Development of Compact Shock Energy Absorber to Improve Structural Crashworthiness

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ABSTRACT
This paper describes the development and analysis of a new compact shock energy absorber (SEA). The device utilized the unique reversible phase transformation behavior of Ultra High Molecular Weight Poly-Ethylene (UHMWPE) material under pressure. UHMWPE acts as an excellent damper as it transforms into a viscous fluid state under critical compressive stress. A prototype test confirmed the device’s high energy absorption as well as high damping capabilities at high deformation rate. The results of the test were used to calibrate a finite element (FE) model that enables scalability of the SEA for practical applications. Preliminary design and FE simulations were made under a Federal Railroad Administration (FRA) sponsored program to use SEA to enhance locomotive crashworthiness. The primary objective of the program was to prevent locomotive override in the event of an inline collision with a consist of hopper cars at a closing speed of 30 mph. The FE model, without SEA, was validated to a previously performed full-scale locomotive crashworthiness test. The simulation results with a number of shock absorbers used as crash energy management (CEM) system show no locomotive override up to 30 mph collision speed.

Keywords: Shock energy absorber, structural crashworthiness, ultra high molecular weight poly-ethylene, phase transformation, impact velocity, locomotive collision, finite element simulation, locomotive crashworthiness

INTRODUCTION
Insuring crew and public safety is a vital area for railroad research. The work described in this paper is part of an ongoing program within the Federal Railroad Administration (FRA) to improve the crashworthiness of locomotives and reduce the severity of rail collisions. The main objective of the current work is the development and validation of Crash Energy Management (CEM) to limit the possibility of locomotive override during an in-line collision. This approach permits absorption of a portion of the impact energy associated with the collision. Managing the energy during the event is advantageous as it dissipates peak impact forces, reduces extent of damage or loss of crew survival space, and decreases the potential for locomotive override onto the impacted vehicle. To insure railroad safety, the design of transportation systems includes regulations for structural crashworthiness verification, in addition to validation of design strength requirements. The Association of American Railroads (AAR) Standard S-580 on Locomotive Crashworthiness Requirements [1] and 49 CFR Parts 229 and 238 [2] provide design guidelines and practices for structural design of rail vehicles. In Europe, the European Standard EN 15227 defines crashworthiness requirements for rail vehicle bodies [3] including requirements for energy absorption during crash events. Structures cited include couplers, draft gear, and buffing systems – either side mounted or behind the draft gear. The more recent standard, EN 15551 published in 2009 [4], defines the design

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requirements of buffers for locomotives and passenger coaches to meet the crashworthiness requirements of EN 15227 in normal service. U.S railroad locomotives, however, do not use side buffers. This implies that in the event of an inline crash, the energy absorption/dissipation is achieved only in the coupler and draft gear or through the deformation of other structures. In the case of a high speed collision, the excess kinetic energy is transferred to the impacted rolling stock and, very often, converted into potential energy by way of locomotive override.

This paper describes the conceptual design and viability of shock energy absorbers (SEA) fitted to the locomotive under-frame to minimize the possibility of its override at a collision speed of 30 mph. This involved innovative design and prototype test-validation of a new kind of SEA, finite element modeling (FEM) and calibration of a freight train collision with a hopper car consist, the results of which was available from a previous locomotive crashworthiness test performed at Transportation Technology Center in Pueblo, Colorado.

New SEA Concept Evaluation and Prototype Test

Several high capacity shock absorbers were assessed for possible applications to locomotive CEM. The stroke length and overall size requirements of oleo/oleo-pneumatic systems and collapsible buffers using crushable materials/tubes proved too large for the locomotive fore-body. This led to the exploration of innovative designs for a compact shock energy absorber (SEA) suitable for CEM systems in a freight locomotive. The SEA makes use of a low cost, commercial-off-the-shelf (COTS) plastic material - Ultra High Molecular Weight Polyethylene (UHMWPE) as the core material. A series of laboratory scale tests were performed to understand and evaluate the deformation and energy absorption behavior of cylindrical bars of UHMWPE material under high compressive loads. For quasi-static compression test, an INSTRON servo-hydraulic test machine was used. Figure 1(a) shows the quasi-static compression test setup and Figure 1(b) shows the force versus displacement response of the UHMWPE material subjected to plunger displacement rate of 10 inches/minute.

