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Design and Evaluation of Advanced Systems for Locomotive Crew Emergency Egress

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13. ABSTRACT (Maximum 200 words)
This report presents the results of the second phase of a program to develop innovative concepts for locomotive crew egress following a crash that damages the cab. The roof-mounted hatch system was fabricated as a working prototype and installed in a full-scale mockup of a toppled locomotive. Usability testing with experienced train crewmembers and emergency responders demonstrated the system's usability. Crewmembers exited the cab in under 20 seconds when uninjured. Two secondary egress systems were also designed and fabricated. A windshield that can be removed from the cab interior employs double looped cutting wires to sever the window gasket, thus allowing the glazing to be pushed out. A proof-of-concept prototype was installed and tested in the locomotive mockup. A removable door hinge, the other secondary egress system, employs a lever-actuated mechanism that releases the hinge leaf from the door, allowing a jammed door to be removed and allowing the crew to escape the cab. Easily removable hinge pins provide a means for emergency response personnel to easily remove the door from the exterior. A training video for emergency responders explains the structure and features of a locomotive and suggests techniques for removing crewmembers from the cab following a crash.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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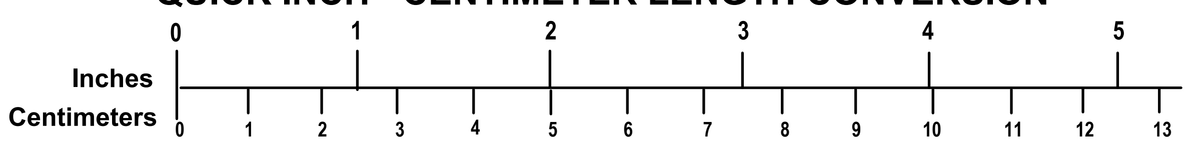
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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This report presents the results of the second phase of a program to develop innovative designs for a locomotive crew egress system. The Federal Railroad Administration (FRA) Office of Research and Development funded this work under Contract DTFR53-01-D-00029. Mr. John Punwani, the FRA Contracting Officer's Technical Representative, provided guidance and encouragement to the study team.

The usability tests would not have been possible without the generous cooperation of officers from the Brotherhood of Locomotive Engineers and the United Transportation Union, as well as the Fitchburg, MA, Fire Department. The authors wish to thank all of the participants in the usability tests who provided valuable feedback on the design and operability of the hatch system. The next phase of the development of the hatch system will incorporate their feedback and suggestions.

Special thanks are extended to Ms. Sarah Acton and Mr. John Flynn of Foster-Miller. Ms. Acton assisted in the recruiting of participants for the usability tests and in conducting the tests. Mr. Flynn was responsible for installation of the hatch system in the mockup. He also assisted with prototype construction and testing for the removable windshield and the removable hinges.

Dr. Peter Boyce, a consultant from the Lighting Research Institute at Rensselaer Polytechnic Institute, provided guidance on lighting options for the hatch system. Mr. Allen Bieber, an engineering consultant, reviewed the hatch and windshield designs and advised Foster-Miller on locomotive cab structural design issues.

Executive Summary

This report presents the results of the second phase of a program to develop innovative concepts for a freight locomotive crew egress system. The Phase I program evaluated three concepts that would be of particular use following a crash that toppled the locomotive. These concepts were (1) hand/footholds to aid climbing inside a toppled locomotive, (2) a roof-mounted escape hatch, and (3) an externally removable windshield. Feedback from train crews and emergency response personnel determined that the roof-mounted escape hatch with hand/footholds to facilitate its use was the preferred approach. Train crews were unanimous in their opinion that the removable windshield would have to be usable from the cab interior to be helpful to the crew.

Construction of a wooden system mockup in a toppled condition facilitated evaluation of the hatch system concept. Two test subjects were able to exit via the hatch system in under 30 seconds (s), thus demonstrating the concept's feasibility and utility.

Based on the results of Phase I, the current project had the following goals:

- Refine the locomotive cab roof escape hatch concept from a laboratory mockup into a working prototype device.
- Develop improvements in the secondary egress routes from the locomotive cab.
- Develop a training video suitable for rescue personnel describing the basic configuration of the locomotive and suitable techniques for effecting rescue of crewmembers following an accident.

Prototype Roof Hatch System

The roof-mounted hatch system consists of the hatch along with interior hand/footholds to facilitate access to the hatch and exterior grab irons to facilitate crew egress, as well as entry by emergency responders. The hatch opening is 21.8 inches (in) wide by 29.5-in long. It is defined by a steel frame weldment, with integrated points for the latches. Stiffeners around the roof opening maintain roof strength. Turning the handle approximately 40° in either direction and pushing the hatch panel outward releases the hatch. The hatch assembly encloses the operating mechanism.

A comparison of the roof areas with and without the hatch and their corresponding buckling loads indicate that the overall strength of the roof does not appear to be greatly changed by the addition of the roof hatch opening. This assures that the presence of the hatch will not compromise the roof's structural integrity.

The basic hand/foothold design is similar in approach to the hatch. The basic structure is a steel outer frame intended for integration into the roof of the locomotive. The hand/foothold hinges into the external frame so that it can be held flush to the interior cab roof when not in use. The rung itself is a single steel bar, 1 in. in diameter and approximately 11-in long.

Existing emergency lighting standards applicable to transportation vehicles formed the basis for the design of the lighting and marking scheme that would provide adequate illumination in the worst-case scenario of a smoke-filled cab following a nighttime crash. The lighting system incorporates two different techniques. The first technique created luminance contrasts for the details of the hatch and the hand/footholds. The second technique provided emergency lighting for the escape hatch and the hand/footholds. Photo-luminescent materials create the desired lighting scheme. These materials are inexpensive, reliable, easy to install, and virtually maintenance free.

To evaluate the overall utility of the egress concepts developed under this program, Phase I included construction of a full-size mockup of a freight locomotive cab. Phase II involved installation of the hatch system, including the hand/footholds and emergency lighting system, as well as the removable windshield, in this structure.

Usability Testing

Usability testing examined the functionality of the hatch system in the mockup facility. Both train crew personnel and emergency response personnel participated in the tests. An Institutional Review Board reviewed and approved the study design. A total of six train crewmembers, four conductors and two engineers, participated in the usability testing. In addition, an emergency rescue crew from the Fitchburg, MA, Fire Department provided the emergency responder usability assessment.

Train crew participants evaluated four different scenarios. Participants were able to use both arms and legs to access the hand/footholds and grab irons to quickly extricate themselves from the cab. In the uninjured/daylight scenario, the average exit time was under 17 s. Darkness added only 3 s to the exit time.

Teams of emergency responders, dressed in full rescue gear with all necessary rescue equipment on hand, attempted to remove an injured 230 pound (lb) male from the cab. A minimum of three people was required to carry out the rescue. Rescue time ranged from 8.5 to 9 minutes (min).

Overall, the usability tests showed that design of the hatch system was effective in its purpose. It allowed for a safe and efficient escape for train crewmembers and was sufficient in permitting rescuers to successfully retrieve an injured victim from inside the cab using a backboard. The hatch and hand/footholds were very straightforward and easy to use, while the grab irons provided adequate holds to assist with entry and exit. Photoluminescent materials also successfully illuminated the escape route during darkened conditions.

Train crew and rescue personnel made several suggestions for improving this egress system. Their suggestions included placing photoluminescent or retroreflective materials around the exterior of the hatch, replacing the folding bars on the hand/footholds with fixed bars, and placing small horizontal grab irons above-left and above-right, as well as below-left and below-right of the opening.

Removable Windshield

Current locomotive windshields have one of two basic designs: frame mounted or non-frame mounted. Development and testing of the removable windshield concept used the non-frame mounted design because candidate gasket-cutting methods could more easily be evaluated and demonstrated without the frame.

The researchers evaluated four design concepts for cutting the gasket. The double twin loop cutting wire proved to be the most effective technique. With this method, each loop must cut half of the gasket on the top of the windshield, the top outer corner, and the entire length of the small vertical side of the windshield for a total of 48 in. Prototype testing showed that, with that amount of the gasket cut, the bottom length of the gasket acts as a hinge, and the glazing is easily pushed from the windshield. One actuator, a winch, collects both wires, which are inserted through black rubber sleeves as they approach the winch.

A prototype windshield was fabricated and installed in the mockup. Usability testing demonstrated that the maximum force required to activate this emergency egress system was 10 foot-pounds (ft-lb). Once the gasket was cut, the torque required to maintain the cutting process was about 4 ft-lb. The time required to cut the gasket, push out the glazing, and exit the cab was approximately 50 s.

Removable Door Hinge

A locomotive crash may cause the hinged doors of the locomotive to become inoperable. An innovative door hinge provides a means for the crew to release the hinges from the cab interior and remove the door. The door side of each hinge is held firmly in place inside a machined slot of the hinge attachment steel block with a single fastener bolt. A weld holds the machined block to the edge of the door panel. Four compression springs in blind holes of the block hold the leaf of the hinge in position. When the emergency hinge release handle is actuated, it releases the fastener nuts, which in turn release the hinges. For evaluation of this system, a rear door was fabricated along with the hinge release mechanisms. A laboratory test of this door in a test rig representing a locomotive door frame verified the functionality of the removable hinges. Easily removable hinge pins provide a means to facilitate cab access for emergency rescue personnel from the exterior.

Training Video

This work also included preparation of a training video, “Locomotive Emergency Response Operations,” for emergency response personnel. The video provides rescue professionals with the specifics of locomotive construction and features. It also describes potential locomotive accident scenarios and suggests appropriate methods for responding to such incidents.

Recommendations for Future Research

The results of the Phase II work suggest areas for further research relative to improved egress systems for locomotive cabs. These include further refinements to the hatch system design, usability tests of the hatch system under a partial rollover condition, and validation of the functionality of the removable windshield and door hinges under accident conditions. Advanced egress systems that incorporate smart technologies, such as those employed in Intelligent Transportation Systems, also merit consideration.

1. Introduction

In 1992 Congress enacted the Rail Safety Enforcement and Review Act. This legislation required the Federal Railroad Administration (FRA) to conduct an inquiry into locomotive crashworthiness and the safety effects of cab working conditions on productivity. In response to this mandate, FRA undertook a comprehensive study of many aspects of locomotive crashworthiness (FRA, 1996). While the focus of this study covered many issues, it did suggest that the roof of the cab be considered as an emergency egress route. Since publication of this report, FRA has undertaken research projects that address many aspects of locomotive crashworthiness and its relationship to crew survivability. This report addresses improvements in crew egress routes, as well as access for emergency rescuers following a locomotive crash.

1.1 Background

In 2000, FRA initiated a preliminary study of existing cab egress issues (Kokkins, 2002). The objectives of this study were to survey, identify, and evaluate many aspects of current locomotive design and operation that affect crew egress or access by emergency rescue crews after a crash. This work included a broad survey of current egress and survivability issues and identified many opportunities for improvements. One area that this study identified as requiring improvement was equipment related to egress routes for crewmembers following a crash, particularly an accident in which the locomotive sustains structural damage and egress routes are limited.

A subsequent egress research program focused on evaluating three innovative egress concepts that would be of particular use following a crash that toppled the locomotive (Carter, Gertler, Acton, & Kokkins, 2003). These concepts were (1) hand/footholds to aid climbing inside a toppled locomotive, (2) a roof-mounted escape hatch, and (3) an externally removable windshield. Feedback from train crews and emergency rescue workers on the three concepts determined that the roof-mounted escape hatch with hand/footholds to facilitate its use was the preferred approach. This user feedback also led to several improvements in the basic concepts. The hatch redesign allowed it to fall away from the roof when opened, and the hand/footholds became an accessory to the hatch rather than a stand-alone system. To be a viable egress option for the crew, the removable windshield would have to be usable from the cab interior.

Construction of a system mockup facilitated evaluation of the hatch system concept. The research team constructed a full-sized locomotive cab, with an integrated hatch and hand/foothold system. The mockup is a wood-framed, plywood-sheathed structure representing a generic freight locomotive cab using dimensions common to General Electric (GE) and General Motors Electromotive Division (EMD) road locomotives currently in service (Figure 1). The mockup orientation represented a toppled locomotive for egress evaluation.

Two test subjects representing a likely range of personnel working as crew in locomotives provided a means to evaluate the utility of the egress system. Neither of the subjects was familiar with locomotive equipment or operations. Both were able to exit the toppled cab utilizing the hatch in 30 s or less.

An indepth analysis of the likely cost of the hatch system was not possible at this stage of development. A preliminary study, however, identified the cost implications of several aspects of the design. These issues relate to the initial engineering rather than the recurring component costs in manufacturing. As such, the overall cost for implementing the hatch in new locomotives should be low. After a working prototype is developed, the issue of cost must be re-examined in more detail.

The results of this phase of egress research demonstrated the potential utility of the hatch system. This experience also led to the identification of areas for further research related to improved egress for locomotive crews. These areas were (1) the refinement of the design of the roof hatch system into one that can be manufactured and installed in new locomotives and (2) re-evaluation and development of two secondary egress options, the internally removable windshield and the removable door hinge. The work described in this report focused on these two areas.

