evaluations (ISPEs). The SaferCushion could be outfitted easily with an RFID chip that could be read by a responding police officer, thus automatically linking the police report to the impact message sent to the manufacturer and/or State.

2. IDEA PRODUCT

There are currently three categories of crash cushions generally recognized by the industry: (1) sacrificial, gating; (2) sacrificial, non-gating; and (3) reusable, non-gating. This third category is often referred to as "low maintenance." Crash cushions in this category have a robust construction, and in some cases, simply require a few replacement bolts and a vehicle to decompress the system. Some of them have semi-elastic materials that help the system spring back into place, but these systems also take damage in the form of plasticity. This means once they are hit, they are never able to fully restore. The present IDEA project seeks to develop a crash cushion that is low maintenance and truly self-restoring through a system of mechanical devices. It is also to be the first self-healing and self-diagnosing crash cushion, with integrated systems that can check for proper functionality at any time, adjusting as needed, to ensure proper installation and maintenance for a far greater number of collisions.

3. CONCEPT AND INNOVATION

The concept behind the SaferCushion is true self-restoration. It will not depend on construction crews to reset or maintain the device for a majority of instances. Upon impact, the system will absorb the energy of the vehicle. Through a series of sensors, the device will be able to determine when the vehicle has been removed from the scene and trigger a resetting algorithm. This will activate actuators that release the brakes. Then, the drum will be rotated in reverse to pull the system back into position before the band brakes are reset.

Several innovations to crash cushion design will factor into this concept. First, the energy absorbing mechanism is a drum with nylon strap spooled onto its axle. The diameter of the drum, where the band brakes act, is unchanging, but the diameter of the spooled strap decreases as the SaferCushion compresses. This increases the mechanical advantage of the brakes, making the resistance increase as the vehicle travels deeper along the track. This innovation allows for variable resistance, with lighter resistance for small vehicles and greater resistance for larger vehicles.

The SaferCushion will also be the first crash cushion to use a Programmable Logic Controller (PLC) and onboard sensors to govern its response to crashes or maintenance issues. Once the vehicle has been removed for a sufficient amount of time (say three hours to provide a wrecking crew with enough time to load and haul away the vehicle), actuators will be activated by the PLC to compress the Belleville springs on the band brakes. The Belleville springs apply pressure to the band brake straps, which in turn creates the normal force necessary for the development of friction force. The actuators will compress the springs such that tension is removed from the band brakes, and the drum is free to rotate. Then, the PLC will press a drive shaft into the drum and lock it in place. The drive shaft will be attached to a motor that will spin the drum in the reverse direction. This will begin to respool the strap onto the drum, effectively pulling the sled away from the drum. This will continue until the sled reaches a sensor located at the “home” position. At this point, the brakes will be reactivated and the drive shaft will be deactivated.

Communications technology will be integrated into the moving mechanisms to detect high-speed collisions and notify the authorities. This should dramatically improve ambulance response times. In addition, messages will be sent to the owners and manufacturers of the device, provide real-time ISPE data collection.

4. INVESTIGATION

4.1. ENERGY ABSORBING MECHANISM

A crash cushion must be able to absorb the energy of a high-speed crash within a short distance, usually less than 30 feet. As a minimum, to stop a 5,000-lb vehicle traveling 75 mph in 30 feet, energy must be absorbed at an average of 31.3 kip-ft/ft. In addition to such a performance, one objective of this design is to be able to self-adjust and reset. This means that the energy absorbing mechanism must be able to switch off in order to reset the system and switch back again. Such design requirements led the research team to select a rotating drum that would spool a chain or cable or strap in its center. The outer edges of the drum would be outfitted with band brakes, such as those used in small-engine vehicles (e.g., golf carts) or on large oil drills. Golf cart band brakes are exceeding small and oil drill brakes are exceedingly large, so a specially made part was required. Because the size of the band brake was flexible, the research team undertook a developmental project to optimize the size of the bands, drum, and spool. This project included 168 developmental tests to optimize the diameter of the drum, choose the best strap material, and find a bearing capable of withstanding the pressure and speed caused by a crash. This developmental project predated the current research project and has been discussed elsewhere in greater detail *(2)*. The drum used in this mechanism began with a 10-inch diameter, and over dozens of iterations has increased to 20 inches. An axle passes through the drum and spool and is housed in bushing. The bearing inside the bushing is ceramic and was specifically chosen for its ability to handle high pressure and high speed at the same time. This was a critical requirement that, early in the design phase, caused the spool to weld around the axle and the axle to weld into the bushing, preventing rotation. The bands are made from A36 steel with a hemp and wire material bonded to the steel to provide friction and long service life. An image of this energy absorbing mechanism is shown in FIGURE 1.

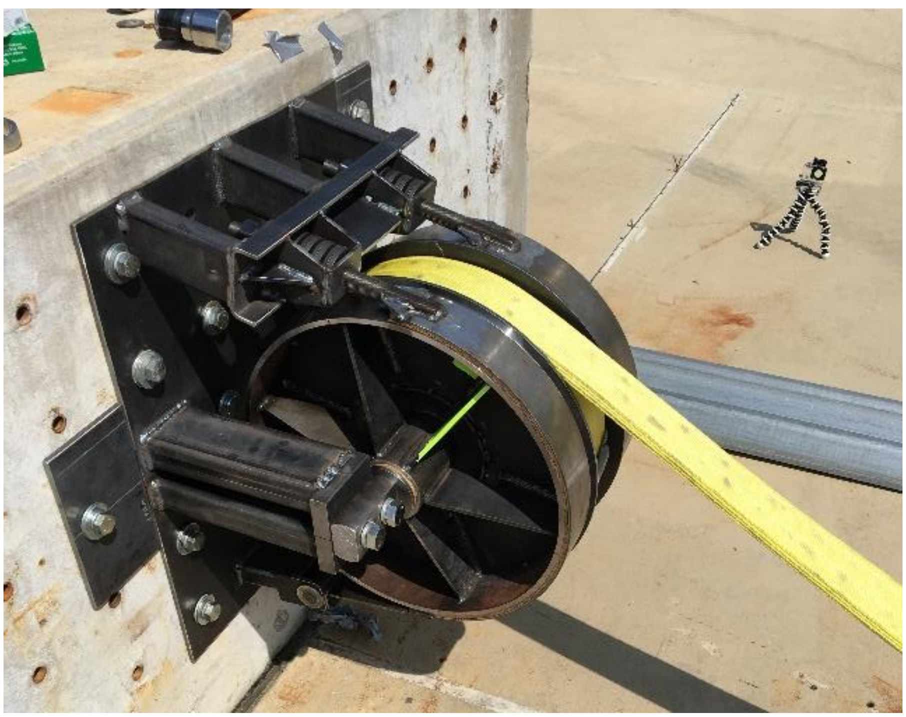


FIGURE 1 Energy absorbing mechanism

4.2. TRACK DESIGN

The track design underwent a series of iterations that began with building a T-shape out of plate steel. Originally, the flanges were not strong enough, so two plates were stacked on top of each other and plug welded together along the length of the track. Impact testing revealed that the spacing of the plug welds (about every 18 inches) were insufficient for composite action, allowing differential bending between the two parts. This created a bowing phenomenon that prevented future sliding, which is critical to the resetting process. Therefore, a thicker one-piece approach was adopted. In the meantime, to increase lateral strength, the bar stock webs were replaced with structural tubing. A cross-sectional view and isometric view are shown in FIGURE 2, with dimensions shown in inches.

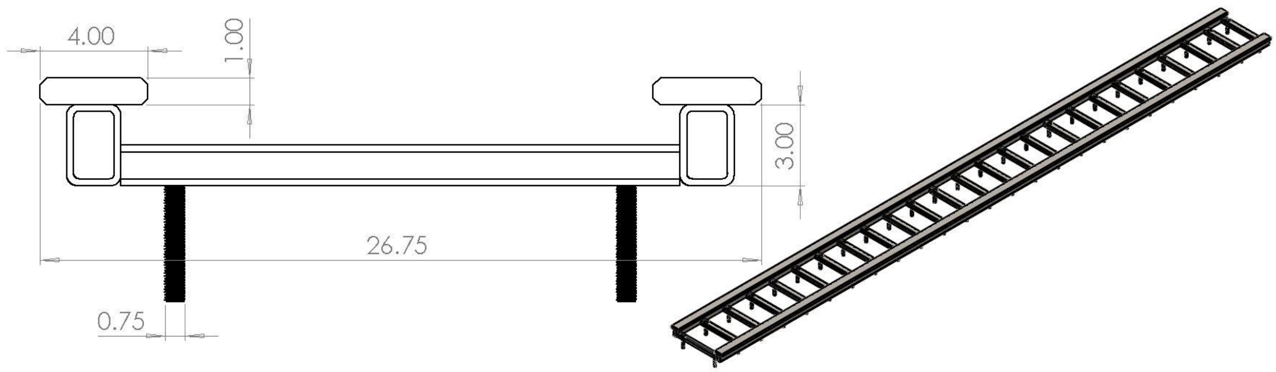


FIGURE 2 Track design

4.3. FOOT DESIGN

One of the problems noted with the track design was that permanent deformation in the track prohibited proper resetting and led to jamming of the feet. Jamming could cause severe vehicle instabilities and needs to be prevented. One step was to strengthen the track itself. In addition, the feet were optimized such that a known weak point was engineered into the shape. This known weak point would control failure (weakest-link design philosophy) and could be tuned such that failure of the feet occurred before any permanent deformation in the track. This approached was considered to be the most cost-effective approach, considering track removal and replacement are extraordinarily expensive endeavors, but foot replacement would be very inexpensive. Along with the geometry of the foot, its material was specified as well. Steel ASTM A36 will be used in the feet. Stronger steel, with a yield strength of 50 ksi, would also work, but it placed more stress on the track. Therefore, because the weaker A36 steel redirected the pickup truck (as determined from modeling), it was chosen for the feet. All optimization was done using LS-DYNA to simulate an impact with the side of the crash cushion. As a guide, crash tests from the *Manual for Assessing Safety Hardware* (MASH) *(3)* were used to create impact conditions for simulations. Specifically, MASH Test No. 3-35 was replicated in the model with the pickup striking the SaferCushion just downstream of the front of the sled. As aforementioned, the vehicle was redirected successfully. Model results of the controlled plastic deformation of the foot are shown in FIGURE 3, noting the lack of deformation in the track. The prototype foot is shown in FIGURE 4 as 3D printed parts inserted into the steel diaphragms. It should be noted that small offsets were added to the feet to prevent large surface-to-surface contact with the flange and web of the track. The dimensions of this part are shown in greater detail in Appendix A.