![Figure 1. UHMWPE Quasi-static compression test: test setup (a), and force vs. displacement plot (b)](image)

The test results offered insight into the deformation and energy absorption behavior of the UHMWPE material, including a phase transformation from solid to viscous fluid at critical compressive stress. The phase transformation process was further examined through quasi-static insertion of a flat-ended round threaded steel bar into the UHMWPE on the INSTRON. The UHMWPE bar was later axially sliced apart to reveal threaded grooves in the plastic and some viscous material oozing out ahead of the grooved section. The viscous material solidified after release, offering proof than the UHMWPE material undergoes a reversible phase transformation during the test. In order to verify the high strain rate (HSR) effects of dynamic impacts, the device was impacted with a pendulum based device at speeds up to 17 ft/s. Subsequent dynamic tests performed with pendulum impact revealed that the associated critical flow stress magnitude for phase transformation depends on the rate of straining of the material. Further, the magnitude of peak dynamic force developed during high speed impact depended on the velocity of impact as well as on the ratio of the cross-sectional area of UHMWPE material to that of the plunger.

Considering the critical flow stress of UHMWPE under quasi-static compression loading as a baseline data, a Dynamic Stress Multiplying Factor (DSMF) was defined as the ratio of peak dynamic stress at higher impact
speed to the flow stress under quasi-static loading condition. The DSMF permits estimation of the critical flow stress and the corresponding peak dynamic force magnitude under high speed impact conditions. Through the evaluation of results of several pendulum impact tests it was possible to evaluate the high strain rate (HSR) deformation and energy absorption behavior of UHMWPE.

The authors investigated scaling effects through both dynamic finite element analysis (FEA) and physical prototype testing. An SEA prototype sized for a locomotive application was developed for evaluation. Based on previous testing, the unit was estimated at 80,000 ft-lb (60 kJ) of capacity. FEA simulation, shown in Figure 2, predicted the performance of the unit from an impact of 27,000-lbs at 13 ft/s. Figure 2(a) shows the finite element model itself, Figure 2(b) shows the von-Mises stress contours at 50 ms after impact, and Figure 2(c) shows the effective plastic strain distribution of UHMWPE material within the cylinder 100 ms after impact.

![Figure 2](image2.png)

**Figure 2.** Finite element analysis of SEA prototype: (a) FEM, (b) Effective (von-Mises) stress contours, and (c) Plastic strain distribution in UHMWPE

The unit was tested at ASF-Keystone in Harrisburg, PA, using 27,000 lb drop hammer. Photographs of the prototype SEA during drop hammer impact test are shown in Figure 4(a) and Figure 4(b). Test data from the 30-in drop height (equivalent to impact velocity of 12.7 ft/s) is shown in Figure 4(c), along with FEA prediction. From Figure 4(c), the total energy capacity during the event can be estimated. The area under the force versus displacement curve is 971,070 in-lb. The total work done by the hammer is estimated at 987,390 in-lb (27,000 lb over 36.57 inches). A small amount of energy is dissipated through friction in the system. Some energy is also dissipated in slight oscillatory motion of the plunger. These are evident in the force versus time and displacement versus time curves shown in Figure 3. In the FEA, dynamic coefficient of friction between UHMWPE and steel plunger was taken as 0.12 based on the data available from the manufacturer. This comparison of FEA results with that obtained from the prototype SEA test showed good overall correlation for peak dynamic force and displacement, allowing for performance prediction for system design during FEA.

![Figure 3](image3.png)

**Figure 3.** Prototype impact force and displacement variation with time plot showing effective damping performance prediction for system design during FEA.

**CEM System for Improved Locomotive Crashworthiness**

Earlier DOT/FRA research on Locomotive Crashworthiness [5] reports that crash energies of approximately 20 Million in-lb are capable of lifting the front of a 200-ton locomotive up to 10 feet during an override. Therefore, any CEM system designed for the locomotive must be capable of absorbing/dissipating a significant portion of this energy to be effective in preventing override.
Figure 4. Results from prototype drop hammer test: (a) before impact, (b) after impact, (c) dynamic force versus plunger displacement plots from test and FEA simulation.

For an in-line collision, contact between the locomotive and a rolling stock or a trailing car begins at the coupler, transfers through the draft gear, into the rear structure of the draft gear pocket, and ultimately to the sill. External structures (those outside of the draft gear) impact the pilot plate and snow plow, transfer into bending these structures, and finally impact the front trucks of the locomotive. In practice, this implies that any CEM system needs to be located within this space to be effective. The overall length of travel is less than 2 ft.

In view of space constraints within the locomotive structure, some distribution of dissipative and structural elements is needed. This approach best utilizes the space underneath the front ladder (stairway) located in the locomotive fore-body such as in an EMD SD70 locomotive.

Crash dynamics define the required load paths. One path must pass through the coupler and draft gear pocket, as this is the first point of contact between rolling stocks. This path is part of the current locomotive structure, and requires only increased dissipation capacity. However, a second path to transfer load between the frame and trucks of the impacted car to the locomotive sill does not exist. The pilot plate and snowplow do not have sufficient stiffness to transfer impact loads back to the locomotive sill.