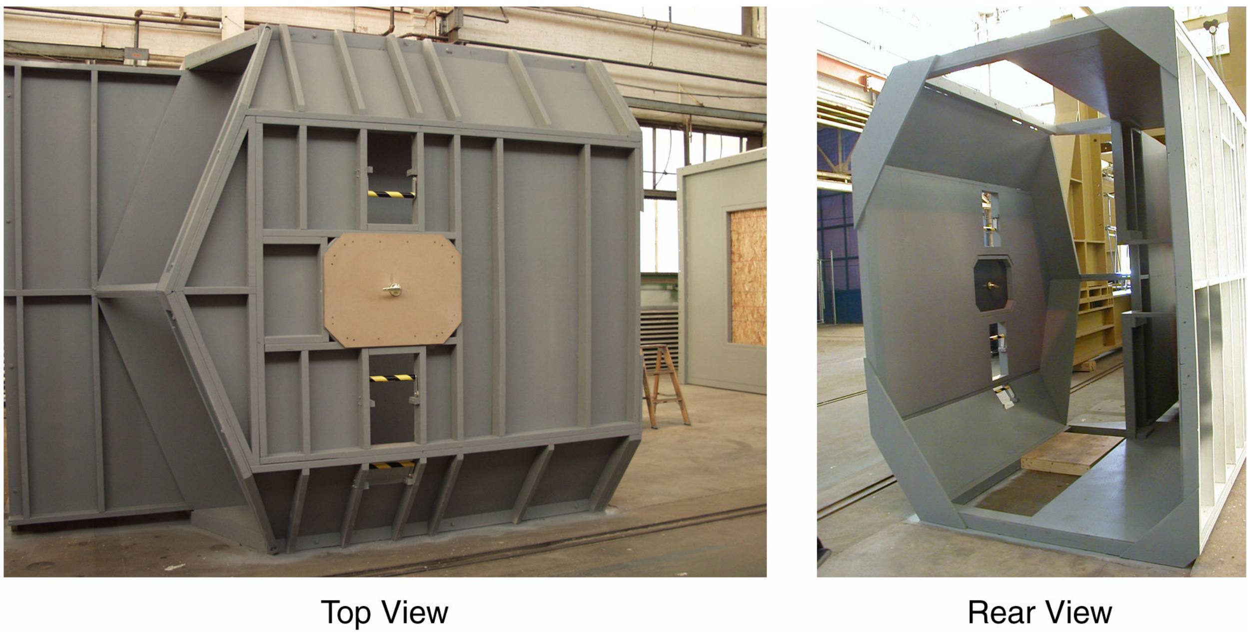

Figure 1. Locomotive cab mockup with proof-of-concept hatch system

1.2 Objectives

The purpose of the research described in this report was to develop and evaluate a prototype roof hatch egress system, as well as secondary systems to enhance crew egress in the event of a crash. The project had the following goals:

- *Refine the locomotive cab roof escape hatch concept from a laboratory mockup into a working prototype device.* By fully developing the roof hatch concept, the major design challenges can be addressed, clearing the way for integration into future locomotive designs. Usability testing by railroad crews is a key element of the design process. Feedback from potential users at this point allows for design refinements and improvements before full implementation.
- *Develop improvements in the secondary egress routes from the locomotive cab.* Phase I of this program evaluated removable windshields and door hinges as possible egress enhancements. In this phase, these approaches must be re-evaluated and designed for incorporation into the egress mockup. The removable windshield concept would provide

a large opening that would be accessible for both railroad crews and rescue personnel for nearly any accident scenario. The removable door hinge pins would provide a means of freeing a doorway jammed due to deformation of the cab.

- *Develop a training video suitable for rescue personnel describing the locomotive's basic configuration and suitable techniques for effecting rescue of crewmembers following an accident.* In the Phase I egress program, feedback from rescue professionals indicated a need for more knowledge of railroad accidents. Currently, rescue efforts may be slowed while personnel develop procedures on-the-fly. Development of a training video provides a means of familiarizing rescue professionals with the specifics of railroad equipment and potential accident scenarios, thereby enhancing their capabilities for rapid emergency response.

1.3 Overall Approach

The overall approach to the development of all three egress concepts–hatch system, removable windshield, removable hinges–has been to develop a proof-of-concept model and then to undertake detailed design and fabrication to produce a working prototype. Since the hatch system potentially involves structural change to the locomotive cab, the design and fabrication process had several steps.

Design of the hatch system began with a structural analysis of the roof. This was necessary to assure that the roof strength would not be compromised by the presence of the hatch. Once the roof structural integrity was established, detailed design of the hatch cover, latching mechanism, and seal could proceed. Design of the hand/footholds did not have structural implications so this design process focused on the mechanical aspects. After design, fabrication, and installation of the complete hatch system in the mockup, the research team could develop and implement a lighting, signage, and marking scheme. Usability tests, conducted in the mockup with train crews and emergency responders, identified areas for design modification.

At this stage of development, the removable windshield became a working prototype for the purpose of illustrating the concept's feasibility. The project team installed and tested the removable windshield for operability in the mockup. The removable door hinges were designed and fabricated first as a working stand-alone prototype. It was not possible to install the door assembly in the mockup because the wooden mockup, in its present configuration, could not support the weight of the steel door and frame. Installation of the hinge system in a test structure, however, did allow evaluation of the door for functionality.

1.4 Scope

The scope of this research was limited to road freight locomotives. While the egress concepts explored in this effort can potentially be incorporated into passenger and switching locomotives, the structural design considerations will differ for each type of locomotive. Since crew egress from a toppled locomotive is the most challenging situation, the present study focused primarily on the hatch system that addresses this scenario. Improvements in secondary egress options, the windshield and rear door, will enhance the crew's survivability whether or not the locomotive remains upright after a crash. The hatch system mockup is a working mechanical prototype. The removable windshield and removable door hinges, although operable, only illustrate the feasibility of the concepts.

1.5 Organization of the Report

Section 2 describes the design and construction of the prototype hatch system that consists of both the hatch and hand/footholds to facilitate access to the hatch. Section 3 describes the usability testing of the hatch system. Sections 4 and 5 focus on, respectively, the removable windshield and the removable door hinge. Section 6 provides recommendations for future egress research. The appendices contain copies of the materials from the usability test process. The training video is a separate stand-alone product. Appendix D describes the content of this video.

2. Prototype Roof Hatch

This section describes the basic design approach for the prototype roof hatch. The objective of this design task was to develop a working model of the hatch, demonstrating possible construction techniques that could be used in a deployable system. The project team constructed the design described below for use in the egress mockup during usability testing.

2.1 Roof Design Changes

Installation of the basic roof hatch concept into an existing locomotive design will require some structural alterations to the roof. In general, an opening will need to be provided in the roof, sufficient to allow the egress of a crewmember. This must be done in a way that does not compromise the integrity of the roof structure. The framing of this opening must provide for the installation of a hatch panel to seal the cab from the elements. The frame must be rigid enough to maintain its shape and not wedge or jam the hatch in the event of a rollover. Identifying the means to implement these changes occurred before the detailed design of the hatch.

2.2 Estimation of Roof Strength for Hatch Opening

Before beginning detailed design of the hatch mechanism, the researchers performed some simple calculations of the roof structure. This was done to insure the integrity of the cab once the hatch was installed. As a first-order approximation, a key assumption was that the roof would be subjected to a frontal impact, with the line of force acting through the structural centroid of the roof panel. Another assumption was that buckling of the roof structure would be a worst-case scenario, causing large off-axis deflections and local deformations in the area of the hatch.

The facing area of the roof structure in the new design matches that of the current roof structure. This insures that the installation of a hatch does not compromise the overall strength of the cab roof. A shift in longitudinal numbers accommodates the required 22-in wide opening. The redesigned roof follows the same basic welded construction techniques as current cab designs. Designers assumed that all structural members are formed from 0.09 steel stock welded to the roof panel. The roof panel itself is assumed to be 0.187-in thick.

A simplified plate buckling analysis provided a baseline estimation of roof strength. This analysis assumed that the roof panel acts as a flat plate with clamped edges and that the principal loading is along the width of the roof panel (along the axis of the cab roof). Using these parameters, the critical bending stress is given by Young (1989) as:

$$\sigma_{crit} = \frac{KE(t/b)^2}{\left(1 - \nu^2\right)}$$

where σ_{crit} = Critical stress for buckling
E = Material modulus (for steel–29 Mpsi)
ν = Poisson's Ratio
t = Plate thickness
a = length of the plate
b = width of the plate

The empirical constant K is a function of the ratio of width and length of the plate. Tabulated values are available in Young (1989). Both the GE and EMD roof panels are roughly square. As given by Young, K is 7.7 for a square plate (a/b=1).

With the critical stress determined, multiplying the critical stress by the facing area of the plate provides the critical load. With the cutout for the hatch, the effective area of the roof is reduced to the area around the hatch itself. For each of the locomotives studied, this is the width of the roof panel less the width of the hatch, applied over the length of the hatch.

This analysis neglects the effects of the longitudinal stiffeners running along the cab roof. As such, it is conservative.

The design process considered likely changes to the roof structure for both a GE and an EMD locomotive. Figure 2 shows the roof structure of the GE AC4400 with and without the hatch opening. Figure 3 shows the equivalent changes for the EMD SD70MAC. These two locomotive designs represent the structures currently under test by the researchers as part of an ongoing study into crashworthiness of freight locomotives.

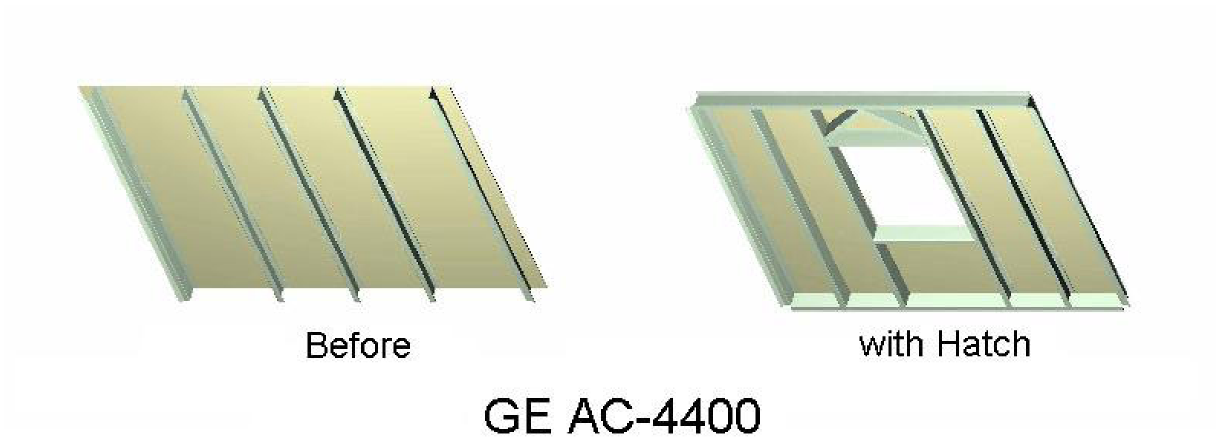

Figure 2. Roof structure for GE AC4400

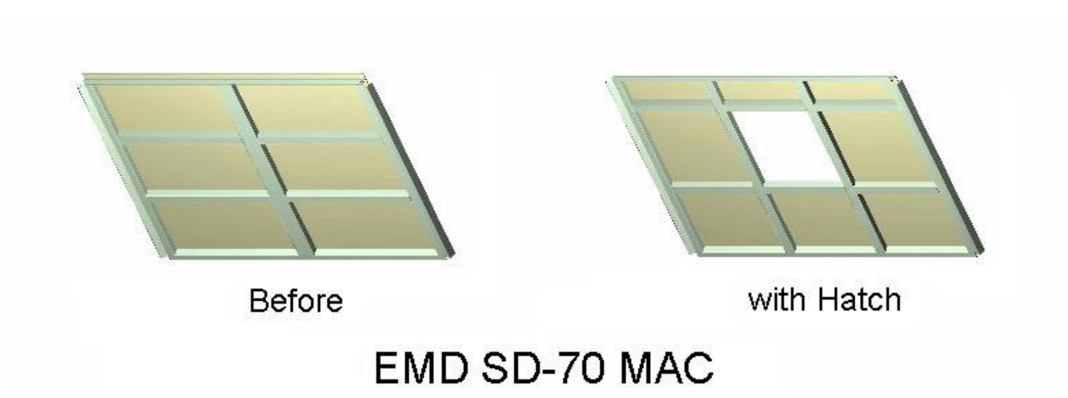

Figure 3. Roof structure for EMD SD70MAC

Table 1 shows a comparison of areas and buckling loads for the cab roofs (both SD70MAC and AC4400).

Table 1. Estimated buckling area of locomotive roof

	EMD SD70MAC		GE AC4400	
	Original	**Modified**	**Original**	**Modified**
Area (in^2)	12.56	8.8	14.04	7.9
Critical Buckling Stress (psi)	1,944	1,590	4,418	5,053
Critical Buckling Load (lb)	41,686	38,128	36,873	40,273

Based on these calculations, the overall strength of the roof does not appear to be greatly changed by the addition of the roof hatch opening. As noted before, this analysis neglects the effects of the longitudinal stiffeners running along the hatch roof. An additional stiffener added to the original structure in both designs framed the hatch opening (see Figure 2 and Figure 3). This added stiffener should ensure that the new structure is stronger than the original design. Once specific loading and design criteria are set, a more detailed analysis may be necessary to verify the actual buckling strength of the structure.

2.3 Design of the Prototype Hatch System

The roof hatch system consists of two elements, the escape hatch and the hand/footholds. The following subsections describe each of these subsystems individually.

2.3.1 Escape Hatch Design

The basic escape hatch must fill the rectangular opening in the cab roof, be operable from both inside and outside the cab, and, ultimately, seal against weather. The prototype design addresses all of these issues, although the current design would not be completely weather tight. In addition, the design of the prototype allowed for its integration into the wooden mockup frame. It would, however, require only small changes to adapt it to an actual locomotive. Figure 4 shows the conceptual design.

In practice, an extruded neoprene rubber gasket seals the space between the hatch panel and the frame. For clarity, the seal does not appear in the figures.