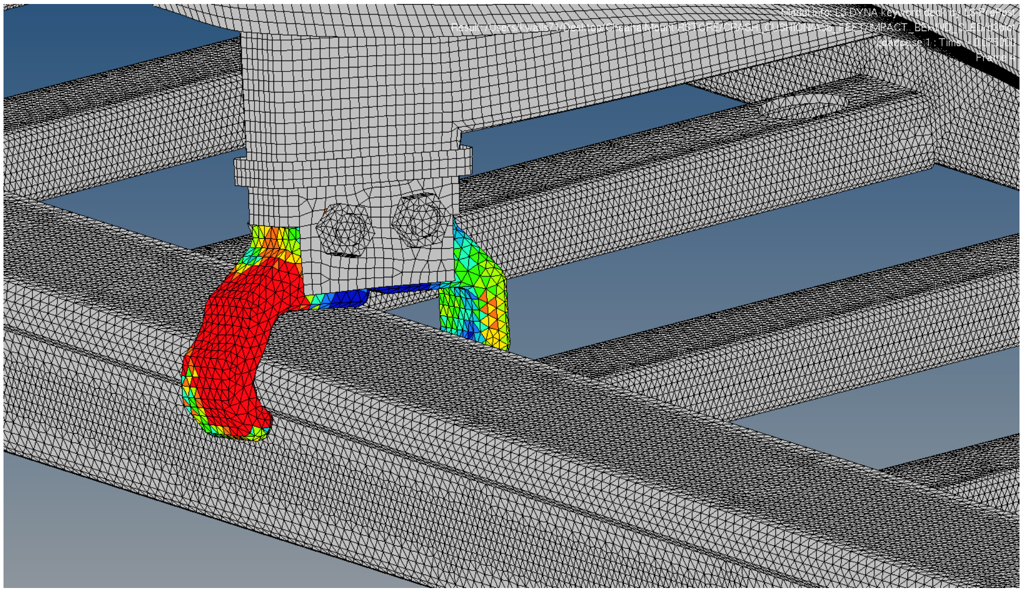


FIGURE 3 Controlled plastic deformation of the SaferCushion feet

FIGURE 4 3D printed foot

4.4. MOTOR AND WINCH SYSTEM DESIGN

The energy of a vehicle is absorbed by a spinning drum with band brakes resisting that rotation. If the direction of the drum is reversed, then the rotating drum would pull the telescoped cushion back into place. To do so, a motorized winch will be attached to the drum. When the winch is not needed, it will disengage with a clutch system integrated into the side of the drum. In an ideal setting, the winch would pull the SaferCushion back into place, weighing at most 3,500 pounds. The weight decreases as each diaphragm reaches its original position. The true force pulled by the winch may exceed this value, however, due to surface imperfections, debris, foot-track engagement, and possible permanent deformation in the track or other parts of the system. As such, a winch was selected with a 12,000-lb pulling capacity. A Pierce PS654 electric winch and worm gear motor was selected accordingly, and an exemplar is shown in FIGURE 5. This winch and motor can easily be integrated with a control system and power source. This winch can be powered by a lithium battery. It is anticipated that small solar panels will be supplied with the crash cushion to recharge these batteries to provide continuous service.

FIGURE 5 Pierce PS654 electric winch and worm gear motor

4.5. SIMULATIONS

Once the SaferCushion structure was drawn in SolidWorks, a surface model was generated and meshed throughout the entire system. Then, it was inserted into a pickup model created and validated by NCAC *(4)* to replicate MASH Test No. 3-35 conditions (i.e., a 5,000-lb pickup truck impacting the safety device at 62 mph and 25 degrees). The impact location was just upstream of the front of the sled of the SaferCushion. The simulation was done using LS-DYNA *(5)*. Originally, instabilities arose from the first choice of a material model, but once *MAT_024 was selected, the model ran successfully. Once the model was debugged, the research team ran multiple models to identify the critical impact location. Measuring downstream from the impact plate, locations at 9 inches (near the front of the sled), 13 inches (middle of the sled), 24 inches (back of the sled), 64 inches (first diaphragm), and 104 inches (second diaphragm) were evaluated. The pickup was redirected in each simulation. An overhead view of the 9-inch impact is shown in FIGURE 6. This image corresponds with the deformed foot shown previously. In addition to the damage to the feet, the panel that was struck by the vehicle also took damage. While the research team does not anticipate significant damage resulting from head-on collisions, these impacts with the side of the cushion will require some repair work. All panels, diaphragms, and feet (the components most likely to see any damage) are modular and easily replaced.

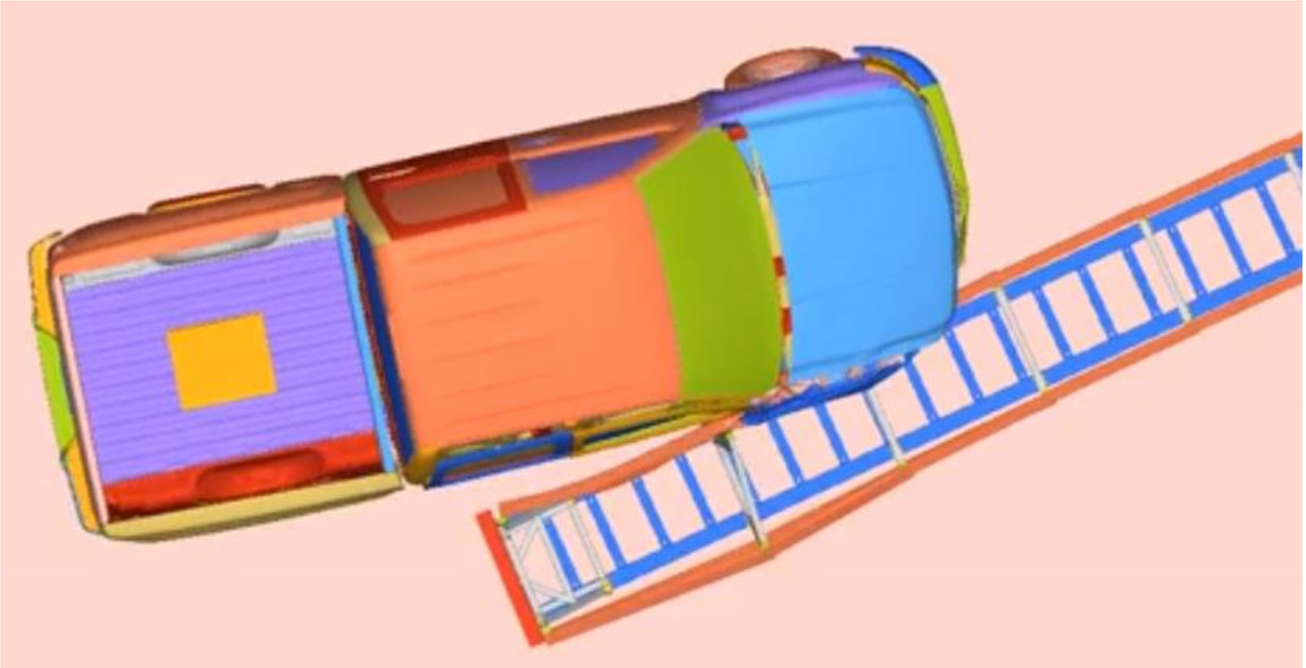


FIGURE 6 Overhead view of Test No. 3-35 simulation

MASH Test No. 3-36 was also simulated to evaluate the stiffness in the transition zone between the SaferCushion and the semi-rigid hazard it is shielding. Crash cushions often shield the motorist from the blunt end of a concrete wall. As such, a model was created with the SaferCushion butting up against a 2-ft wide vertical, concrete wall. Then, using the same vehicle model as before, Test 3-36 was set up in LS-DYNA. Measuring from the concrete backup structure, multiple locations were evaluated, including 22 inches, 44 inches, 66 inches, and 72 inches. In each model, the vehicle pocketed to a degree, with the worst pocketing occurring in the 72-inch model. However, the largest vehicle-hazard interaction occurred with the 22-inch model, where the right front corner of the pickup struck the rigid barrier model. Nevertheless, the pickup was smoothly and safely redirected in all simulations. The results for the 72-inch model are shown in FIGURE 7, followed by the results of the 22-inch model, shown in FIGURE 8.