To create the second load path, the authors designed a relatively stiff reaction plate just forward of the locomotive front trucks. This plate is a sandwich of tubular steel sections covered by two steel faceplates. This provides increased stiffness and reduces the tendency to buckle at impact. Side gussets along the outer edge support the reaction plate. The gusset is a significant increase in stiffness over the current snowplow support, and provides a direct load path to the locomotive sill. The pilot plate and snowplow remain in their current location, but the structural connection passes directly aft to the reaction plate rather than a cantilevered connection to the sill. The space between the pilot plate and reaction plate houses the SEA array. Figure 7 shows the completed arrangement. Where needed, additional box section stiffeners provide greater load-bearing capacity to the reaction plate. Placement of the reaction plate and gussets provide sufficient clearance for truck rotations under normal turning operations. Stiffening of the pilot plate provides for uniform force distribution to the energy absorbing elements.

In Figure 7, six (6) energy absorbing elements are placed between the plates. Distribution of these elements allows for maximum use of space between the point of contact (pilot plate) and the final load transfer component. A central large element provides additional capacity directly behind the draft gear pocket. With the plates in place, the length available for the SEA units is 17 inches. This represents the maximum separation distance available between rear-face of the pilot plate and the front face of the reaction plate. Figure 7 shows a top view of...
the full CEM system. The pilot plate is transparent to show of the energy absorbing elements. The sidewalls of the draft gear pocket slide axially rather than being directly welded to the underside of sill. This allows the draft gear to shift rearward into the SEA during impact. The extended stroke provides for increased energy absorption as well as control of crash force build-up for a longer timeframe. This limits the underbody deformation and prevents the draft gear from dislodging ahead of the trucks.

The stroke of the CEM system allows the draft gear to engage the central energy absorbing element as the impacted car sill strikes the pilot plate. Areas of maximum impulse react with the largest forces by varying the size of the energy absorbing elements. A simplified calculation of the energy in a 30 mph impact indicates an estimated total capacity of 32 million in-lbs for all seven energy absorbing elements in the system. Finite element analyses (FEA) described here shows the effect of dissipation in these areas.

Analysis and Validation of Crash Dynamics
Dynamic finite element analysis (FEA) of the CEM system established the improved performance during inline collision. The analysis simulates an actual test event in which a consist of hopper cars is impacted by an EMD SD70MAC locomotive along with three trailing hopper cars. The test, performed at Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado, provided video, acceleration, and deformation data associated with a 32.1 mph collision. The test data allows for calibration of the FEA model for the baseline locomotive EMD SD70. Following this analysis, the SD70 locomotive model was updated to include the CEM system and the collision event was re-run for the same conditions.

The standard SD70MAC locomotive model is shown in Figure 8. The model uses finer meshing in the front end of the locomotive to allow for observation of extensive post-collision deformation. The remainder of the model uses relatively “coarse meshing” for computational expediency. A similar FE model, shown in the same figure was developed for an open-top hopper car. This model matches a typical Union Pacific Railroad (UP) open-top hopper car. The simulation uses multiple copies of this car throughout the simulation. The overall model represents a consist of 35 stationary loaded hopper cars, although only four are shown in FEM of the consist for ease of computation. The first impacted car utilizes a fine mesh structure to account for large deformations during simulation. The simulated mass represents a fully loaded car. The model uses a coarser mesh version of the car in the second and third positions, both simulated as fully loaded. The fourth hopper car uses the coarse mesh, but has a simulated weight equivalent to that of 32 loaded hopper cars. Its coupler/draft gear stiffness also simulates the equivalent of 32 cars.

Case I – Test scenario from TTCI
The FEA simulation used the standard SD70MAC model, hauling three loaded hopper cars. The speed at impact is simulated at 32.1 mph to match the closing speed for the TTCI test. The impacting components of both the locomotive and the first hopper car of the impacting consist were fine-meshed as described previously. This
provides realistic deformation patterns following the collision with locomotive. Figure 9 shows the full-scale test and simulation results for the standard SD70 front end (without CEM) from the point of impact at 32.1 mph at t=0 millisecond (ms), t=300 ms, and t=500 ms. At t=300 ms the locomotive pilot plates are seen to have deformed to create a ramp that facilitates the locomotive front-end override over the hopper car trucks. At t=500 ms the locomotive front end overrides the truck of hopper car. Comparing the deformation and progression of locomotive override in these frames, it is clear that the simulation well represents the overall collision dynamics.

![Figure 9. Full-scale test and simulation comparison of SD70 without CEM at t=0, t=300 ms, and t=500 ms](image)

**Case II – Modified Locomotive with CEM System**

For this simulation, the CEM system is modeled into the SD70 structure. As seen in Figure 10, the modifications include the stiffened load transfer structure, the separable pilot plate and draft gear pocket, and seven energy absorbing elements dispersed within the locomotive fore-body structure. For the simulation, the stationary hopper car consist was identical to Case I. The collision speed of 32.1 mph is identical to Case I to allow direct comparison of CEM system performance.