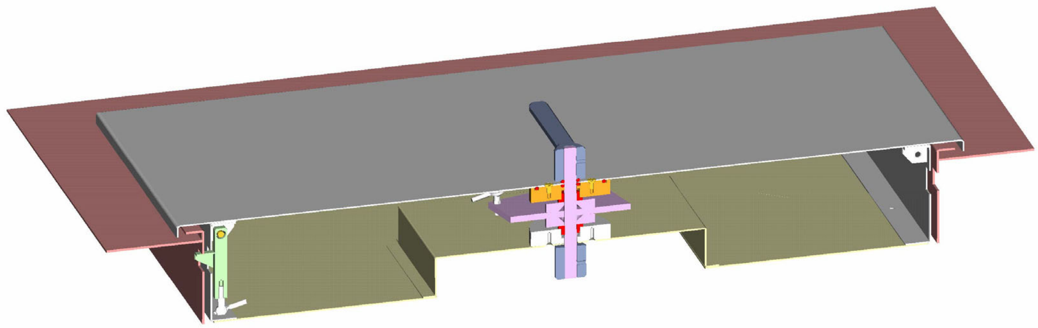

Figure 4. Conceptual design of the emergency escape hatch

2.3.2 Frame Design

The design of the frame mimics the rectangular opening used in the roof evaluations. The free area is 21.8-in wide by 29.5-in long. A steel frame weldment, with integrated points for the latches, defines the opening. Figure 5 shows the hatch and frame. For clarity, the inner hatch frame is not part of this illustration. In practice, the open space in the hatch would contain an acoustic dampening material to reduce noise transmission through the hatch.

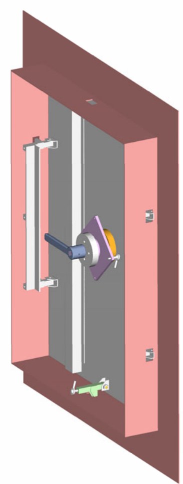

Figure 5. Hatch and exterior frame

2.3.3 Mechanism Design

The operating mechanism is an integral part of the hatch assembly. The exterior structure of the hatch is a steel assembly consisting of an upper panel, a lower enclosure, and steel bezel to cover the mechanism.

Turning a handle on either the interior or exterior of the cab disengages the latching mechanism. Both handles are tied to a common shaft, which in turn is tied to the actuator plate. Two non-metallic bearings guide the shaft rotation. A round guide plate ties the bearings to the hatch structure. O-rings provide a seal for the outer guide plate and outer end of the shaft. Figure 6 shows the handle assembly. Tie rods join the actuator plate to the latches. A single latch is at each end of the hatch. Along the sides of the hatch, two latches are joined by a common bar so that they can actuate simultaneously. Figure 7 shows the mechanism schematically.

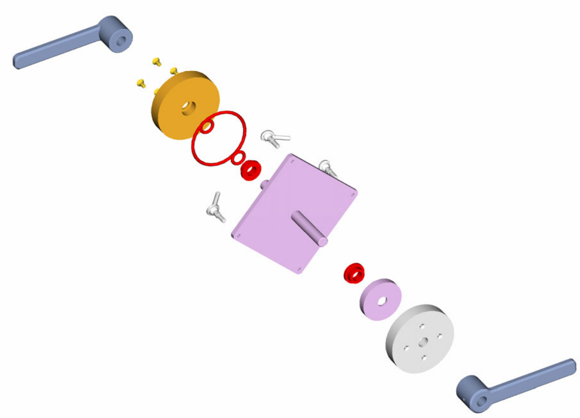

Figure 6. Handle assembly

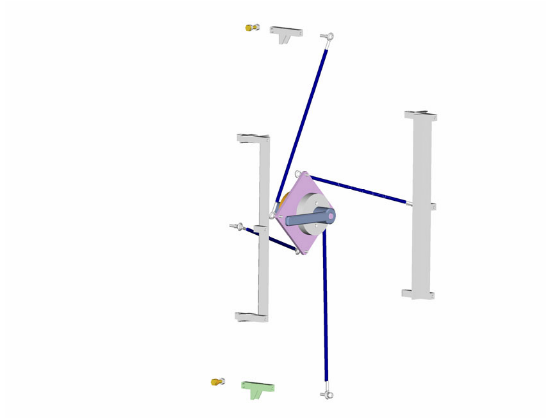

Figure 7. Mechanism schematic

The latches pass through openings in the lower enclosure frame. Figure 8 shows this frame, along with the latch components. These openings coincide with the latching points in the outer locomotive frame. Figure 9 shows a detail of the end latch.

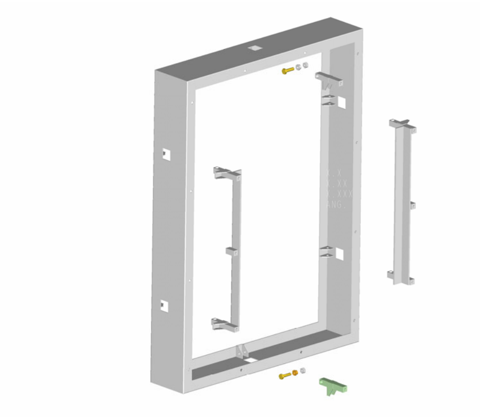

Figure 8. Lower enclosure frame

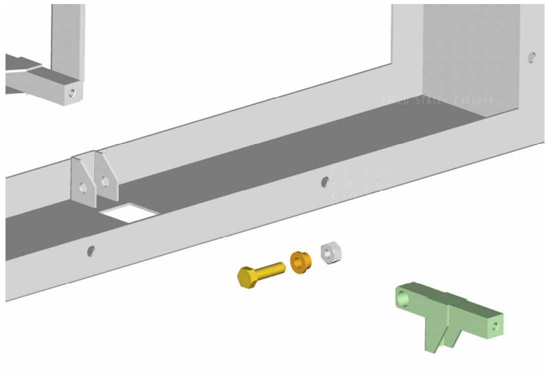

Figure 9. Latch details

Turning a handle approximately 40° in either direction releases the hatch from the opening. Removal requires an outward push.

2.3.4 Hand/Foothold Design

The basic hand/foothold design is similar in approach to the hatch. The basic structure of the mechanism is a steel outer frame intended for integration into the wood-framed roof of the mockup. This approach allows the basic design to be adapted to an actual locomotive frame with a minimum of changes.

As shown below in Figure 10, the hand/foothold hinges into the external frame so that it can be held flush to the interior cab roof when not in use. The rung itself is a single steel bar, 1 in. in diameter and approximately 11-in long. When stowed, it is held in place by a detent pin. When needed, pulling outward on the rung deploys the hand/foothold. This overcomes the detent force, allowing the rung to swing downward as shown in Figure 11. Two angular braces fold out with the rung to provide added support.

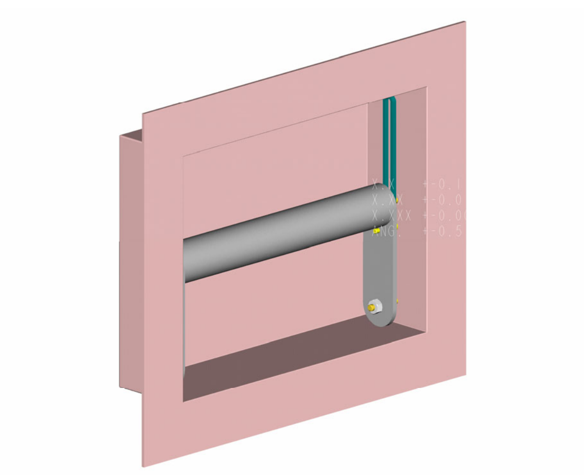

Figure 10. Hand/foothold, stowed

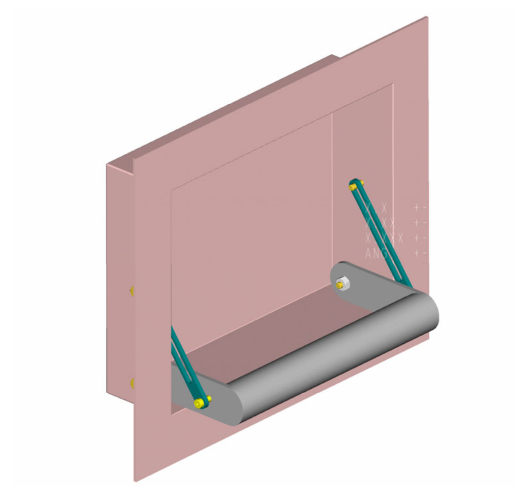

Figure 11. Hand/foothold, deployed

The hand/foothold design assures that it is usable in either the deployed or stowed condition. If the hand/foothold is jammed in the stowed condition, sufficient space still exists around the rung to allow grasping or standing if need be.

2.4 Prototype Construction

Local machine shops manufactured the hatch system in accordance with fabrication drawings. The structural elements consist of welded sheet metal. The mechanism is a combination of custom-machined parts and commercial off-the-shelf hardware. Although the design process involved some effort to keep the costs of the prototype low, the designers did not try to minimize the overall manufacturing costs for the system. Since some redesign would likely be required after functional testing, cost reductions in the design were beyond the scope of this phase.

2.4.1 Prototype Hatch

The prototype hatch is a welded steel frame that supports the removable door panel. The panel itself consists of a welded steel outer shell, an integrated latching mechanism, and a cover panel. Tie-rods couple the latches to the rotating mechanism.

The series of photographs that follow show the hatch with the cover plate removed so that the mechanism can be more easily seen.

Figure 12 shows the center rotary mechanism. In this photo, the mechanism is slightly skewed from the latched condition. Four tie-rods can be seen leading from the square actuating plate to the latch cams. In the latched condition, the mechanism is a point of minimum mechanical advantage. In this way, the device operates into increasing mechanical advantage as it is opened. When first assembled with a neoprene foam weather gasket in the hatch panel, the reactive pressure exerted by the gasket force was sufficient to force the hatch open. To correct for this, four detents in the bearing plate (round metallic plate visible in Figure 12) lock the mechanism in the latched position. With the detents installed, it requires approximately 10 lb of force to actuate the mechanism and overcome the detents. In Figure 13, the mechanism is in the open condition.

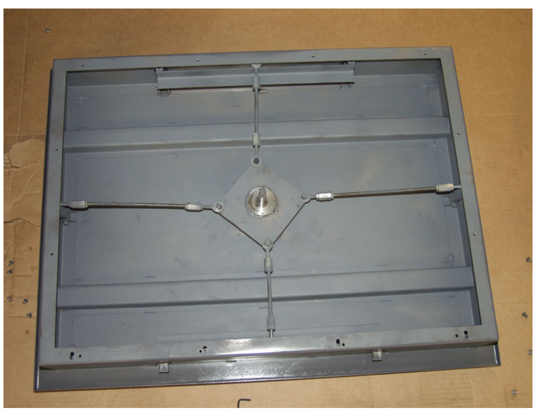

Figure 12. Latching mechanism near the closed position

Figure 13. Latching mechanism in the open position

Along the long axis of the hatch panel, two latch cams are actuated from a single point, as shown in Figure 14. The tie-rod attaches to a central point along a latching bar. The bar is welded to the latch cams at each end and pivots about a single axis. In this way, the side latches operate both cams simultaneously.

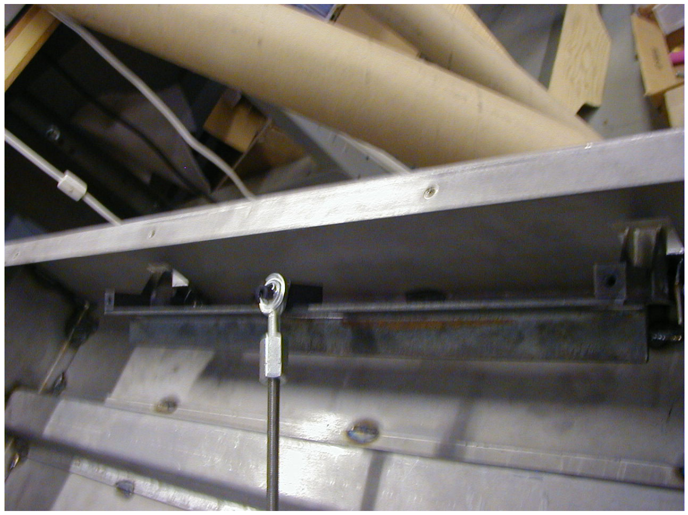

Figure 14. Side latch cams and latching bar

Figure 15 shows an end panel latch cam from inside the hatch. The cam is in the latched position. The top end of the cam attaches to a tie-rod through a rod-end bearing that provides angular freedom along with rotary motion. Figure 16 shows a view of the cam from the outside of the hatch. In this condition, the cam protrudes through the hatch and would lock itself to a similar opening in the frame.

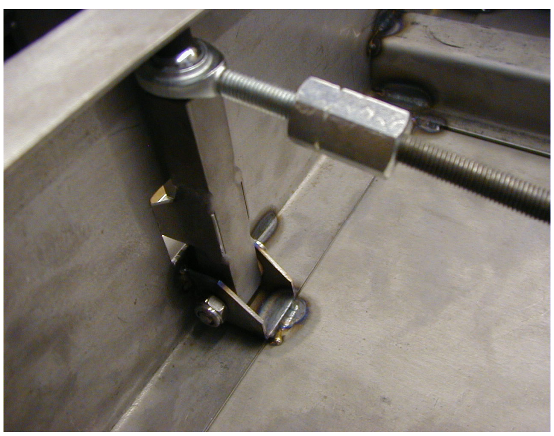

Figure 15. Latch cam in the latched condition, interior

Figure 16. Latch cam in the latched condition, exterior

As the mechanism rotates, it pulls the cam back from the side of the hatch, allowing the entire latching surface to recede into the inner frame, as shown in Figure 17. Figure 18 shows an external view of this. In this condition, the entire latch face is withdrawn into the hatch panel, allowing the hatch to be freely removed from the frame.

Figure 17. Latch cam in the open position, interior

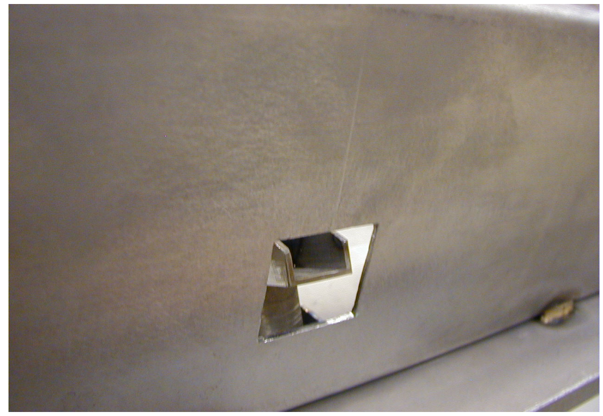

Figure 18. Latch cam in the open position, exterior

2.4.2 Prototype Hand/Footholds

The prototype hand/footholds use the same welded steel construction as the hatch. The outer frame supports a movable rung. The frame is seam welded along the upper corners and closed at the back. A series of holes drilled along the perimeter provides a means of mounting the frame to the wooden locomotive cab mockup. In practice, the frame would be welded into the cab roof structure.