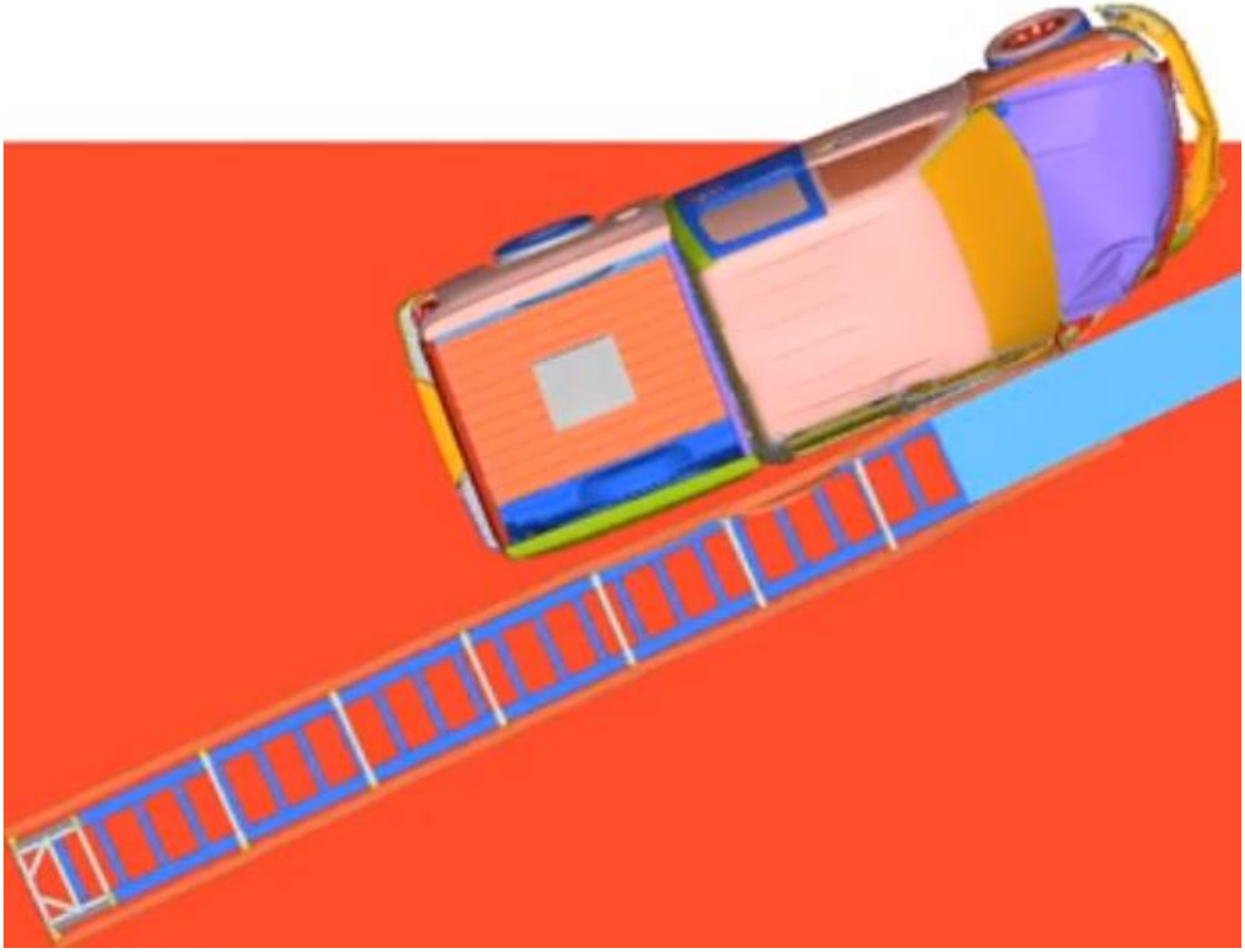


FIGURE 7 Results of 72-inch MASH 3-36 simulation

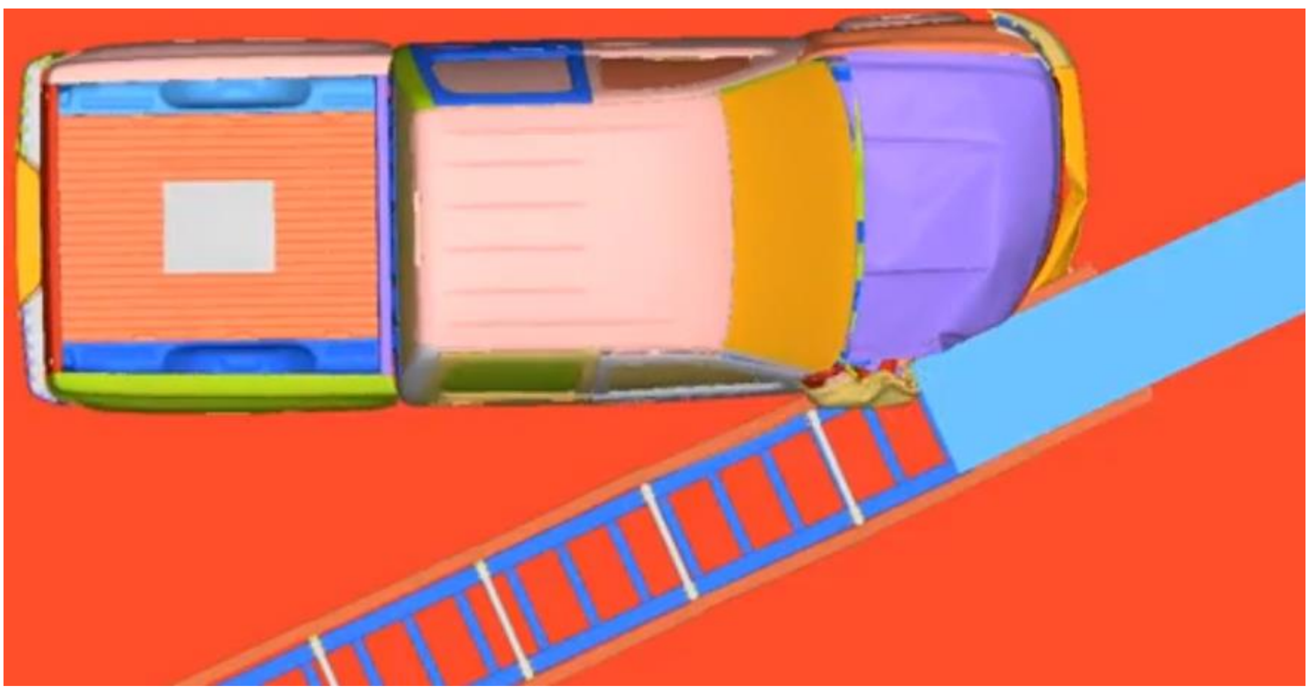


FIGURE 8 Results of 22-inch MASH 3-36 simulation

4.6. BENCH TESTING OF WINCH

The Pierce PS654 winch and worm gear motor was connected to the crash cushion to investigate the control of the winch through a Programmable Logic Controller (PLC). To complete this task, an old track design, using a T-shape for each track instead of the tube shown previously, was set up on stanchions. The sled was attached to the track using prototype steel feet. These feet were half the thickness of the one shown previously, requiring two prototype feet through the thickness. Also, the edges were sharp rather than rounded. These two differences combined to create a more tortuous evaluation. In other words, if the winch was able to pull the sled with these feet, it would be able to do so with the more expensive, filleted feet. The bench test set up is shown in FIGURE 9.

FIGURE 9 Bench testing set up: (left) PLC; (middle) winch; (right) sled and feet

The winch was tested four times, wherein each time, the cable from the winch was attached underneath the sled only. In the first three tests, a pull time of 10 seconds was manually conducted, and the distance the sled traveled was recorded. Measurements were taken for both sides of the track and averaged together. The starting position was marked with a permanent marker to aid in taking this measurement. The fourth test was conducted similarly except that it was pulled the full length of the available track. The actual time and distance were recorded. The results of these four tests are given in TABLE 1. It should be noted that the bench test was done with a sled only, rather than the full weight of a compressed SaferCushion. Since none of the sharp-edge feet jammed during the pull testing, it can be surmised that the results in the table represent theoretical maximum speeds, meaning it would take at least 2 minutes to reset a fully compressed system. The research team has targeted between 3 and 5 minutes as a reset time goal. Therefore, this bench testing demonstrated that the chosen winch and worm gear motor should be able to operate under the desired conditions.

TABLE 1 Bench test results

Test No.	Distance Pulled (in)			Time (sec)	Average Pull Rate (feet/min)
	Leg 1	Leg 2	Average		
1	20-5/16	19-7/8	20.09	10	10.05
2	17-5/16	16-3/4	17.03	10	8.52
3	17-7/8	17-15/16	17.91	10	8.96
4	119-5/16	119-9/16	119.44	60	9.96
				Aggregate Average	9.69

4.7. PROTOTYPE FOR CRASH TESTING

The prototype SaferCushion that was tested included the sled and first diaphragm, along with a four-corrugation panel attaching them. The sled and diaphragm were attached to the track via “feet”, similar to the simulated design discussed in Section 3.3. That design was modified slightly to space its edges away from the underside of the track, thus minimizing the effect of “biting”, which occurs when the edges of the feet cut into the broad sides of the flange or web of the track, dramatically increasing the effective coefficient of friction. When this has happened in the past, the sliding action stops, but the energy of the impacting vehicle is still high enough to be considered dangerous. The redesigned prototype makes use of the same controlled failure modes as the predecessor from Section 3.3. Therefore, no additional analysis was required as to its strength in redirection impacts. A detailed construction drawing is provided in Appendix A.

Casting of prototypes will be carried out in future developmental work for this device. In the meantime, for evaluation and proof of concept, the prototype feet with offsets were manufactured through a process of laser cutting, grinding, and welding. The basic shape of the foot was cut with a laser to a depth of 0.75 inches. The required thickness was 1.5 inches, but laser cutting at the full depth was both expensive and less precise. Therefore, the half-thickness parts were welded together to form the full thickness. In addition, the sharp edges were blunted and offset with half-inch round bar stock that had been cut in half. This provided the ¼” offsets shown in the design drawing.

The track and drum assembly were secured to the concrete with concrete wedge bolts. The front end of the track and the drum assembly used 3/4-inch bolts, and the remainder of the track was secured with four 5/8-inch bolts every three feet.

A nylon strap was wrapped around the drum and extended along the ground, underneath the sled, and around an idler at the front of the track. After wrapping around the idler, it attached to the leading edge of the sledge as close to the ground as possible. Upon impact, the sled would slide toward the drum while pulling nylon strap off of the drum. To resist the rotation of the drum, 20-inch diameter band brakes were mounted on either side of the spooled strap. On one end of the bands, an eyelet was secured to a dead-man pin. On the other side, the bands were welded to 1-inch diameter threaded rod with a pitch of 13 threads per inch. These rods were fit through a thick steel plate and housing that was securely welded to the frame of the assembly. Then, Belleville washers were slid onto the threaded rod and held in place by a nut and flat washer. To apply tension to the band brakes, this nut was turned to a specified thickness.

The Belleville washers were statically tested to stroke 0.087 inches at 40,703 pounds. This was the distance required to flatten the washer entirely. In the crash cushion, they were stacked in parallel using eight total Belleville washers per band. This magnified the distance to flat by eight, making it 0.696 inches for the same load of 40,703 pounds. The nut was turned onto the threaded rod until it was finger tight. Then, a paint marker was used to draw lines across the nut and the threaded rod, marking the “home” position. Tests in this project varied with either one or two complete turns of the nut. The force applied to the band brakes through the Belleville washers was noted by the following equation:

$$F = \frac{1}{P} \times \frac{N}{D_{flat}} \times F_{flat}$$

Where F = force applied to the band brakes
P = the pitch count or the number of threads per inch on the threaded rod
N = number of turns of the nut
D_{flat} = distance to flatten the stack of Belleville washers (0.696 inches, in this case)
F_{flat} = force required to flatten the stack of Belleville washers (40,703 pounds, in this case)

4.8. CRASH TEST CONFIGURATION

The tests done near the end of Stage 1 were bench tests, conducted at a quasi-static rate. There was no impact. In this stage, the SaferCushion was partially constructed and installed at BLASER. A photo of the test installation is shown in *FIGURE 10*. A rigid bogey vehicle, weighing 4,263 pounds, was used to impact the SaferCushion. It was proposed that 45 tests would be conducted with varying angles, repeating each condition five times. However, previous research proved that the rigid bogey vehicle was not capable of substantial redirection during a collision, and as such, would not replicate a real-world crash. Also, the prototype feet were not considered as robust as a fully cast part. As such, the number of tests were reduced to minimize the likelihood of a failure that would damage the test facility, the energy absorbing drum, or the bogey vehicle. Therefore, the test matrix was reduced to a single angle with one test at each speed. Speeds were selected in 5-mph increments starting at 10 mph and ranging to 30 mph. Two things need to be noted. First, the rigidity and mass of the bogey vehicle make these low-speed impacts more severe than the corresponding speeds with real vehicles, which are deformable. Second, a vast majority of real-world impacts occur at speeds less than the standardized crash test speed and are closer to those used in this project.

The pre-test configuration shown in FIGURE 10 includes labels for some of the components discussed herein. In this photo, the drum from FIGURE 1 is under a plastic sheet to protect it from concrete dust during the test installation. The track was bolted to the ground using concrete wedge bolts. The bolts at the front of the track, by the idler, were ¾” wedge bolts. The rest, along the length of the track and in the cross-members of the track were 5/8” wedge bolts. The drum apparatus and structure were bolted down similarly with ¾” wedge bolts. The sled was constructed of rectangular diaphragms and 2”x4” structural tubing. The impact plate was welded directly to the first diaphragm, which was cross-braced with an angled tube down to the second set of feet, visible in the figure. The first panel and second diaphragm were welded together for this series of tests to ensure that the lead diaphragm would benefit from the increased moment arm that the first panel affords. This is a surrogate for a full system installation. Finally, an idler was installed at the front of the track. A strap was unspooled from the drum and fed along the ground and underneath the sled. That strap wrapped around and over the idler and connected to a large pin at the base of the sled. This connection was approximately flush with the impact plate to limit any superfluous rotation about that point.