The CEM-integrated FE model of locomotive assumes each SEA as a spring element, with each unit designed to have its characteristic critical peak force corresponding to UHMWPE phase change, at the end of stroke and the available maximum stroke as summarized in Table 1.

In Table 1, important geometric parameters, computed critical forces and maximum energy absorption capacity of all 7 SEA units are indicated and it is to be noted that one each of the small, medium and large size SEA unit is used on either side of the locomotive fore-body. The maximum possible crash energy absorption capacity of the designed SEA units constituting the CEM system amounts to 32.935 Million in-lb. Assuming a 60 percent efficiency of energy absorption under real life crash scenario, the CEM system can still absorb/dissipate 20 Million in-lb of crash energy, which may suffice to prevent the locomotive override which is suggested as the minimum requirement in the DOT/FRA report (5). Figure 11 shows the sequence of post-collision behavior of the locomotive with CEM system at 300 ms.

![Figure 10. FE Model of CEM system integrated to an SD70 under-frame](image)
and at 500 ms. This figure also shows that the energy dissipation and deformation control has maintained inline motion, creating large deformation in the impacted hopper car. The broken pilot plate does not form the ramp-like structure ahead of the locomotive’s front truck. This appears to prevent the locomotive fore-body from riding onto the hopper car. From Figure 11 it is observed that at 300 ms, the locomotive wheels have lifted slightly above the rails, but by the 500 ms mark the wheels have dropped back onto the rails. The locomotive nose has severely damaged the hopper car structure and spilled the simulated content (coal particles) of the hopper car.

Table 1. Design characteristics of SEA units comprising of the CEM system

<table>
<thead>
<tr>
<th>SEA Unit</th>
<th>Plunger Dia. (in)</th>
<th>UHMWPE Dia. (in)</th>
<th>Stroke (in)</th>
<th>Critical Force at Phase Change (lb)</th>
<th>Force at End of Stroke (lb)</th>
<th>Max. Energy Capacity (In-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central SEA</td>
<td>5.5</td>
<td>8.0</td>
<td>6.5</td>
<td>1,455,000</td>
<td>1,746,000</td>
<td>8,657,000</td>
</tr>
<tr>
<td>Small Size SEA</td>
<td>2.0</td>
<td>4.5</td>
<td>6.25</td>
<td>149,225</td>
<td>179,000</td>
<td>847,000</td>
</tr>
<tr>
<td>Medium Size SEA</td>
<td>3.75</td>
<td>6.0</td>
<td>6.0</td>
<td>635,000</td>
<td>765,000</td>
<td>3,435,000</td>
</tr>
<tr>
<td>Large Size SEA</td>
<td>5.5</td>
<td>8.0</td>
<td>6.0</td>
<td>1,455,000</td>
<td>1,746,000</td>
<td>7,857,000</td>
</tr>
</tbody>
</table>

Results from FEA Simulation with CEM System
Simulation of the locomotive with CEM showed that the intended goal of preventing locomotive override is achieved and the crash energy is dissipated in the CEM system as well as by extensive fracture and large scale deformation of the impacted hopper car. A closer examination of the draft gear and the central SEA deformation reveals that the sequence of energy dissipation events such as the shear pin failure, the coupler/draft gear collapse, the sliding of draft gear pocket walls to activate the full plunger displacement of the central SEA behind draft gear took place as envisioned in the design of CEM system. In essence, the crash energy dissipation by the central SEA was fully effective and it performed in the simulation as per design. However, the other six SEA units fitted between the modified pilot plate and the reaction plate on either side of locomotive did not perform as effectively and contributed partially to the crash energy dissipation through part of the designed plunger travels for each of the six SEAs. But a significant achievement of these distributed SEAs in preventing the locomotive override is that together they increased the stiffness of the pilot plates which inhibited formation of a ramp ahead of locomotive front truck. This resulted in the inability of the locomotive to climb over the hopper car. Instead, it enabled extensive crushing of the impacted hopper car structure by the locomotive.

Conclusions
In this paper, novel design of a new class of compact shock energy absorbers using low cost UHMWPE material is presented whose efficacy has been demonstrated through laboratory scale testing and also through prototype test and finite element analysis. From these design, testing and FEA simulation studies it can be concluded that it is possible to innovatively design crash energy management systems for railroad locomotives and other rolling stocks. However, this requires further focused investigations involving freight as well as passenger locomotives and coaches in order to optimize the low cost SEA/CEM system for improved crashworthiness.
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