The rung pivots at the lower corner such that in the stowed condition, it resides in the center of the box. A detent pin holds the rung stowed, and pulling on the rung will cause it to open when needed.

The following photographs show the hand/foothold. Figure 19 shows the hand/foothold in the stowed condition. The mounting holes are visible along the lower edge.

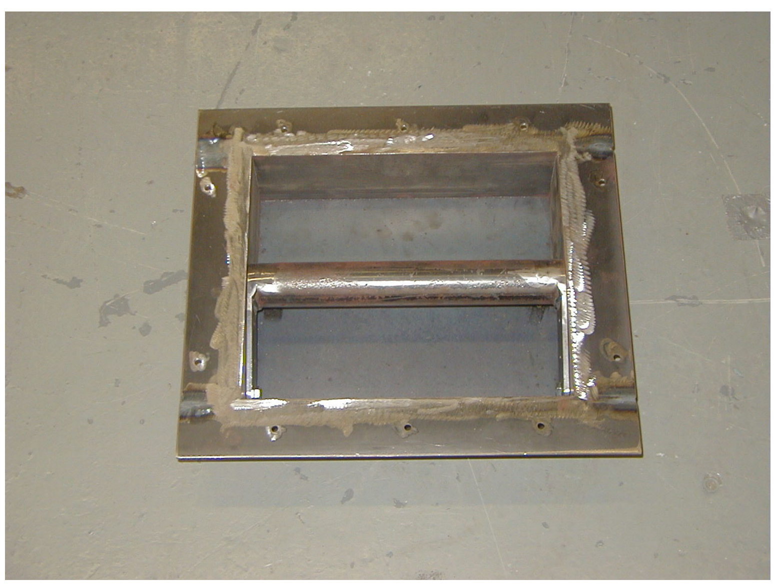

Figure 19. Hand/foothold in the stowed condition

Figure 20 shows the detail of the rung. In the stowed position, the outer surface of the rung is flush with the frame of the box. This provides sufficient space around the rung for grasping or standing should the rung become jammed as the result of an accident. In practice, it might be necessary to recess the rung slightly, which can be controlled by the placement of the detent pin.

Figure 20. Stowed rung detail

Figure 21 shows the rung in the deployed position. When open, the edges of the rung support sit on the side of the box to help support the climbing load. Given the construction of the frame and rungs, the designers felt that the overall load capacity was sufficient to allow for climbing without additional support. For that reason, the designers eliminated the diagonal braces of the original design.

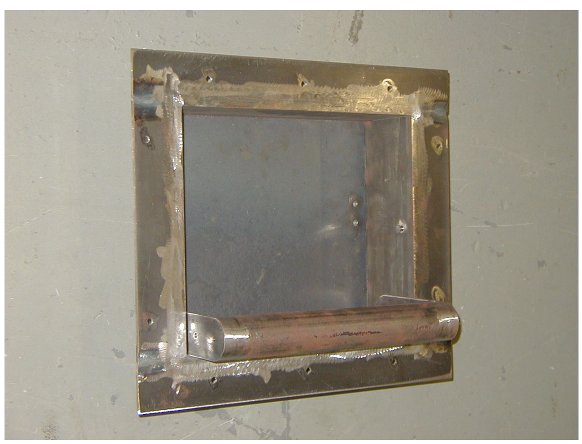

Figure 21. Hand/foothold in the deployed condition

Figure 22 shows the tip of the detent pin. Figure 23 shows the corresponding socket in the rung support. The detent pin is actually a spring-loaded steel ball, locked into a threaded housing. A tapped hole in the side panel of the box provides a means of adjusting the locking load on the rung. Functional testing indicated that the rung could be actuated with a force of 18 lb. This is equivalent to a 6.5–g vertical acceleration of the 2.75 lb rung. In general, this is well below the common accelerations seen in normal operation. It is also well within the capability of a crewmember to operate in the event of an accident.

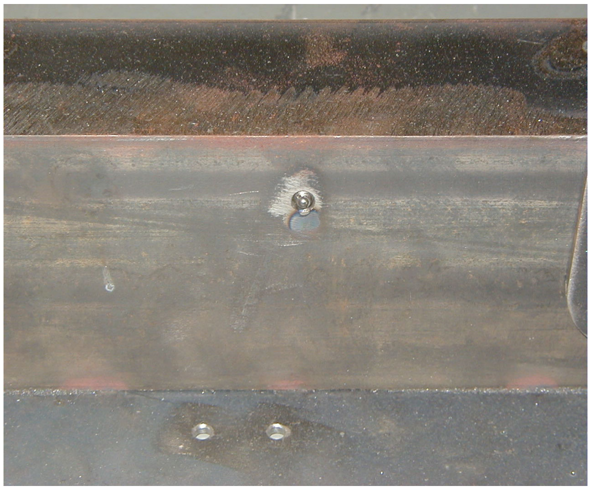

Figure 22. Detail of locking detent pin

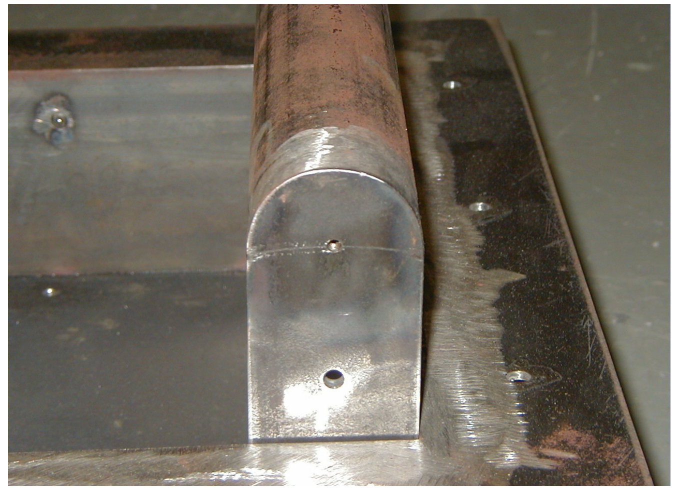

Figure 23. Detail of detent socket

2.5 Alleviation of Noise due to Roof Hatch

The small outward projection of the removable roof hatch might cause the noise level inside the locomotive cab to increase to some extent when the locomotive is at running speed. The following factors are the likely sources of this additional noise:

a) Vibration of the hatch in its installed position or chattering of the metallic linkages employed for the hatch release mechanism.
b) Turbulent airflow past the projected surface of the hatch above the roof surface.
c) Any external noise transmitted through gaps between the hatch cover and the cutout.

Keeping the basic comfort of the crew in mind, simple but effective solutions offer the potential to eliminate any further rise in noise level inside the cab beyond the existing operational noise level in the absence of the removable roof hatch.

a) Vibration of the hatch in its installed position or chattering of the metallic linkages employed for the hatch release mechanism

The present design of the removable hatch cover incorporates thick rubber gaskets in the underside of the hatch. These gaskets eliminate metallic contact between the cutout of the roof and the hatch, especially when it is latched in closed position. Threaded connections permit adjustment of the length of the linkages of the hatch. Therefore, any slackness in them should be adjustable. In order to avoid any likely chatter due to resonant vibration caused by the excitation of the locomotive chassis while traveling at high speeds, however, acoustic (sound absorbing) materials readily available in the form of tiles or quilts should be packed into the gap between the hatch cover and the linkages. This would help dampen the vibration of linkages, if any.

b) Turbulent airflow past the projected surface of the hatch above the roof surface

The present design of the roof hatch cover projects slightly above the locomotive roof surface. When the locomotive runs at higher speeds, this would act as a bluff body and is likely to produce a turbulent flow past the hatch cover and may transmit a wheezing sound inside the cab. To overcome this source of noise, smooth aerodynamically shaped wedge blocks made of neoprene rubber will be permanently bonded along all four edges of the roof hatch cutout to make the air flow past the projecting hatch cover. Additionally, packing the underside of the hatch cover with acoustic materials would further diminish any noise from outside the roof going into the cab.

c) *Any external noise transmitted through gaps between the hatch cover and the cutout*

The use of a strong neoprene rubber gasket around and in the underside of the hatch cover should eliminate any gap between the cover and the cutout. Therefore, the hatch cover in closed condition is expected to make this opening both water and air-tight and hence preclude any transmission of noise. The additional use of sound absorbing material at the cutout in the underside of the hatch cover in its latched condition should inhibit noise transmission of any kind through the roof hatch.

If the above precautions are a part of the design and fabrication of the removable roof hatch, then the present noise level inside the locomotive cab should remain unchanged.

2.6 Emergency Lighting

Crew egress from a locomotive cab in an emergency situation can be critically dependent on adequate interior lighting. In nighttime conditions or in a smoke-filled environment, lighting and related luminescent materials would facilitate the identification of egress routes and apparatus, as well as improve the chances for crew survivability.

2.6.1 Emergency Lighting Requirements/Standards

Because an escape hatch is a new concept for freight locomotives, no current lighting standards exist. Lighting standards in other transportation modes and other industries, however, do exist. Compiling and analyzing these standards provides boundaries for the level of lighting needed to effectively mark the emergency exit.

Many organizations have developed standards for emergency lighting levels (see Table 2). Although these standards vary in their recommended levels of illumination at points of egress in emergency situations, most ranged from 5–20 lux or 2–20 mcd/m^2. These guidelines generally provide for enough light at floor levels to allow passengers to find their way to an exit in a darkened environment.

Table 2. Emergency lighting standards

Standard For Emergency Lighting	Application	Illumination	Illumination Period
International Marine Organization (IMO) Resolution A.752	Electrically powered systems as low level lighting on passenger ships–All active parts	Minimum of 10 cd/m^2	60 min
	Electrically powered systems as low level lighting on passenger ships–Point source in miniature incandescent lamps	150 mcd mean spherical intensity	
	Electrically powered systems as low level lighting on passenger ships–Point source emitting diode systems	Minimum peak intensity of 35 mcd	
European Standard 1838	Horizontal luminance on the floor along the center of an escape route	Not less than 1 lux	
NFPA 101: Life Safety Code	Along the floor of the escape route	10 lux initially, with a minimum of 1 lux	90 min
Canadian Railway Act–Part XIV; Division 300.05	In areas where employees pass while carrying out procedures	35 lux (3 fc)	No specified length of time
United Kingdom Rail Safety Standards Board Railway Group Standard GM/RT 2176	Minimum luminance at vehicle egress points at floor level	20 lux	90 min
	Minimum luminance on emergency equipment provided to assist in egress from a vehicle	20 lux	
	Minimum luminance on an escape route at floor level	5 lux	

2.6.2 Approach

The method of lighting specific to a locomotive cab should stem from what is needed in the most adverse conditions. In a worst-case scenario locomotive accident, crewmembers would be disoriented and injured. A nighttime wreck would result in a dark, smoke-filled cab with no power. Although the cab environment is a relatively confined space, about 9.5 x 7.5 ft, and is overly familiar to train crews, locating the exit in this condition would prove very difficult. The primary objective, therefore, was to determine the best method for illuminating the egress system under this worst-case scenario.

The lighting system employs two different techniques. One technique emphasizes the luminance contrasts of the details of the escape system. Starting at the handle of the hatch and working outward, reflectance levels were alternated by using colored paint. More specifically, the handle of the hatch was left gray–a low reflectance color–while the recessed portion in the center of the hatch was painted white–a high reflectance color. The rest of the escape hatch apart from the recess was again painted gray, to contrast with the white recessed area. The rationale behind this approach is that the human visual system is designed to detect luminance contrasts, so the higher the luminance contrast, the more likely it is to be seen, particularly at very low light levels. The design team used the same strategy for the hand/footholds.

A second technique employed was providing emergency lighting for the escape hatch and the hand/footholds. Determining the method of illumination involved consideration of a number of factors. Detailed analysis of cost, maintenance, visibility, reliability, available space, vibration, and temperature determined the best possible material for use in a locomotive cab.

2.6.3 Candidate Technologies

The following technologies currently exist in emergency vehicle lighting systems used in aircraft, helicopters, and civilian transportation systems (including railroads) throughout the world:

- Incandescent (filament bulbs)
- Fluorescent (mercury-based vapor excited by an AC or DC source)
- Halogen (filament bulbs)
- Light emitting diodes (LED)
- Electroluminescent (phosphor-based compounds excited by a DC or AC power supply)
- Self-luminescent (phosphorous-coated capsule excited with Tritium gas)
- Photoluminescent (silicate and alkaline aluminate-based compounds; zinc chromate and strontium aluminate)
- Chemiluminescent (hydrogen peroxide mixed with oxalix phthalate that charges a fluorescing dye, which releases light)

Investigation of the qualities of these materials and consideration of the requirements and concerns of lighting the cab led to the selection of photoluminescent materials. These materials are inexpensive, reliable, easy to install, and virtually maintenance free. Vibration would not be an issue because no battery packs or other pieces are required. The materials are typically flame-retardant and designed to withstand salt spray mist, water, and cleaning agents.

The potential drawbacks of using photoluminescent materials are that (1) initial afterglow luminance is highly temperature dependant (e.g., afterglow luminance generally increases and decreases with temperature), (2) they require sufficient levels of incident light in order to fully saturate, and (3) the light could potentially be a distraction to operators driving under nighttime conditions. Considering that these materials will be placed on the interior of the locomotive cab, however, cold temperatures would not be an issue. Furthermore, installing an LED light source with a peak emission around 400 nanometer would make it possible to continuously energize the photoluminescent materials while producing very little visible light in the cab. The need exists for further research to determine if photoluminescent lighting will hinder driving abilities at night.