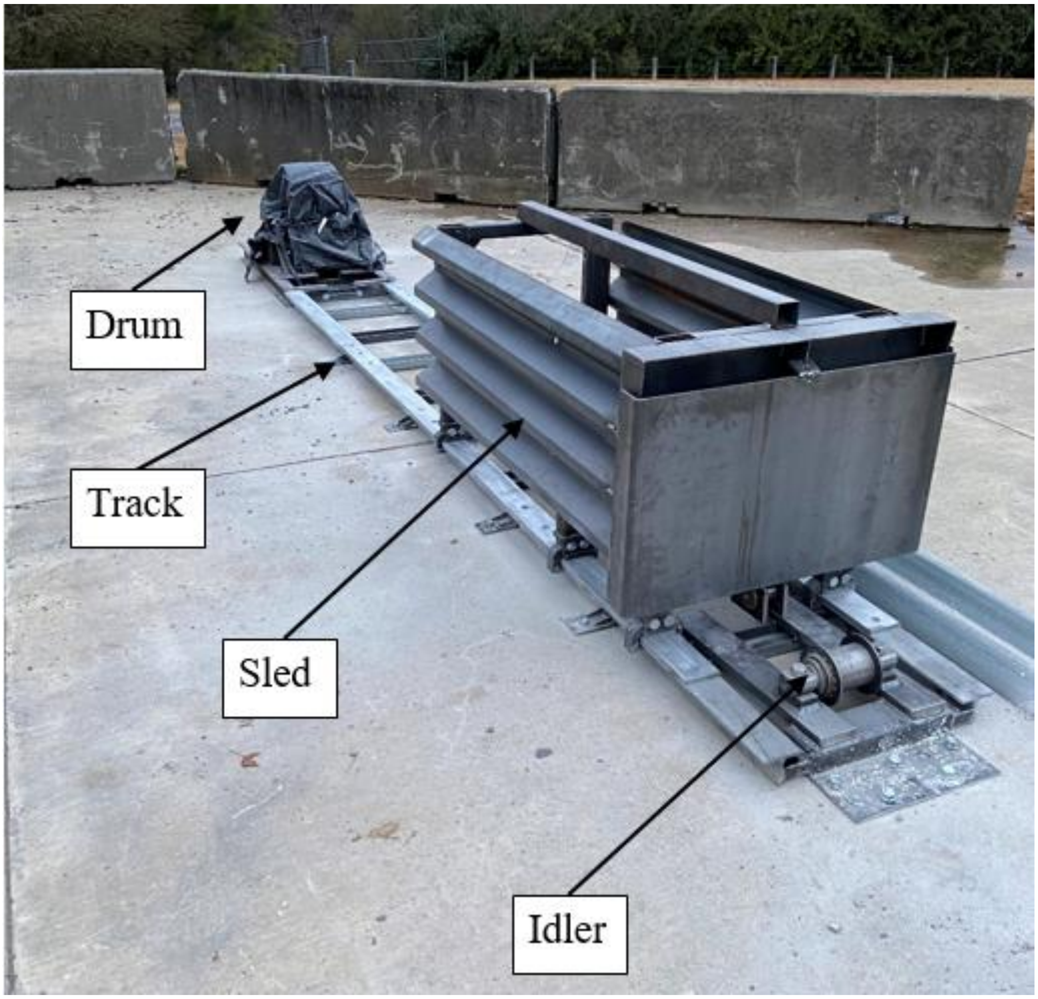


FIGURE 10 Test Installation for Stage 2 Testing

For each test, the bogey vehicle was instrumented with an accelerometer, providing valuable data on the rate of energy absorption in the system. Before the tests, the bands were tightened with either one or two turns on the nut, equating to a tensile force in each band of either 4,499 or 8,997 pounds. Then, once cameras were set to record and the accelerometer was armed, a tow vehicle pulled the bogey vehicle up to the target speed using a 1:1 cable tow system. Just prior to impact, the cable released from the bogey vehicle, which was guided down the tarmac with one side of tires riding in the valley of a string of W-beam guardrail (visible on the right side of the image shown in FIGURE 10).

4.9. TEST RESULTS

As described previously, five tests were conducted at varying speeds. The first test was targeted for 10 mph, but the accelerometer data was not recorded. Therefore, data on four of the five tests were analyzed. The test conditions and results are shown in TABLE 2. In most of the tests, the nylon strap demonstrated elasticity as it pulled the sled back toward the front by some amount (noted as “Spring Back” in the table of results). This was especially pronounced for the final test, where the spring back was nearly four times higher than any other test. This may have been a function of the greater force in the bands, the speed and energy of the bogey vehicle, the smoothing of the track due to previous tests, or some combination thereof.

TABLE 2. Test Descriptions and Results

Test No.	Force in Bands (lbs)	Speed (mph)	Sliding Distance (in)	Spring Back (in)
1	4,498.6	10.0	30.5	0.0
2	4,498.6	14.0	47.0	7.0
3	4,498.6	17.2	83.0	6.5
4	8,997.2	25.0	49.0	4.0
5	8,997.2	27.2	61.5	27.5

The available accelerometer data was output as a comma-separated values (CSV) file with more than 160,000 data points. Only the acceleration in the X-direction was analyzed, given the constraints of the test configuration. To do so, the CSV data was read into a Matlab program. In addition, the bogey weight, sliding distance, and spring back were entered into the program. Then, the acceleration was integrated to get a velocity trace, and that trace was investigated to determine a guessed velocity at time zero in the data such that the minimum velocity, later in the event, correlated with a full-stop (velocity of zero). Then, by inspection of the acceleration data, the time of actual impact was identified and used to mark the impact velocity and the beginning of the displacement. Then, using this impact velocity and the entered bogey weight, the kinetic energy was calculated. The kinetic energy was divided by the distance traveled (both for including and excluding the spring back distance) to determine the average force of deceleration (F_{avg}). Previous work using this W-beam guidance for the bogey vehicle has demonstrated that the rolling resistance along this configuration was 1,000 lbs-ft/ft. This constant was coined the Energy Absorption Rate (EAR) of the rail. It is related to the average force of deceleration and the EAR of the drum according to the following equation (results shown in TABLE 3):

$$F_{avg} = EAR_{rail} + EAR_{drum}$$

TABLE 3. Energy Absorption Performance

Test No.	Force in Bands (kips)	No Subtraction of Spring Back		Subtraction of Spring Back	
		EAR-Drum (kip-ft/ft)	Average	EAR-Drum (kip-ft/ft)	Average
2	4.4986	8.59	8.18	10.02	9.24
3	4.4986	7.77		8.45	
4	8.9972	22.18	20.29	24.07	25.57
5	8.9972	18.39		27.06	

In tests 2 and 3, the Belleville washers were tightened with one revolution of the nut around the 1”-13 threaded rod. In tests 4 and 5, two revolutions were used, thereby doubling the band brake pressure. When the distance of the spring back was included in the total displacement, the average EAR increased from 8.18 to 20.29 kip-ft/ft, growing by a factor of 2.48. Similarly, when the spring back distance was not included (that is, the distance traveled was reduced), the averages were 9.24 and 25.57 kip-ft/ft, respectively, or an increase by a factor of 2.77.

4.10. DISCUSSION

The primary objective of this testing was to investigate the robustness of the design and its proclivity for resetting. The impact plate was struck five times at varying speeds, increasing each time. After each impact, the damage level was assessed to determine if an additional test could be run. Plasticity in the feet were checked to make sure they were able to hold the sled down on the track. The track itself was examined for bowing. After the fifth test, there was some evidence of the track bowing up, but it was not the entire track, and it did not prohibit sliding. The test program was stopped after the fifth test due to a lack of available stroke in the track for higher speed tests. In the future, the one-piece track will be longer and able to accommodate more sliding.

The tension in the band brake was also directly related to the stopping power of the drum. When the band pressure was doubled, the energy absorption rate more than doubled, indicating a non-linear positive corollary between band pressure and EAR.

In addition, as the strap was unspooling, it was hypothesized that the resistance would increase due to the increasing mechanical advantage. This advantage was created by the relative separation the two main forces: (1) the strap; and (2) the band brakes. This effect was visible in the crash test data. The accelerations were integrated twice to determine displacement. The accelerations were also converted to force through Newton's 2nd law. The bogey was faced with 4x4 wooden boards to minimize the ringing in the data, but that was not sufficient to ensure a perfectly plastic collision. As a result, early displacements showed high forces with great oscillations. Later in the event, the noise damped out and the bogey face was held against the impact plate. At this point, the increasing resistance with displacement became visible, as shown in FIGURE 11. All available force-displacement data (there was not data for the first test) is provided in Appendix B. Photos of each test are provided in Appendix C through Appendix G.

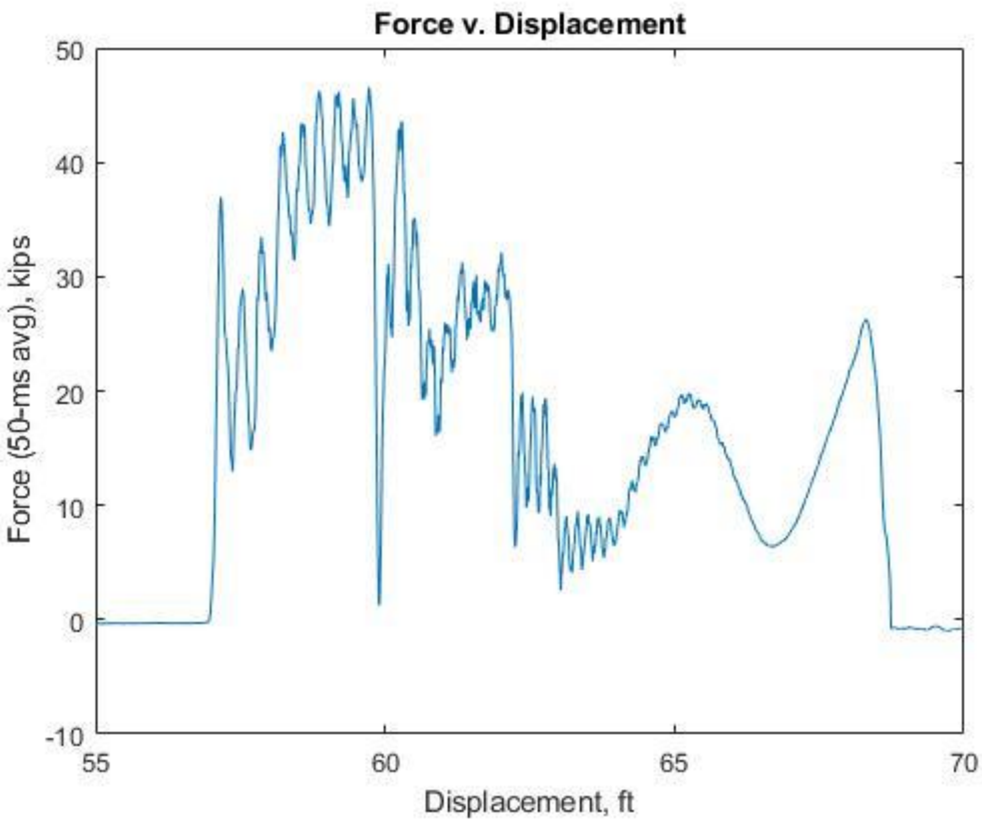


FIGURE 11 Force-displacement data for the fifth test

Given that a reusable, low-maintenance crash cushion is expected to remain in service for 10 years or more, durability was the leading consideration for the strap used to spin the drum during a crash. These nylon or polyethylene materials are extremely strong for their weight, and as such, the loading of the strap was not considered a prominent concern. Ultra-violet rays from long-term exposure, however, can degrade many kinds of strap material. The research team selected a material that had been designed to withstand UV rays.

The steel components of the device were overdesigned for side impacts, resulting in a weak-chain failure of the feet first, which are easily replaceable. Because of this approach, each component, including the feet, were overdesigned for head-on collisions. These are the most common collisions with short systems, such as crash cushions, and are the type of collisions that result in a resettable system. Because the structural parts are so overdesigned, the stresses in these parts during a collision are not expected to cross the S-N curve for material fatigue. These two considerations make this crash cushion well-suited for long-term use, whether it sits in the sun without being struck or it is struck several times a month.

5. FUTURE WORK

5.1. COMPILE DATABASE OF RECEIVED MESSAGES

Sending the messages following a crash, as described in the previous section, is one innovation, but having a compiled database of these messages is important to demonstrate the practicality of the proposed method. The purpose of the database will be to provide a continuous log of information. For example, a confirmation could be sent after every self-check, along with a warning after any failed self-checks or failed resets. This will enable State DOTs to diagnose and fix any system in the field faster than ever before. Currently, some devices can go weeks or months without being repaired, following a crash, because the State simply doesn't know of the damage. This is often through no fault of the State's but simply due to large state highway networks and a tendency in the motoring public to drive away from non-injurious crashes, leaving behind a compromised safety device. This message system, as part of the onboard electronic design, will be finished and a database will be designed to help gather and analyze data in real-time.

To date, ISPEs are not used in the final approval of a safety device, despite the recommendation for doing so in almost every standardized crash test guideline. The research team sees two possible paths to pursue in generating these ISPEs.

First, the message will contain the date, time, and location of the crash. With this information, the owner or manufacturer of the device should be able to locate a corresponding crash report and compile the necessary data to conduct a traditional ISPE. This is not an automated method and would require a significant effort to locate and procure the crash reports. However, it is the method that requires the least amount of additional work from police investigators.

Second, the responding officer who generates the police report could send a second message. At the present time, the form of this second message is uncertain, but it could include a basic message, such as a crash report number, or a more complex one, like a digital copy of the crash report itself. Either way, locating and procuring the crash report would be made significantly easier, but in the case of the latter, a nearly real-time ISPE can begin to take shape.

The research team will investigate the feasibility of method during the full-scale compliance test evaluations. Once the system is operational on a real-world highway, a clearer picture will begin to emerge on the biggest flaw in traditional ISPEs, the lack of data for unreported crashes.

5.2. EVALUATE BANDS/DRUM/ELECTRONICS

High-speed MASH tests are very dynamic and may distort some of the critical components of the structure. This could inhibit the ability to be reset. The critical components need to be able to withstand the forces they experience without taking damage. After each test, a visual inspection will occur to ensure that no permanent deformation has occurred. Likewise, the continued functioning of the motor and the receipt of messages will indicate to the research team that the electronic system is still functioning.

In addition to operational performance, the accelerometer data will be analyzed to determine forces on the test vehicle, distances traveled, and the rate of energy absorption in the system. As part of the previous effort to develop the energy absorption system, it was observed that the tension in the strap increases as more of it is unspooled. This is due to the fact that the radius of the spooled strap decreases as it is unspooled, creating less and less of a moment arm. With a lower moment arm, the force has to increase to balance the resisting torque generated by the band brake. This same pattern will be identified and quantified at higher speeds and for greater lengths of unspooling.

6. CONCLUSIONS

Crash cushions are typically required to absorb large amounts of energy in a short space. This constraint on space is usually a function of the high-volume nature of some roadways, where exit and on ramps create “gore” areas with a short space preceding a bridge rail, for example. In this scenario, a 50-ft-plus length of guardrail with a guardrail terminal would not be suitable. Some of these areas experience such high traffic volumes that the crash rate at those locations far exceeds the national average. Such an occurrence, commonly referred to as a black spot, may be related to other external factors beyond traffic volume. Whatever the cause for the high frequency of crashes, low-maintenance crash cushions are ideally suited for this application. They are more expensive to construct and install, but due to the reduced life-time costs, they become more cost-effective over time.

The SaferCushion is being developed to elevate the category of “low-maintenance” crash cushions to even higher performance. In particular, it has been designed to allow for reverse telescoping after an impact. A spool with a strap acts as the energy absorbing mechanism as the crash cushion is compressed, causing the strap to unspool and the drum to attempt to rotate. This rotation is resisted by band brakes and applied friction. After a collision, the band brakes are released, and a motor spins the drum backward, re-spooling the drum and pulling the crash cushion back into position.

The critical components to the sliding action were developed using the weakest-link methodology. These parts include the diaphragms, feet, and track. To repair the track is very expensive, and as such, the design objective was to protect the track as much as possible. Diaphragms are easier and less expensive to repair than the track, but the feet are the easiest and least expensive to repair. Therefore, the feet were designed to deform and release from the track before the track experienced plastic deformation. The diaphragms were reinforced around the feet to ensure much greater strength to facilitate primary failure in the feet.

A winch with a 12,000-lb pull force was chosen to rotate the drum and pull the SaferCushion back into position. Bench testing was carried out using a PLC to control the winch motor and evaluate resetting speeds. In addition, this bench testing utilized prototypes of the track and feet that were previously shown to be averse to easy sliding. The sharp edges of the feet tended to bite into the track. Therefore, since this bench pull testing was successful, it was determined that the sliding of the modified feet on the one-piece track would be easier.

Bogey testing was done on the sled, track, and drum assembly to evaluate the robustness of the design. Five tests were done at varying speeds, ranging from 10 to 30 mph, and with varying band brake pressures. The energy absorption rate was shown to be directly related to the band brake pressure in a non-linear relationship. As the band brake pressure doubled, the energy absorption rate increased by a factor of 2.5 to 2.8. After the fifth test, some damage was observed in the track, but it was not enough to prohibit sliding. In addition, the damage was due to a lack of complete composite action in the built-up flange of the track. This will not be a problem with the final design, which will include one-piece flanges on the track.

7. PLANS FOR IMPLEMENTATION

A journal paper was written and submitted for peer review for the Early Career Technical Conference, 2019, in Birmingham, AL. This paper detailed the entire development of the structure of the crash cushion, including the optimization of the feet via computer simulation. It can be found on the website of the Early Career Technical Journal *(2)*.

Development on the SaferCushion will continue past this project. The research team will continue to collaborate with an electrical engineer to implement the control system to activate and deactivate the brakes, pull the system back into position, and run periodic systems checks. Once these details are finalized, detailed drawings will be produced.

The SaferCushion will be compliance tested by a third-party crash test facility according to the requirements set forth in MASH. Upon successful completion of these tests, all pertinent information will be sent to the FHWA along with a request for a federal letter of eligibility. Finally, it will be marketed and made available to any states seeking to install truly self-restoring and self-reporting crash cushions.

8. COMMENTS FROM REVIEWERS

The research team received comments and questions from reviewers by TRB IDEA. The comments were addressed with clarifications made to the body of the text. Comments and questions that were not addressed in the preceding sections are addressed in this section.

1. The research and report concentrate on the restoring functionality of the crash cushion but fails to mention details on the rest of its components. And, even though it is not mentioned, this might be due to the fact that the system seems to be developed as a proprietary device. Developing a proprietary device at a university?
    a. The report describes the energy absorbing mechanism, the structural design of the telescoping panels and diaphragms, the design of the feet and track, and the sizing of the motor that will be used to restore the system following an impact. The circuitry for the programmable logic controller is still being programmed and will be part of the final design sent for compliance testing. This is a proprietary device being developed at a university, which is common.

2. Bogie testing conducted on the energy absorbing drum and sled would have benefited from having the rest of the system installed. As such it only gave useful information on those selected components but not of the complete system as it would be installed in the field.
    a. The research team agrees that a full installation would have provided information about the performance of the system in the field. However, the component-level development required isolating each component to understand its unique performance. Many of the tests conducted on the drum involved nothing but the drum, brakes, and strap. In these setups, the research team was able to quantify the initial rate of energy absorption and how that rate changed as strap was unspooled. This was critical for the completion of the study. Additional testing is planned to test a fully installed system, which was not possible toward the end of the study due to various external factors.

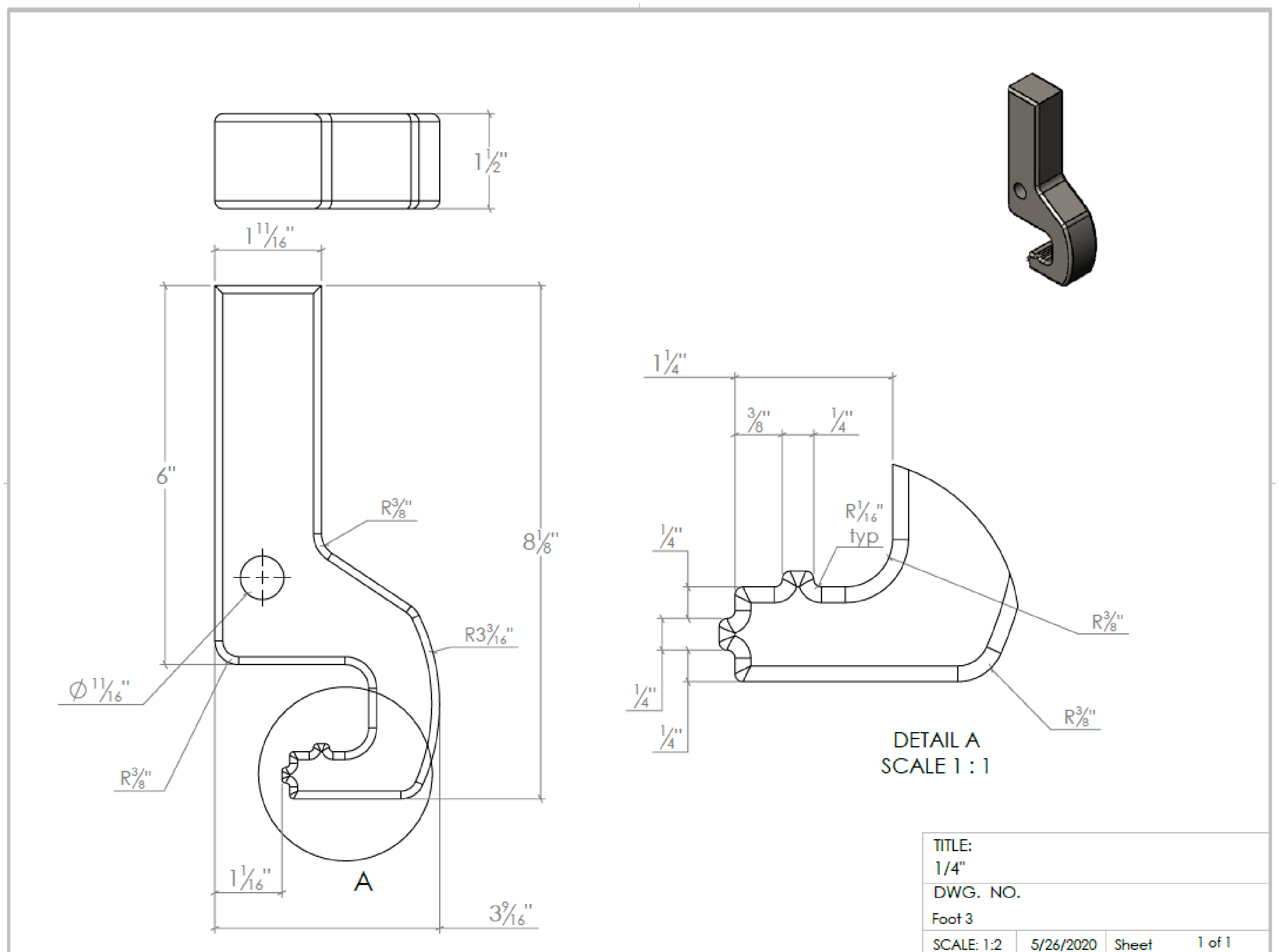
3. As the research stands, it would be only as a proof of concept and therefore not ready for implementation, as preliminary testing was only conducted on components of the system and not the complete product as it would be installed out on the field. This system would need further research on the rest of its component, and the whole system as a whole; finalizing the system with the set of full scale crash tests outlined in the American Association of Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH).
    a. The research team agrees with this comment completely, and plans are underway to continue the development, bringing to the point of full-scale crash testing according to the requirements of MASH.