Recent research has produced new inorganic compounds whose photometric characteristics greatly exceed those of the conventional zinc sulphide compounds. Strontium aluminate compounds, available in flexible vinyl and rigid PVC sheets, offer much brighter (15 times) and longer lasting photoluminescence. They can be formulated to produce a range of colors. These products generally exceed existing photoluminescent lighting standards (see Table 3).

Table 3. Photoluminescent lighting standards

Standard For Photoluminescent Lighting	Application	Illumination	Illumination Period
APTA SS-PS-002	Standard emergency signage for egress/access of passenger rail equipment	not specified	
IMO Resolution A.752	Photoluminescent systems as low location lighting on passenger ships after the removal of all external illumination sources	15 mcd/m^2	10 min
		>2 mcd/m^2	60 min
DIN 67 510	For the purpose of egress, photoluminescent material must provide certain luminance at certain times	17 mcd/m^2	10 min
		4 mcd/m^2	30 min
		1.7 mcd/m^2	60 min
		0.3 mcd/m^2	240 min
ASTM E 2073-00	Standard specification of photoluminescent safety markings	20 mcd/m^2	10 min
		2.8 mcd/m^2	60 min

2.6.4 Implemented Approach

The researchers placed peel-and-stick versions of both zinc sulphide and strontium aluminate materials along the recessed walls of the hatch and hand/footholds in the mockup. They also placed exit signs made of these materials on the flat surface of the hatch, above and below the hatch handle (see Figure 24). All participants in the usability testing said they could see the photoluminescent materials very well in the dark, and all rated the strontium aluminate as being brighter than the zinc sulphide. A rough cost estimate of the strontium aluminate material is between \$25 and \$35 per thousand in^2.

One concern mentioned earlier was whether strontium aluminate would be so bright as to be distracting during nighttime operation. Usability test participants felt that this would not be the case.

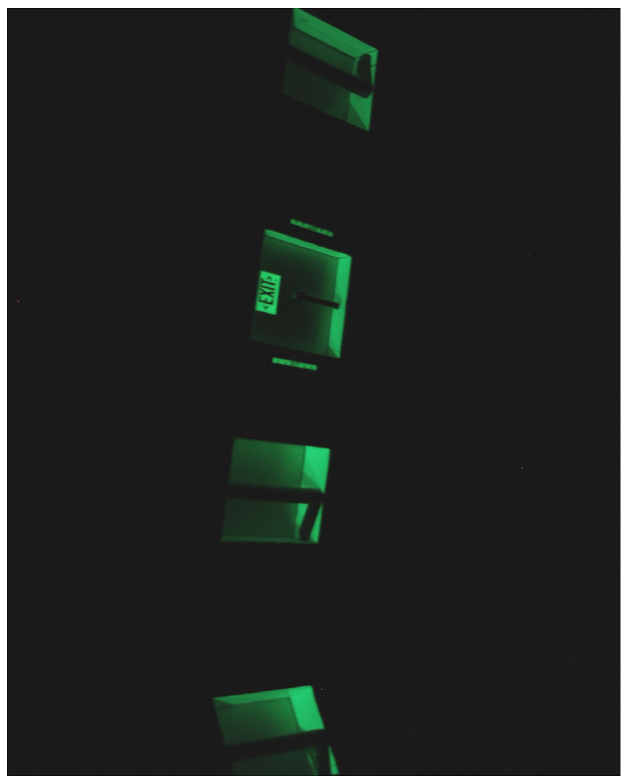

Figure 24. Photoluminescent materials on sides of recessed areas

Photoluminescent material is the most appropriate lighting source to use in a locomotive cab environment. It provides for a low-cost, low-maintenance, high-visibility, and high-reliability solution, without being a distraction during normal operation. An in-locomotive, onsite test with the manufacturer's product wherever possible and certified photometric test reports can provide assurance that the appropriate amount of light diffuses in a dark or smoky environment. A need exists for further research to determine if the stronger photoluminescent materials will be a nuisance during nighttime train operation.

2.7 Prototype Hatch System

A full-size mockup of a freight locomotive cab provided the means to evaluate the overall utility of the egress concepts developed under this program. The mockup is a wood-framed, plywood-sheathed structure representing a composite locomotive cab. The cab dimensions reflect sizes common to both GE and EMD locomotives currently in service. The cab interior is 9.5 ft wide, 6.5 ft from floor to ceiling, and 7.5 ft from the operator's console to the rear wall. In its current configuration, there is no rear wall, thus allowing improved viewing and access during testing. The mockup construction provided openings for a roof hatch, hand/footholds, and grab irons in place. Currently, the mockup represents the basic configuration of the operator's station, roof, windshield, chair, and hood, and it does not include the front doors or electrical switching panels. The research team assembled the mockup on its side, which simulates a 90° rollover derailment, allowing evaluation of the egress system. Figure 25 shows an exterior view of the mockup, and Figure 26 shows an interior view.

Figure 25. Mockup of toppled locomotive cab with egress system

The hatch itself is a steel assembly consisting of an upper panel, a lower enclosure, and an internal latching mechanism. The overall assembly weighs approximately 40 lb. The hatch releases from the opening when the handle turns approximately 40° in either direction. An outward push on the hatch panel frees it from the opening. The mechanism has a cover with appropriate placards for its use applied to the surface. The signage is informative to persons unfamiliar with its use, so they could readily identify the device, operate the hatch, and clear the opening for egress. Photoluminescent strips provide illumination of both the hatch and the hand/footholds. Two grab irons fixed to the cab's exterior will aid the exiting crewmembers and rescue personnel in entering the locomotive. The grab irons are 22 in long and are of a 1-in diameter. Figure 25 illustrates the vertical placement of the grab irons on either side of the roof hatch when the locomotive is in a toppled condition.

Figure 26. Interior view of cab mockup with hatch system

3. Usability Testing

The objective of the usability testing was to examine the functionality of the proposed emergency egress roof hatch system (roof hatch, hand/foothold, and grab iron designs) for a locomotive cab. Many transportation vehicles, such as buses, airplanes, and boats, have successfully utilized roof hatches for egress/access for many years; however, the effectiveness of a roof hatch design for locomotive egress was unknown.

Specifically, the purpose of this usability evaluation was to obtain both quantitative and qualitative feedback as to the effectiveness of the locomotive roof hatch system. Railroad locomotive engineers and conductors, as well as emergency rescue personnel, participated in the tests to determine if they could safely enter and/or exit the cab in the event of a locomotive tip-over.

3.1 Use of Human Research Participants

An Institutional Review Board (IRB) convened by Dunlap and Associates, Inc. conducted a human subjects review of the study design, protocol, and materials to be used in the usability study. The IRB consisted of individuals with expertise in research involving human subjects. The IRB found no risk to human participants in the proposed research design and consequently approved the research plan for the usability study on September 4, 2003.

3.2 Participant Recruitment

Because the knowledge base, physical characteristics, responses, and actions of a typical user are of the highest interest during usability testing, actual qualified locomotive crewmembers and current emergency response personnel were eligible to be research participants. The researchers coordinated with local United Transportation Union and Brotherhood of Locomotive Engineers representatives to identify six volunteers for this research. In order to obtain data and feedback from an emergency crew perspective, the researchers recruited five volunteers from the local Fitchburg, MA, Fire Department. The following were the criteria to identify candidate participants:

- Only current engineers or conductors were eligible to participate.
- Train crew candidates all had at least 1 year (yr) of road freight experience.
- Emergency response participants were actively employed with a local fire department.
- All candidates were in good health and fit for duty.

A researcher contacted potential train crew participants to request their participation in the project. The researcher told candidates that participation was voluntary, confidentiality would be maintained, and each volunteer would be compensated $60 by the research team for his/her involvement in the study. The researcher scheduled individuals willing to take part in the experiment for a 45-min time block at their convenience.

The research team recruited a group of rescue personnel separately from a local fire department for participation in the study. A block of 4 hours (h) was arranged with the crew to run through a variety of rescue scenarios. Compensation for fire crewmembers was at their standard hourly rate.

3.3 Experimental Study

3.3.1 Pre-Experimental Preparations

Each participant began with pre-experimental preparations. The researcher explained that the purpose of the study was to assess the effectiveness of a new roof hatch egress system for use in locomotive accidents. Next, he/she was given an Informed Consent form to read and sign (see Appendix A).

The experimenter then answered any questions that the participant may have had regarding his or her participation in the study and the material covered by the Informed Consent form. Upon agreeing to participate and signing the Informed Consent form, the experimenter gave train crew participants a brief background survey that solicited age, gender, height, weight, job title, and experience. The experimenter also explained that, although the speed with which the participant could enter and/or exit the locomotive was of interest, it was secondary to the participant's safety and his/her evaluation of the hatch system.

At the conclusion of the pre-experimental preparations, the experimenter asked the subject if he/she had any questions about the material just covered or the upcoming procedure. The experimenter then escorted the participant to the locomotive mockup.

3.3.2 Experimental Design

The experimental design for testing the effectiveness of the roof hatch system was a 3x2 repeated measures design, where independent variables were injury type (no-injury, broken arm, broken leg) and visibility [high visibility (natural light) and low visibility (photoluminescent light)]. Because evaluation of visibility required only one trial for each participant, it was not necessary to fully cross all conditions (and run participants through darkened scenarios more than once). The ordering of participant trials was counter-balanced to control for any effects of learning. Height and weight of participants were factors that were analyzed after the fact, but definition of the experimental groups did not use these factors.

3.3.3 Test Facility

The hatch itself is a steel assembly consisting of an upper panel, a lower enclosure, and an internal latching mechanism. The overall assembly weighs approximately 40 lb. The hatch releases from the opening when the handle turns approximately 40° in either direction. An outward push releases the hatch panel from its frame. Once pushed away from the locomotive, a tether line system removes the hatch from the opening and surrounding area. The tether line is a safety measure to move the falling hatch away from the egress area during usability testing.

The tether line is a cable attached to the emergency hatch. From the hatch, the cable runs through a pulley system and is connected at the opposite end to a counter weight. As the hatch begins to fall to the ground, the cable pulls the hatch away from the egress area. At the same time, the counter weight slows down the descent of the hatch and allows the hatch to softly come to rest on the ground, a safe distance from the participants. In this position, neither hatch nor tether line is an obstacle to the participants. Figure 27 through Figure 30 show the tether line safety system installed for the falling hatch.

3.3.4 Test Procedure

Crew participants began their trials inside the locomotive cab. To simulate an accident scenario and possible disorientation, crew participants put on a blindfold, as the researcher assisted in turning the individuals around twice before sitting them down on the floor of the locomotive cab. Next, the researcher asked each subject to remove the blindfold, exit through the hatch, and lower himself/herself to the padded floor. No further instruction was given at this time, as it was important to determine if crewmembers would be able to exit effectively without receiving special egress training. The researcher asked each participant to exit several times, simulating different physical (injury type) and environmental (visibility) conditions.

Types of injuries that were simulated included a broken arm and a broken leg. This was accomplished by asking participants to either place their dominant hand in their pocket or behind their back (broken arm scenario), or to avoid using one leg (broken leg scenario) as they exited the cab.

Visibility was altered from high visibility to low visibility to simulate both daytime and nighttime conditions. The nighttime scenario was achieved by simply covering all open areas of the mockup with a dark tarp, to keep any light from entering the cab, while the daytime or high-visibility scenario was simply performed under ambient daylight. Photoluminescent materials placed in the recessed areas around the hatch and hand/footholds facilitated simulations of nighttime egress. This provided enough light for participants to clearly view the hatch and hand/footholds, and dimly lit the interior. Once the participant removed the hatch, natural light filled the cab, allowing complete visibility to aid in exiting.

After each trial, participants filled out a subjective survey form (post-scenario survey, see Appendix B) in which they rated a number of features of the roof hatch system. These questions pertained to ease of exit, visibility of the hatch/foothold/grab irons, amount of force exerted to open the hatch, overall effectiveness of the system, and possible improvements. The survey consisted of five-point Likert scales, categorical responses, and open-ended questions. After the crewmembers finished all trials, they provided comments and/or suggestions regarding the grab irons, hatch, hatch markings, and hand/footholds. The researcher recorded these suggestions, along with the subject's time to exit on a data sheet (see Appendix C).

Emergency response personnel performed several trials. The first crew consisted of two rescuers, then three, four, and five, respectively. This was done to determine the number of rescuers that would likely be required in a roof hatch rescue. In all cases, they began their trial outside the locomotive cab, dressed in full rescue gear, with all necessary equipment on hand. The researcher simply instructed them to enter the cab, place an injured person on a body-board, and exit the cab with the injured person. All trials took place in high-visibility conditions (daylight), as emergency workers should always be equipped with means of lighting. A trial was stopped if the researcher determined that more crewmembers were necessary to remove the victim from the cab.

Following these trials, emergency response participants filled out a subjective survey form (post-scenario survey, see Appendix B) similar to that filled out by crew participants. After completing this form, the researchers asked participants to give comments and/or suggestions

Figure 27. Hatch is attached to a tether line

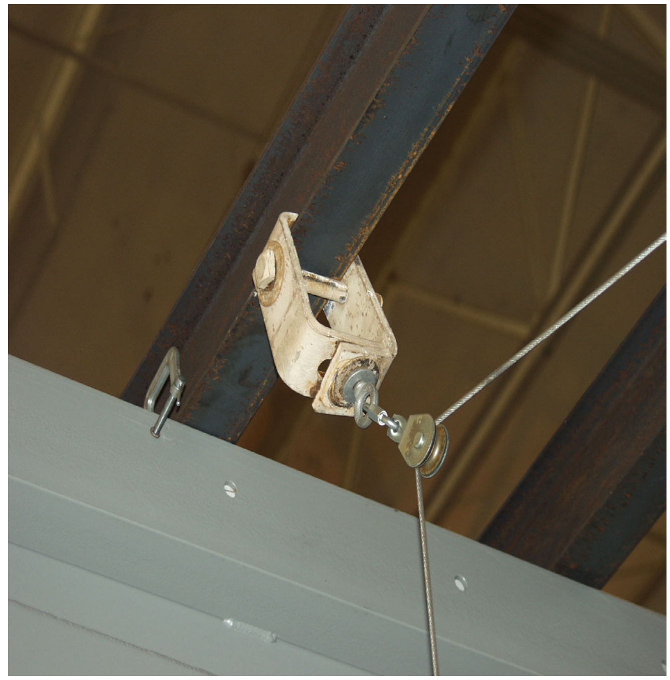

Figure 28. Tether line is run through a pulley system

Figure 29. Pulleys remove hatch from egress path

Figure 30. Counter weights allow hatch to settle gently

regarding the grab irons, hatch, hatch markings, and hand/footholds. The researcher recorded these comments, along with the participants' time to enter *and* exit, on a data sheet (see Appendix C).

In all instances, video recording documented the participant's performance. This in no way jeopardized the confidentiality of the participants and was done simply to capture each performance in the event it required referencing at a later time. The collection of these data during the experiment did not interfere with the tasks of the volunteers. Two researchers were present at all times to monitor for participant safety.

3.4 Results

Separate subsections below describe the results of the train crew and emergency responder usability tests.

3.4.1 Train Crew

Six train crewmembers, four conductors and two engineers, participated in the usability testing. The average crew member was 40.8 yr old, 5 ft 11 in, weighed 191.6 lb, and had 20 yr of experience. The largest participant was 6 ft 1 in and weighed 215 lb, while the smallest participant was 5 ft 10 in and weighed 180 lb.

As anticipated, the no injury condition resulted in the quickest escape time. Participants were able to use both arms and legs to access the hand/footholds and grab irons to quickly extricate themselves from the cab. It took subjects only slightly longer to escape in a darkened environment. All participants reported that the photoluminescent materials placed on and around the hatch and hand/footholds provided adequate escape route lighting. Escaping with a simulated leg injury took somewhat longer, as participants were asked not to use the leg to stand up or to bear any weight. These subjects were able to use the hand/footholds to hop up to the hatch opening and were then able to reach outside the cab and get hold of the two grab irons. This was enough to allow the participants to pull themselves out. The simulated arm injury seemed to cause the greatest problem for participants. This is probably because most participants, four of six, chose a head first approach to exit through the hatch. These subjects used one arm to take hold of a grab iron and then pulled the rest of their bodies through the opening. Nonetheless, under all conditions, escape time was under 30 s (see Table 4).

Table 4. Average time for train crew participants to exit locomotive

Scenario	Average exit time (s)	Ease of exit rating
No injury	16.93	4.0
In darkness	19.60	NA
Leg injury	23.83	3.1
Arm injury	27.78	2.3

Participants' subjective ratings on ease of exit with various physical injuries correspond with actual exit times, with no injury, leg injury, and arm injury, receiving ratings of 4.0, 3.1, and 2.3, out of 5 (extremely easy), respectively. Ease of exit rating in darkness is assumed to be equal to

Figure 31. Interior and exterior views of crewmember egress

that of the no injury condition, since the intended meaning of this rating is how physically easy it is to exit.

3.4.2 Emergency Rescue

Rescue groups of two, three, four, and five attempted to extricate a simulated victim from the cab. The victim for all trials was a 5 ft 11 in male weighing 230 lb. A two-person crew could not safely remove the victim through the cab hatch. The crew managed to lift the victim up to the hatch and rest the backboard in the opening but was unable to remove him safely. A three-person crew utilized all three people to lift the victim up to the hatch opening; then, after one rescuer exited the hatch, the remaining two slid the victim out on the backboard, face-up, to the rescuer on the outside. The rescuer on the outside then held the victim vertically on the backboard until the remaining rescuers could exit the cab and assist in lowering the victim safely to the ground. The four-person crew used a similar method of removing the victim, sending three rescuers inside the cab to lift the victim, while one remained on the outside. After the lift, one rescuer climbed out, and the remaining crewmembers slid the victim out of the hatch to the two rescuers on the outside. The two rescuers on the outside once again held the victim vertically on the backboard until the remaining rescuers could exit and assist in lowering the victim safely to the ground. Finally, the five-person crew used the same method for removing the victim, but instead sent four rescuers into the cab for lifting, before one climbed out. Once again the remaining crew slid the victim out to the rescuers on the outside, and the rescuers on the cab exterior held the victim vertically until the rest of the crew exited the cab and assisted in lowering the victim to the ground (see Table 5 for times). Figure 32 shows one of the teams removing an injured crew member.

Table 5. Time for rescue personnel to extricate victim from cab

	Crew Size			
	2	**3**	**4**	**5**
Total Time to Enter and Exit (min:s)	8:00[1]	8:40	8:37	9:00
Successfully Removed Victim?	No	Yes	Yes	Yes

[1] Total time for two-person crew to enter locomotive and lift victim up to hatch opening

Increasing the number of rescue personnel beyond three did not seem to improve rescue time. Based on participants' feedback, however, additional personnel did make it easier to remove the victim.

Figure 32. Views of emergency personnel entrance, victim preparation, and extrication

3.4.3 Train Crew Subjective Data

All participants used the hand/footholds, with the bottom foothold being used most often. Four of the six participants simply stepped into the recessed areas without folding out the hand/foot bars in their first trial, stating that they did not realize they folded out. Some of these individuals stated that the hand/footholds may not be necessary, and that in an emergency situation, they may not take the time to fold them out. Using the fold-out is necessary, however, when using the hand/foothold above the hatch opening because it is the only thing to grab. Overall, subjects rated the hand/footholds as extremely easy to use and relatively effective in their placement.

Participants rated the hatch as very straightforward to use and physically very easy to open and push out.

All participants used grab irons, located on the cab's exterior, but many participants suggested additional grab irons or changes in their current location. Five of six participants stated that they would like a grab iron placed horizontally above the hatch opening, providing them with a better place to grab onto upon exit. Two participants suggested diagonally slanting grab irons above the top corners of the hatch.

In the darkened scenarios, participants rated the hatch as being very easy to see, stating the photoluminescent materials worked very well in lighting the area. Hand/footholds received only a mediocre rating for visibility. One subject stated that the first thing he saw was the bright glow of the hatch, and he just went toward it, without noticing anything else.

3.4.4 Emergency Personnel Subjective Data

Emergency personnel rated the hatch as very straightforward to use and extremely easy to open and lift away from the opening. In fact, after the first two trials, the rescue crew propped the hatch against the side of the locomotive mockup, using it as a stepping stool to boost themselves into the opening and to step down onto when exiting.

Participants gave the placement of the grab irons only a mediocre rating for entry. One rescuer attempted to hold one of the irons and swing feet first into the opening, only to have his grip slide down the vertical grab iron. Rescuers stated that placing grab irons above and below the hatch, however, would likely interfere with getting out. They suggested that having a foothold on the exterior of the locomotive would help dramatically with entry.

Another suggestion was to add texture to the grab irons to provide better grip.

Rescuers rated the placement of the grab irons somewhat higher for exiting the cab. They seemed to exit a bit easier and stated that the grab irons provided good leverage for getting out.

Rescuers were very pleased with the design of the hand/footholds. They rated them as extremely straightforward and easy to use, and most were pleased with their placement as well. More than one rescuer stated that the pull-down stepping bars made the steps easier to use with their large fire boots, as opposed to simply stepping into the recessed well.

Overall ease of entering and exiting the cab received a mediocre rating from the rescuers. Two factors resulted in this rating. First, participants had a difficult time entering the cab without an exterior foothold or other device to allow them to boost themselves into the hatch opening. Second, rescuers stated that the current size of the hatch was adequate but sometimes made it difficult to enter or exit in full turnout gear (including an oxygen tank on their back). One participant said that if the hatch was as large vertically as it is horizontally, it would make the rescue crew's job easier.

3.5 Discussion

Overall, the design of the hatch escape system was effective in its purpose. It allowed for a safe and efficient escape for train crewmembers and was sufficient in permitting rescuers to successfully retrieve an injured victim from inside the cab using a backboard. The hatch and hand/footholds were very straightforward and easy to use, while the grab irons provided adequate holds to assist with entry and exit. Photoluminescent materials also successfully illuminated the escape route during darkened conditions.

Both train crew and rescue personnel had suggestions for improving the egress system. The following suggestions were made:

- ***Hatch/Opening***

  Rescuers had two suggestions regarding the hatch. First, they stated that bigger is better regarding their interests. Specifically, they would like the opening to be as large vertically as it is horizontally. A larger opening would allow easier entry and egress. One point to consider here, however, is that the larger the opening gets, the larger and heavier the hatch becomes. The second suggestion related to night rescue. Rescuers stated that photoluminescent or retroreflective materials around the exterior of the hatch would provide clear visibility to the rescue route.

- ***Hand/Footholds***

  A few of the train crew participants said they did not realize the bars in the recessed areas folded out. With entire work days spent in the cab environment, however, crewmembers would be well aware of this function. Other train crew participants stated that the folding bar may not be necessary for the hand/footholds and that the recessed area may be enough by itself. These participants did, however, grab the folding bar above the hatch to pull themselves toward the opening. Because of the necessity of the folding bar above the hatch, it means the hand/footholds below the hatch should also be fitted with folding bars, in the event the locomotive rolls over on its opposite side. Rescue workers stated that the folding bar was useful because of their large fire boots. One concern of a train crewmember was that over time, the folding bars would become loose and make constant noise throughout normal operation. He suggested replacing the folding bar with a fixed bar to avoid this issue.

- ***Grab Irons***

  The primary suggestion from train crew participants was that a grab iron placed horizontally above the hatch would make exiting the cab easier. This would of course require one to be placed below the hatch as well, in the event the cab tipped on its opposite side. The rescuer's comments were counter to this, however, suggesting that grab irons above or below the hatch might hinder one's exit. Rescuers instead suggested perhaps placing small horizontal grab irons above-left and above-right, as well as below-left and below-right of the opening, allowing for an overhead grab, but not impeding an entry or exit. Another suggestion was to replace the vertical grab irons on either side of the hatch with diagonal grab irons in each corner. This may also allow for an overhead grab without hindering entry or egress. A final suggestion was to add texture to the grab irons for improved grip.

4. Removable Windshield

The collision or derailment of a locomotive can result in structural damage to the cab or cause the locomotive to roll onto its side. This can block the egress routes used during normal operation from the cab. Primary emergency egress can be accessed through a roof hatch as described in the previous section. Secondary emergency egress options include a locomotive windshield that can be removed from the cab interior by the crew and removable hinges on the rear door of the cab. This section discusses development of the removable windshield.

4.1 Current Windshield Design

Two basic types of windshields are currently used in locomotives: frame mounted and non-frame mounted. Frame mounted windshields are typically found in newer model locomotives manufactured by GE. The GE windshield dimensions are approximately 52 in by 17 in. With a framed windshield, the glazing manufacturer inserts the glazing into a frame assembly with a gasket. Then, the installer places the entire frame assembly, with glazing and gasket, into the locomotive windshield frame. With the non-framed windshields, typically found in EMD locomotives, the glazing installs directly into the locomotive windshield frame with a gasket. The dimensions of a windshield of an EMD SD70MAC are approximately 57 in by 19 in.

Figure 33 and Figure 34 show an example of a framed windshield. Figure 33 shows an assembled GE windshield frame including gasket and glazing. Figure 34 shows a closeup view of the frame assembly. The entire frame assembly shown in these figures goes into the locomotive windshield frame. In Figure 34, the arrow on the right side of the image points to one of the screws that are used to fasten the assembly to the locomotive. The arrow on the left side of the image points to the weather stripping material used to create a tight fitting seal between the assembly and the locomotive. Figure 35 shows a section of a framed windshield showing details of assembly including the glazing and gasket.

Figure 33. GE windshield frame assembly

Figure 34. Closeup view of GE windshield assembly

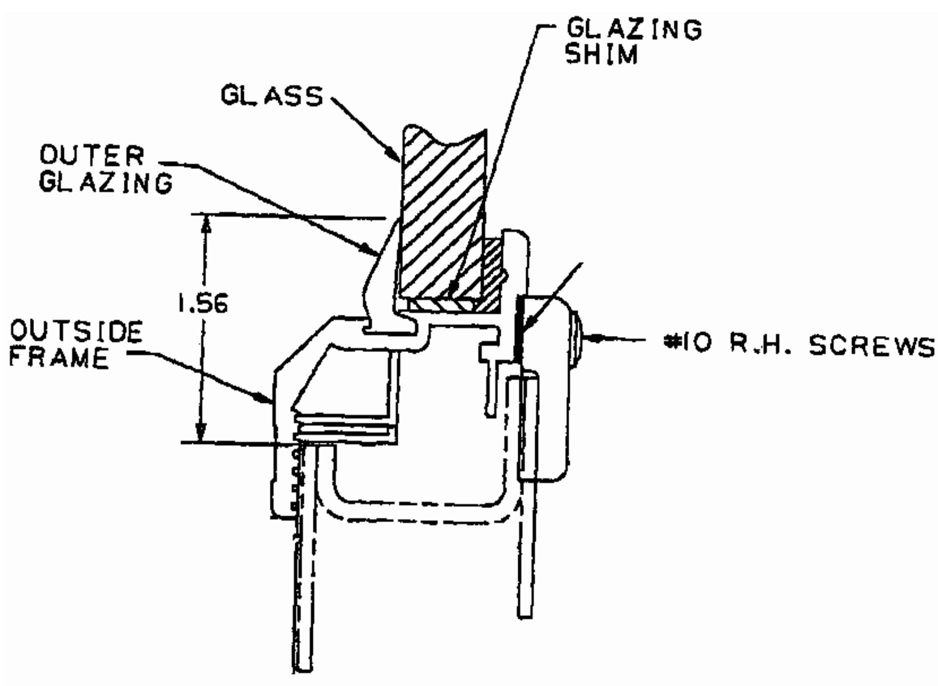

Figure 35. Detail sectional view of framed windshield assembly

Non-framed windshield installations use only a gasket to hold the glazing into place. The section view in Figure 36 is an example of a non-framed windshield gasket currently used for normal operation. The gasket section shown does not include emergency egress modifications. The installer pushes the small fins on either side of the gasket upward and inward against the main body of the gasket to insure a tight fit against the locomotive frame. The curved void at the bottom of the gasket also helps to provide a tight fit by allowing the gasket to compress to the same width as the windshield frame. Once the gasket is in the frame and the glazing is in the gasket, the zip flap folds closed and locks into place, applying a pressure against the glazing to complete the installation. Figure 37 is a sketch that illustrates the non-framed windshield assembly after installation into a locomotive windshield frame. A cut in the gasket at a critical location detaches the zip flap, thus allowing the removal of the glazing outward for emergency egress.