4. More research will also be needed on the durability of the system as it is being advertised as a reusable system. Research was only conducted at lower speed, and only of some components of the systems, so it would be useful to know how the system would hold up against crashes with higher speeds.
    a. A durability discussion was added to the “Discussion” subsection of Section 4.
    b. On the issue of low versus high speeds, the research team agrees that additional testing is needed, using real vehicles at high speeds. However, the loading from the bogey vehicle, which is not deformable, offered an extreme loading condition that helps mitigate the lack of speed. In essence, the lack of energy absorption through vehicle crush led to increased loads and stresses in the object being struck.

9. REFERENCES

1. National Highway Traffic Safety Administration (NHTSA), *Work/Construction Zones*, https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/workzones.pdf, accessed: 1/7/2019.
2. Walls, K.C. and Schrum, K.D., “Structural Design of a New Crash Cushion,” *Journal of UAB ECTC,* Volume 18, Section 4, 2019, pp. 88-95.
3. *Manual for Assessing Safety Hardware* (MASH), 2nd ed., American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
4. Mohan, P., et al., *Modeling, Testing, and Validation of the 2007 Chevy Silverado Finite Element Model*, Working Paper NCAC 2009-W-005, October 2009.
5. *LS-DYNA Keyword User’s Manual, Volume I*, Livermore Software Technology Corporation (LSTC), R11, 18 October 2018.