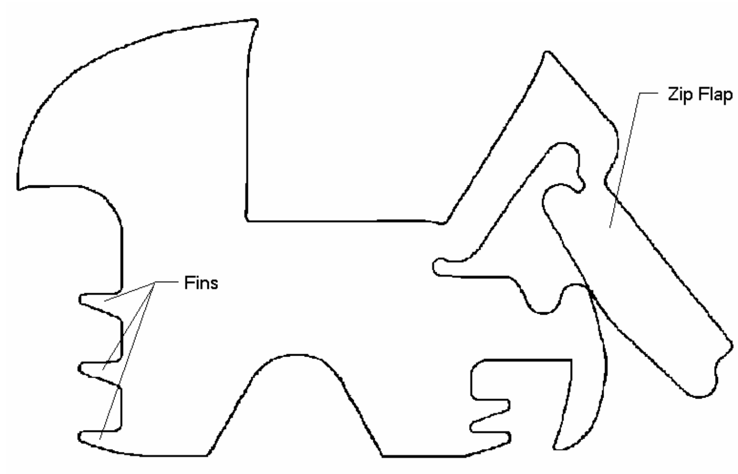

Figure 36. Sectional view of a gasket currently used in locomotive windshields

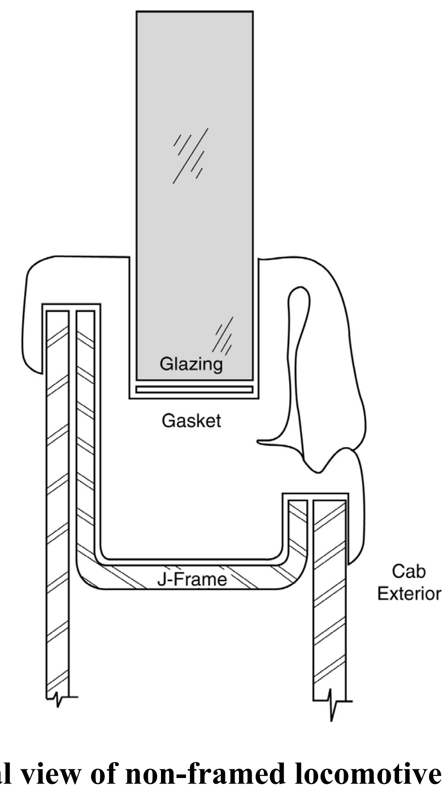

Figure 37. Sectional view of non-framed locomotive windshield assembly

4.2 Candidate Designs for a Removable Windshield

Windshield removal from the cab interior requires cutting the gasket on the windshield assembly. After cutting the gasket, the glazing can be removed from the windshield frame. The initial concept for emergency egress through the windshield used a tensioned wire to fold and deform the gasket to an altered position and allow removal of the glazing. Experiments with conceptual scale models to investigate the folding method determined that the wire tends to cut and tear rather than fold the gasket. Based on these findings, the researchers evaluated the following candidate cutting methods:

- Single Loop Folding Wire
- Single Loop Cutting Wire
- Double Loop Cutting Wire
- Single Loop Wire with Cutting Blade

The design used for cutting the gasket applies to both the framed and non-framed windshields. The non-framed windshield, however, provides a less difficult platform to develop this egress system. Therefore, the prototype locomotive windshield for this research was based on a non-framed windshield assembly.

4.2.1 Single Loop Folding Wire

This concept requires modification of the windshield gasket geometry so that a wire, when pulled, can bend the outer edge of the gasket. During installation, a single loop of wire is embedded within the modified windshield gasket. The standing end of the wire remains fixed while the running end is free to move during emergency actuation. Since the gasket loops around the windshield, the loop tries to decrease in size with a hoop tension when pulled. As the wire loop reduces in size, it pulls on a fold added to the gasket. The gasket deforms and bends into a position that no longer holds the glazing firmly in place but allows the gasket and glazing to be pushed out of the windshield frame. Figure 38 shows a sketch of the modified gasket in a normal operating position for the folding method. Figure 39 shows the conceptual sketch of the gasket after emergency activation when the gasket has folded.

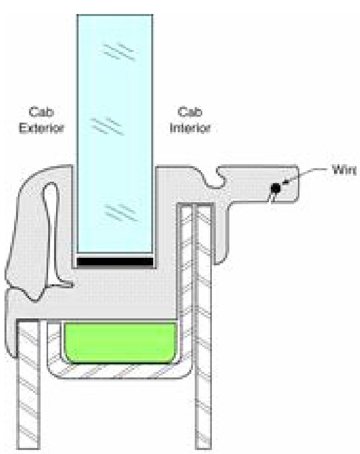

Figure 38. Single loop folding wire, normal position

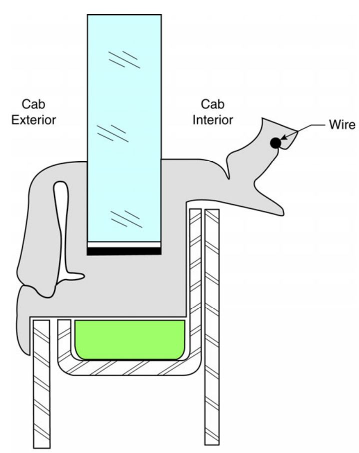

Figure 39. Single loop folding wire, released position

4.2.2 Single Loop Cutting Wire

The single loop cutting wire was the initial concept that appeared to be the most feasible option for removing the window gasket from the cab interior. As with the folding concept, the gasket has an embedded wire and a modified geometry to facilitate the removal procedure. Instead of folding the gasket, however, the wire severs the gasket, allowing removal of the glazing for egress. One end of the wire is free to move while the other end remains fixed to create an inward hoop tension in the wire. Figure 40 shows the schematic travel path of the wire as it cuts through the gasket. As tension increases in the wire, the gasket begins to fail at the first corner opposite to the direction of wire retrieval. After the wire cuts the gasket at the corner, it cuts the two sides adjacent to the corner. Continued retrieval of the wire causes additional cutting of the gasket until the glazing is free to be removed from the windshield frame.

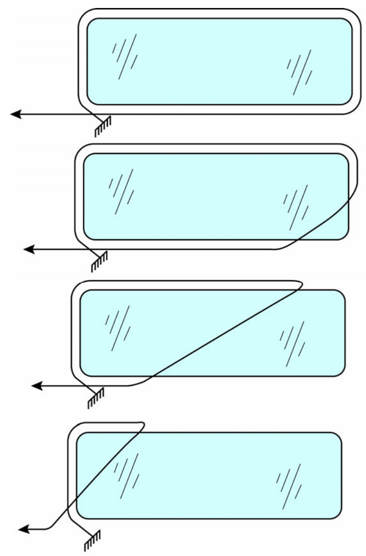

Figure 40. Schematic retrieval path of a single loop cutting wire

The gasket currently in use on locomotive windshields (Figure 36) requires geometry modifications to function properly for the single loop wire cutting method. Figure 41 shows the slight changes in geometry required. The important change in the geometry is to increase the length of the slot below the folding flap. The small diameter wire is embedded into the gasket at the end of the slot and rests there passively until needed. This method also requires an upward curve at the end of the slot. The curve will prevent the wire from sliding up toward the fold in the flap and will concentrate the stress on the proper location of the gasket. Figure 42 shows a sectional view of the gasket that illustrates the normal operating position of the single loop cutting wire installed with the glazing.

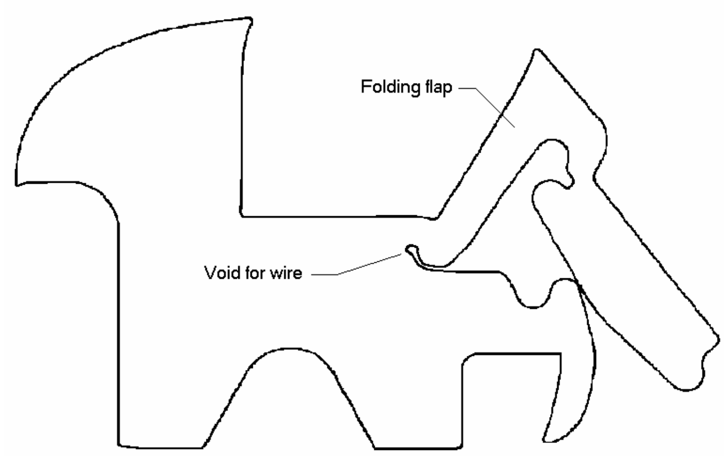

Figure 41. Sectional view of the gasket with modified geometry

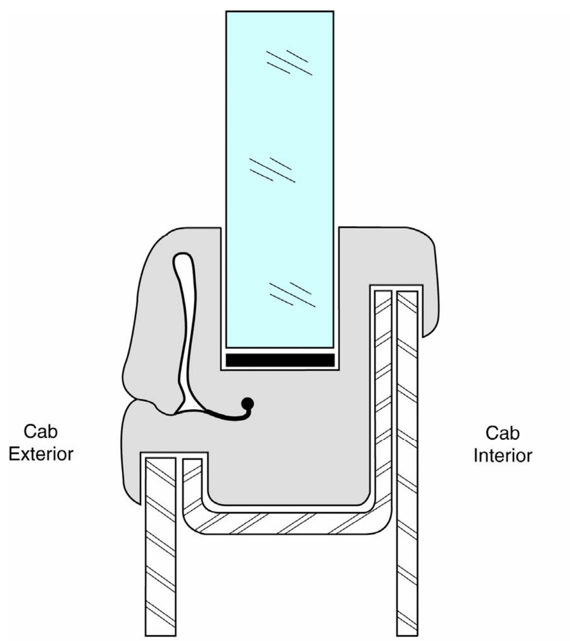

Figure 42. Sectional view of the assembled gasket with single loop cutting wire

As the wire cuts through a critical section of the gasket, the folding flap portion of the gasket detaches from the remainder of the gasket. During the cutting procedure, the wire that has already cut the gasket slides along the exterior surface of the glazing, as illustrated in Figure 43. With the gasket cut, the folding flap no long restrains the glazing, which is then easily removable, as shown in Figure 44.

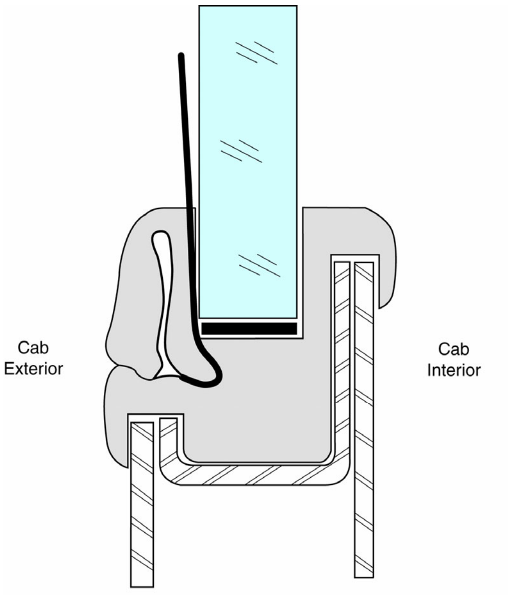

Figure 43. Sectional view depicting cutting action of single loop wire

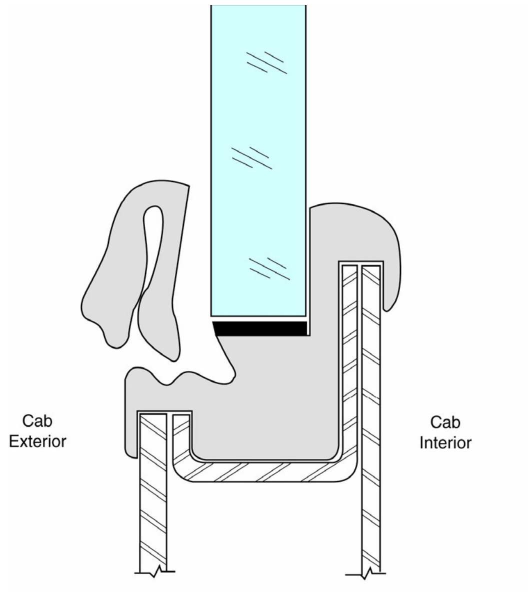

Figure 44. Sectional view showing the severed gasket

4.2.3 Double Loop Cutting Wire

Similar to the two methods previously discussed, the double loop cutting wire utilizes a wire embedded in the gasket and installed around the windshield. In addition, one end of the wire remains fixed while the other end of the wire is free to move. When the wire is tensioned during this method, however, the wire does not apply an inward force to bend or cut the gasket. Two wire loops around the windshield. Under tension, the loop doubles back on itself, creating a rolling bight that cuts the gasket. Figure 45 shows the schematic retrieval path of the wire.