10. APPENDIX A – DRAWING OF FOOT WITH OFFSETS



11. APPENDIX B – FORCE-DISPLACEMENT DATA

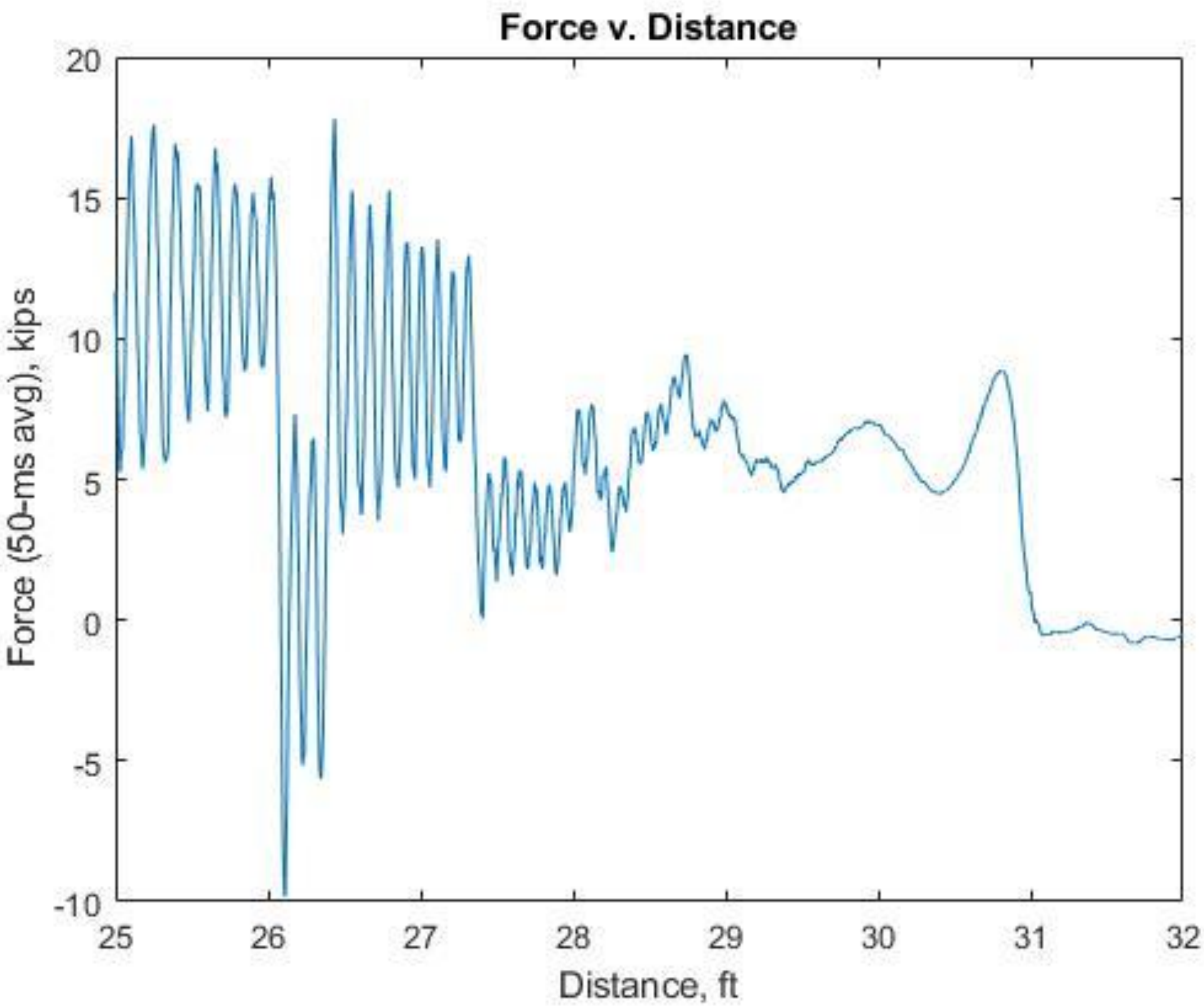


Figure B 1 - Test 2 data

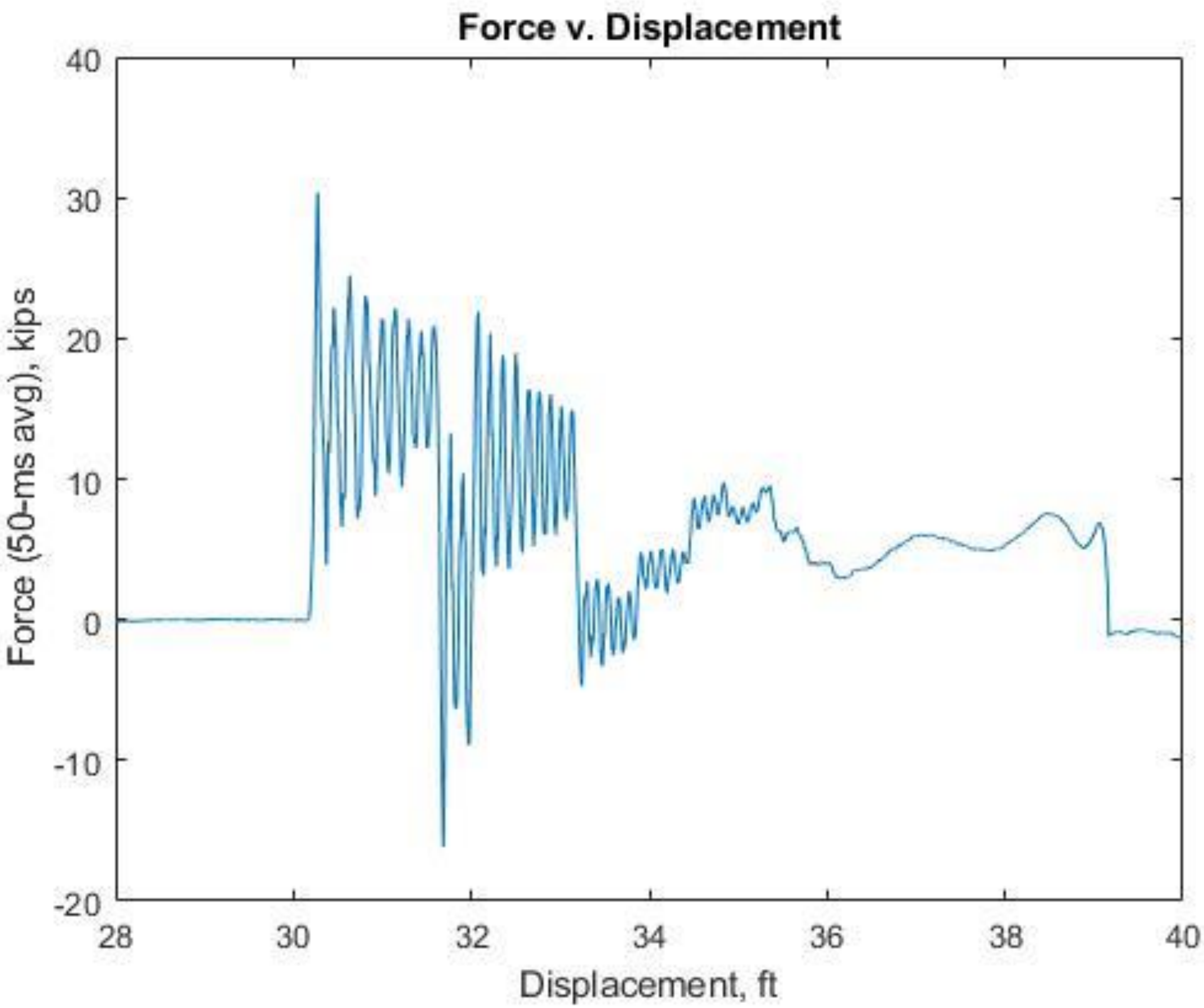


Figure B 2 - Test 3 data

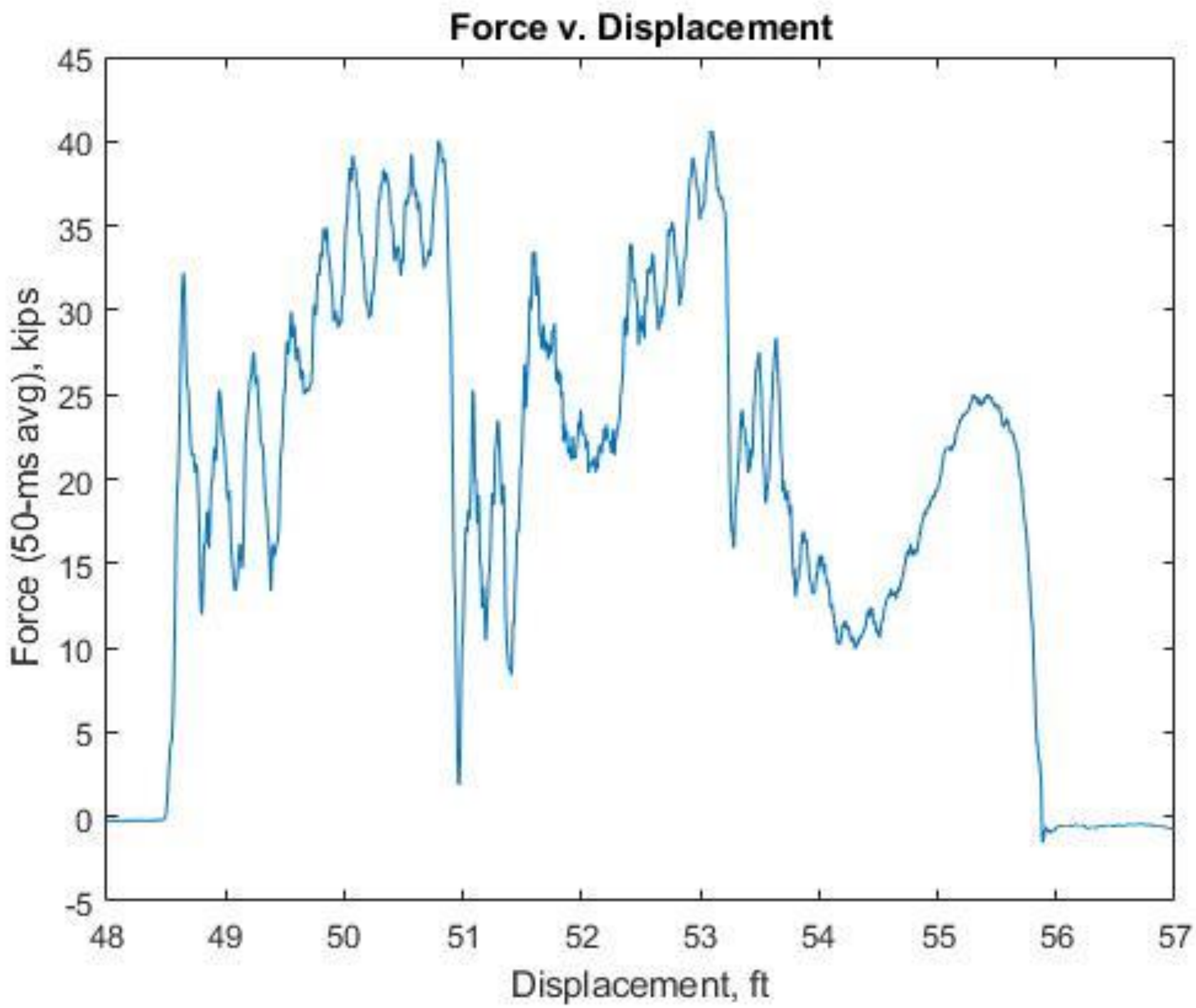


Figure B 3 - Test 4 data

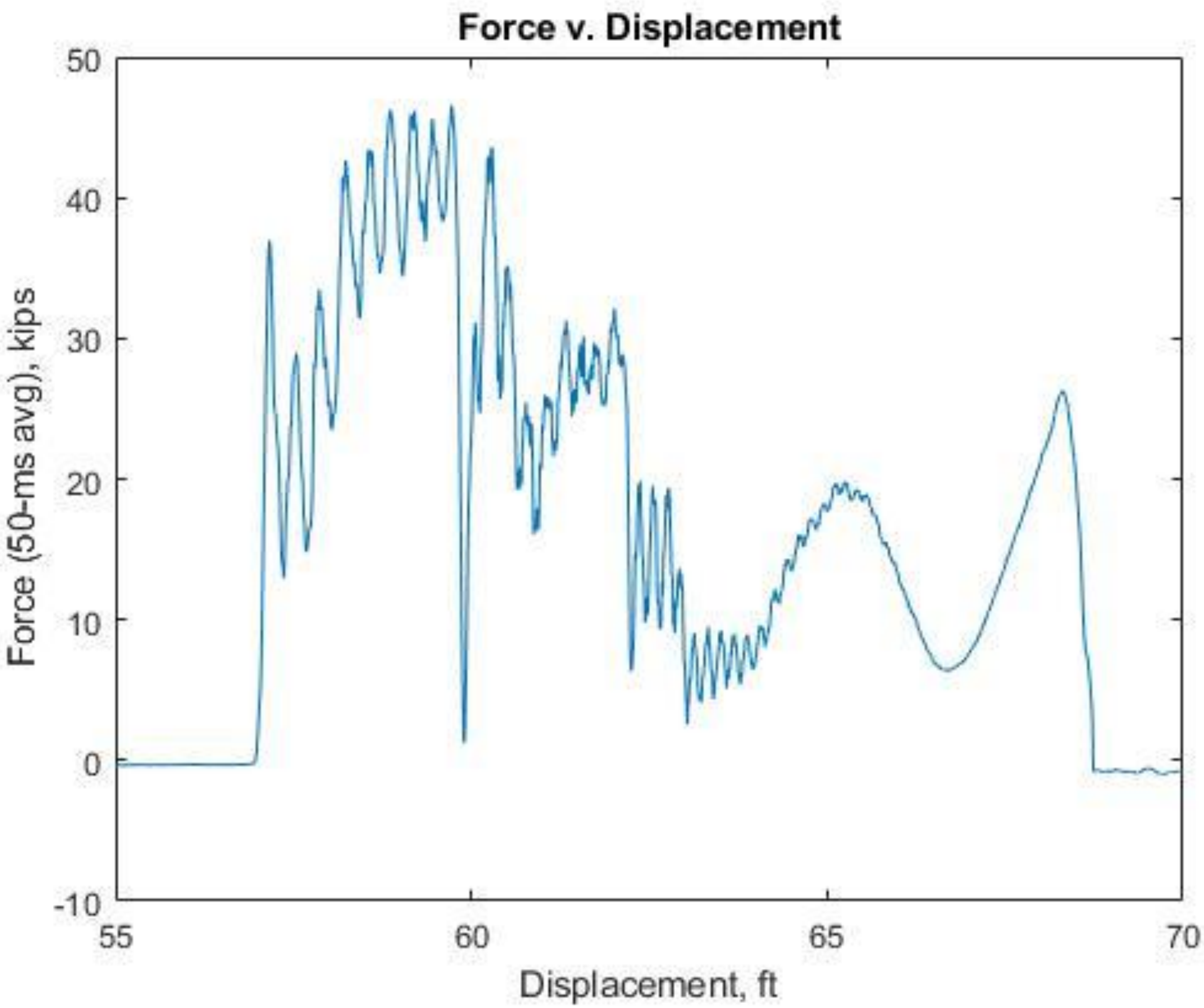


Figure B 4 - Test 5 data

12. APPENDIX C – PHOTOS OF TEST 1

Figure C 1 – Pre-impact of test 1

Figure C 2 Maximum displacement of test 1

Figure C 3 - Unspooling for test 1

13. APPENDIX D – PHOTOS OF TEST 2

Figure D 1 - Pre-impact of test 2

Figure D 2 - Maximum displacement for test 2

Figure D 3 - Position after spring back for test 2

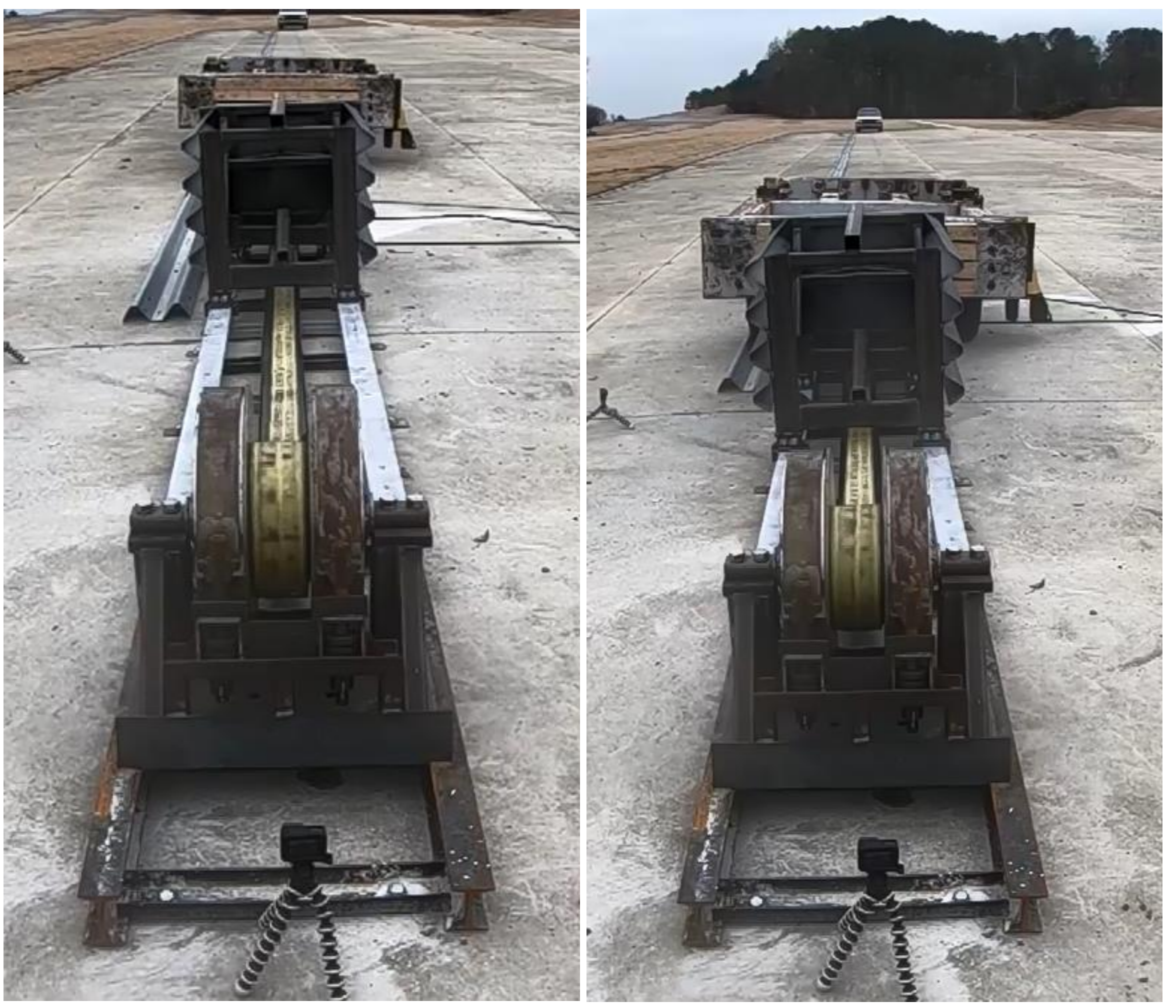


Figure D 4 - Unspooling for test 2

14. APPENDIX E – PHOTOS OF TEST 3

Figure E 1 - Pre-impact of test 3

Figure E 2 - Maximum displacement for test 3

Figure E 3 - Position after spring back for test 3

Figure E 4 - Unspooling for test 3

15. APPENDIX F – PHOTOS OF TEST 4

Figure F 1 - Pre-impact of test 4

Figure F 2 - Maximum displacement of test 4

Figure F 3 - Position after spring back for test 4

Figure F 4 - Unspooling for test 4

16. APPENDIX G – PHOTOS OF TEST 5

Figure G 1 - Pre-impact for test 5

Figure G 2 - Maximum displacement for test 5

Figure G 3 - Position after spring back for test 5

Figure G 4 - Unspooling for test 5

17. APPENDIX H – RESEARCH RESULTS

Sidebar Info

Program Steering Committee: TRB IDEA Program Committee

Month and Year: February 2021

Title: Non-Gating Guardrail Terminal

Project Number: 203
Start Date: January 2018
Completion Date: December 2020

Product Category: Crash Cushion

Principal Investigator:
Dean Sicking, Professor and Associate VP for Product Development, University of Alabama at Birmingham
E-Mail: dsicking@uab.edu
Phone: 402-450-6295

TITLE:

SaferCushion

SUBHEAD:

Proof of concept for using a mechanism to absorb energy and act to fully and automatically reset itself

WHAT WAS THE NEED?

There are approximately 100 fatal crashes involving highway construction and maintenance crews each year. Every minute they spend on the roadside installing and repairing safety hardware puts them at risk. Crash cushions are often installed in tight spaces with high traffic volumes. Further, low-maintenance crash cushions are installed at high crash frequency locations, making repairs on these systems very dangerous. Therefore, a need has been identified for a low-maintenance crash cushion that is capable of restoring itself through automated, mechanical means such that it can perform again and again without placing crew members at risk.

WHAT WAS OUR GOAL?

The objective of this research was to produce a crash cushion with an energy absorbing mechanism that can be used to restore the system to its original functionality. The mechanism would integrate with a winch and programmable logic controller to restore a system following the removal of the vehicle while also recording the incident and notifying the owner and manufacturer of the crash.

WHAT DID WE DO?

This research was conducted in two phases. In the first phase, the structure of the crash cushion was optimized using a weak-link methodology. The structure was overdesigned so that it could receive heavy loading with taking damage. The feet, which connect the sliding components to the track, were design to yield before the rest of the structure for collisions with the side of the crash cushion. This made repairs inexpensive and reduced the necessary time to make those repairs. In addition, their shape was determined from testing and modeling to provide the least amount of friction with the track as possible, to prevent the feet from biting into the track and preventing the sliding motion. The full design was simulated using LS-Dyna for several impact conditions, including the Critical Impact Point, often referred to as the “coffin corner” impact, as well as reverse direction impacts and collisions with the front of the terminal at an angle. Finally, a winch motor was chosen to interface with the rotating drum (energy absorbing mechanism) that had a pulling capacity four times greater than the weight of the crash cushion.

The second phase focused on the resetting technology. Specifically, crash tests were conducted with some of the diaphragms and panels sliding on the track when struck by a bogey vehicle. The diaphragms and panels were attached to the drum via a nylon strap. The drum was resisted by band brakes, thereby providing the energy absorption needed to stop the bogey vehicle. After each test, the band tension was released and the sled was pulled back into position, proving that the track and foot prototype was capable of easy reverse motion, even after repeated incidents.

Engineers from the Wisconsin, and Wyoming Departments of Transportation served as advisory panel members. They were joined by a member of the technical community who was employed by Walter P Moore and had experience working with DOTs and Toll Authorities. They provided their own insights at the beginning of the project, as well as at the end. Collaborative efforts to study the field performance of this device are under discussion with the Wisconsin DOT.

WHAT WAS THE OUTCOME?

The energy absorbing mechanism was designed as a rotating drum with a spool the house a nylon (or similar) strap. The rotation would be resisted by band brakes. One outcome of this study was the observation that as the strap unspooled, the resistance from the steady-state bands increased as a function of the changing diameter of the nylon spool. The provided a variable rate of energy absorption, with a lower rate, and lower G-force, for smaller cars and a higher rate for larger vehicles that compress the system further. In addition, early attempts to slide the structure on the track were impeded by the foot design. As a result, another outcome was the design of small offsets around each foot that distanced any edges from the track, preventing them from jamming. This also allowed for reverse motion and for repeatability.

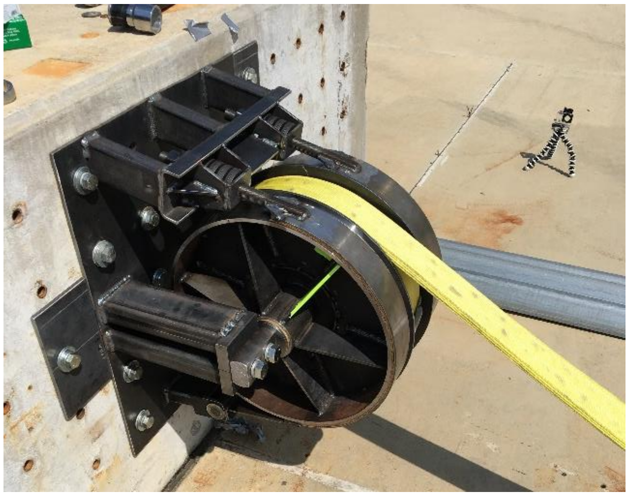
WHAT IS THE BENEFIT?

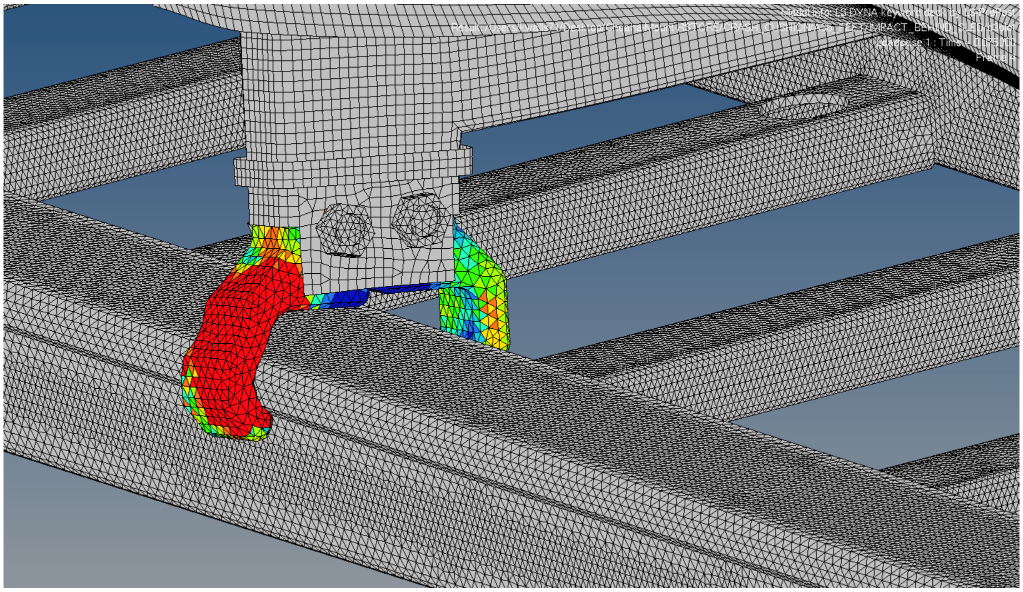
This proof-of-concept for an energy absorbing mechanism that can also act as a tool for resetting, and for a foot/track design that allows for repeated resetting, will provide the foundational elements to continued development of the system. A paper is currently being written to explore the benefits of the variable-rate energy absorption feature of the drum.

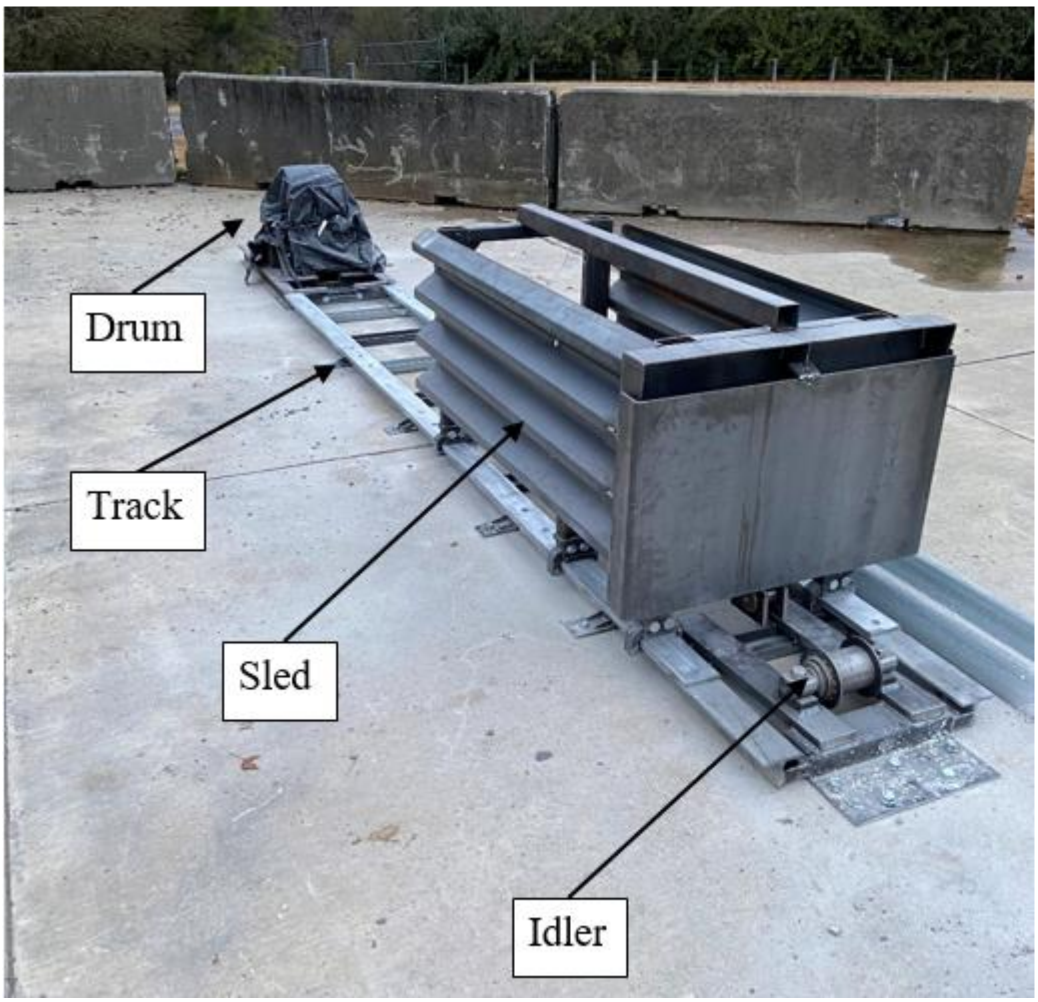
LEARN MORE

<Provide link to final report or other pertinent info, such as how to access an online tool.>

IMAGES






Drum
Track
Sled
Idler