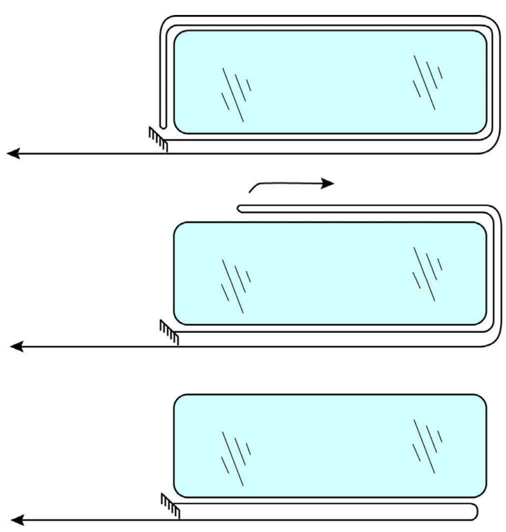

Figure 45. Schematic retrieval path of double loop cutting wire

Conceptual testing of this method showed that less force in the wire is required to cut through the gasket as compared to the single loop method. The advantage of reduced force, however, is offset by an increased amount of wire length required to be pulled during its retrieval.

The fixed end of the wire rests on the interior side of the gasket close to the glass while the running end is on the external side of the gasket. The installation process includes insertion of the cutting wire around the glazing side of the zip strip to create the double loop. The sketch on the left side of Figure 46 shows the double loop cutting wire assembly during normal operation, before the gasket is cut. The sketch on the right side of the figure shows the gasket with the critical section cut allowing emergency removal of the windshield.

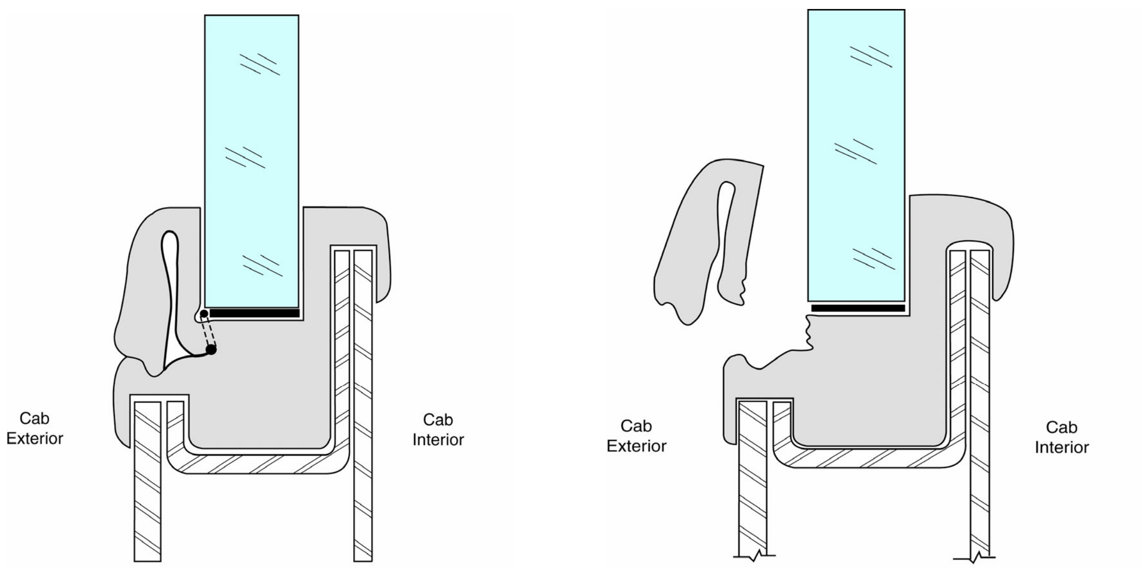

Figure 46. Sectional view of gasket before and after cutting by the double loop wire

4.2.4 Single Loop Wire with a Cutting Blade

The final candidate gasket design for an easily removable windshield is the single loop wire with a cutting blade. As with the other methods, the gasket surrounding the glazing has an embedded wire. With this option, the wire is not required to fold or cut the gasket. Instead, the end of the wire has a cutting blade. As the wire is retrieved, it pulls the blade and cuts the critical section of the gasket in its path. A shim guide is important with this cutting method to facilitate the wire retrieval and to keep the blade at a proper orientation and cutting angle. The wire connects to the base of the blade at a cylindrical shank. The blade shank and wire are installed into the shim guide with only the blade exposed and extending out to cut the critical gasket section. Figure 47 shows a sectional view of the assembled gasket with single loop wire in normal position, before cutting the gasket. After the critical section of the gasket is cut away by the blade, the windshield glazing is free and can be pushed out of the frame for emergency egress. Figure 48 shows the severed gasket after the blade has cut through the critical section.

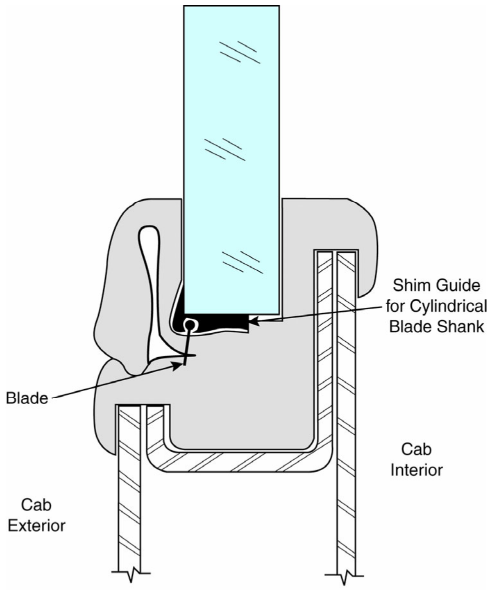

Figure 47. Sectional view of the assembled gasket with single loop wire

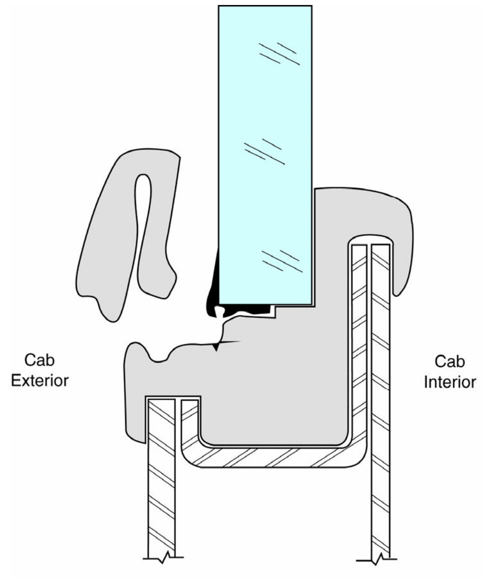

Figure 48. A view of the severed gasket after cutting at critical section

4.2.5 Selection of Candidate Design for Removable Windshield

The following attributes were the basis for comparison and selection of an option for a prototype design:

- Operational simplicity
- Functional reliability
- Cost
- Effort for retrofit in existing locomotives
- Time for deployment

Table 6 contains the ratings for candidate designs with respect to these factors. Based on this analysis, the single loop cutting wire was the preferred concept. The single loop method required a new gasket design with a modified geometry. Figures 36 and 41 show a sketch of the currently used gasket and the gasket modified for the single loop cutting method, respectively.

Preliminary tests of the single loop cutting method with the existing gasket material identified problems with this concept. Although the current gaskets did not have a modified geometry, it was apparent after several tests that the single loop wire method would not sever a rubber gasket. Therefore, cutting the gasket required either a modified single loop cutting method or a completely separate method.

Preliminary testing of the double loop cutting wire showed that the method was effective at cutting the gaskets with varying thicknesses and various sized wire diameters. The double loop cutting method eventually proved successful in the prototype windshield frame and on the wooden mockup locomotive. The next section discusses the specifics of development for the single and double loop cutting methods for severing the windshield gasket.

Table 6. Comparison of performance attributes for removable windshield concepts

Concept	Operational Simplicity	Reliability	Cost	Retrofit Effort	Time for Deployment
Single Loop Folding Wire	Bad	Bad	Good	Good	Medium
Single Loop Cutting Wire	Good	Good	Good	Good	Medium
Double Loop Cutting Wire	Medium	Good	Medium	Medium	Medium
Single Loop Wire with Cutting Blade	Medium	Medium	Bad	Medium	Medium

4.3 Design of Double Loop Cutting Wire

4.3.1 Limitations of the Single Loop Method

As described above, efforts to develop a method to cut a gasket with a wire began with the single loop cutting method. The single loop method proved unsuccessful because friction between the wire and the gasket dissipates some of the force. The remainder of the force is transmitted inward at the first windshield corner, as designed. As the tensile load increases in the wire, however, the wire fails and breaks before reaching a load great enough to begin the severing of the gasket. Instead of a concentrated load, the inward force of the wire distributes along the curve of the 4-in radius locomotive windshield.

Additional tests with the single loop method used various sized wire diameters ranging from 0.018 in to 0.038 in. Additional testing involved decreasing the thickness of the gasket. At the location where the wire will cut the gasket, the current minimum dimension specified by the windshield manufacturer is 0.03 in. Even with the reduced gasket thickness of 0.015 in (half of the minimum required thickness), the cutting wire still could not sever the gasket.

4.3.2 Twin Double Loop Method

The initial process of selecting a concept to release the windshield glazing identified the double loop method as an attractive second choice (see Table 6). The double loop, however, seemed too complicated as the rolling bight of the wire needed to travel most of the circumference of the windshield. Reconsidering this concept, researchers modified the double loop design to include two separate loops (twin double loops). Twin double loops of cutting wire embedded in the gasket, each cut half the length initially assigned to the single wire double loop method. Figure 45 shows the travel path of the cutting wire in the single wire design. Figure 49 shows the travel paths of cutting wires for the twin double loop.

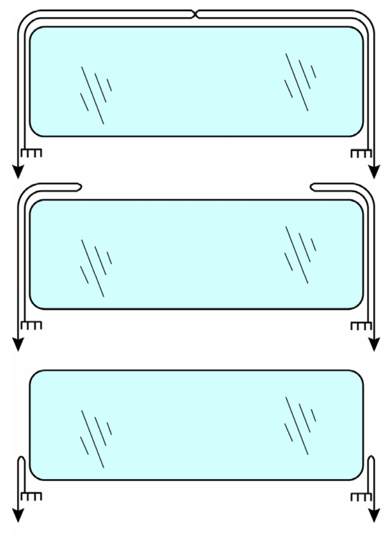

Figure 49. Sketch of retrieval path for twin double loop cutting wire method

Using twin double loop cutting wires simplified the double loop method. Testing the single wire double loop method on the prototype windshield identified two problems. The first was having the rolling bight negotiate the corners of the windshield. The second problem with the single wire method is the large length of wire that must be pulled through the gasket and around the windshield.

As the wire of the double loop method approaches a windshield corner, it has a tendency to leave the desired cutting path and prevents cutting the gasket. Modifying the geometry of the gasket addressed this problem. A modification to the gasket geometry provided for a larger slot to help maintain the proper position of the cutting wire, as shown in Figure 41. However, using a twin double loop system requires each loop to cut through only one corner. The single wire version of the double loop method requires two corners to be cut by the wire.

The second problem experienced with the single wire method is the long length of gasket that must be cut to release the glazing. The dimensions of the non-framed windshield, such as the one in an EMD SD70MAC, are approximately 57 in by 19 in. Prototype testing shows that cutting three of the four sides will release the glazing. Therefore, using the single wire method, a single wire must cut a gasket length of 95 in (19 in + 57 in + 19 in). With the twin double loop method, each of the two cutting wires must cut one short side (19 in) and half of one long side (28.5 in) or a total of 37.5 in. Reducing the length for each of the twin loop wires is significant to successfully cutting enough length of gasket to release the glazing.

The force to actually cut the gasket with the rolling bight of the double loop method is minimal as compared to the friction force created between the wire and the gasket. As the embedded wire is pulled through the gasket, a friction force develops. The accumulated friction force is greater at the corners. With the non-twin method, more than twice as much wire exists to contact the gasket and two corners included in the cutting path.

With the twin loop method, each loop is responsible for cutting half of the gasket on the top of the windshield, the top outer corner, and the entire length of the small vertical side of the windshield for a total of about 48 in (see Figure 49). The twin loop system uses the strength of two wires to resist about the same frictional force encountered with the single wire system. The single wire system failed frequently during prototype testing. Using the twin loop system offers a successful solution to this problem.

After the twin loops of wire cut the gasket, the remaining intact gasket is the long bottom section and part of the bottom corners. Prototype testing shows that with this amount of gasket cut, the bottom length of gasket acts as a hinge, and the glazing is easily pushed from the windshield frame.

4.3.3 Gasket Geometry Final Design

The final gasket geometry design includes modifications to accommodate the twin loop method for cutting the gasket. The design is similar to that used for the single loop method.

4.3.4 Cutting Wire

Wires with diameters ranging from 0.018 in to 0.038 in could cut the gasket during preliminary testing of the gasket cutting. The only size wire, however, that will work with repeated success while the windshield is assembled is a wire with a diameter around 1/32 in. Wires with a smaller diameter will fail due to the decrease in tensile strength. With larger diameter wires, the wires that make up the strand become coarse and abrasive. As the wire cuts the gasket around the corner of the windshield, the coarse strand catches on the glazing. The additional friction developed against the glazing (in addition to the force required to cut the gasket) is large enough to cause the larger wires to fail. The cutting wire that is used is a 1x7 (1 strand with 7 wires per strand) galvanized steel multipurpose wire rope with a diameter of 1/32 in and a breaking strength of 185 lb.

4.3.5 Actuator System

The twin double loop method requires a system to simultaneously retrieve both wires with one actuator. As shown in Figure 49, the twin loop configuration requires the retrieval of two wires from two separate locations. Wire sleeves installed between the windshield frame and a winch guide the wires onto one winch, as shown in the sketch in Figure 50.

A fabricated windshield frame provided a means to perform usability testing of the removable windshield. The image in Figure 51 shows one side of the mockup windshield frame and the actuator for wire retrieval. The installed windshield glazing has a modified gasket. The black tubing shown is a sleeve for the cutting wires. The wire sleeves are the same as those used for the braking and shifting wires on most recreational bicycles. Figure 51 shows the sleeve exiting the windshield frame and guiding the cutting wire to the winch.

Figure 52 shows another view of the wire sleeve as it exits the windshield frame. The cutting end of wire to be retrieved onto the winch runs within the sleeve. The exposed steel wire attached to the bolt shown in the figure is the fixed end of a double loop.

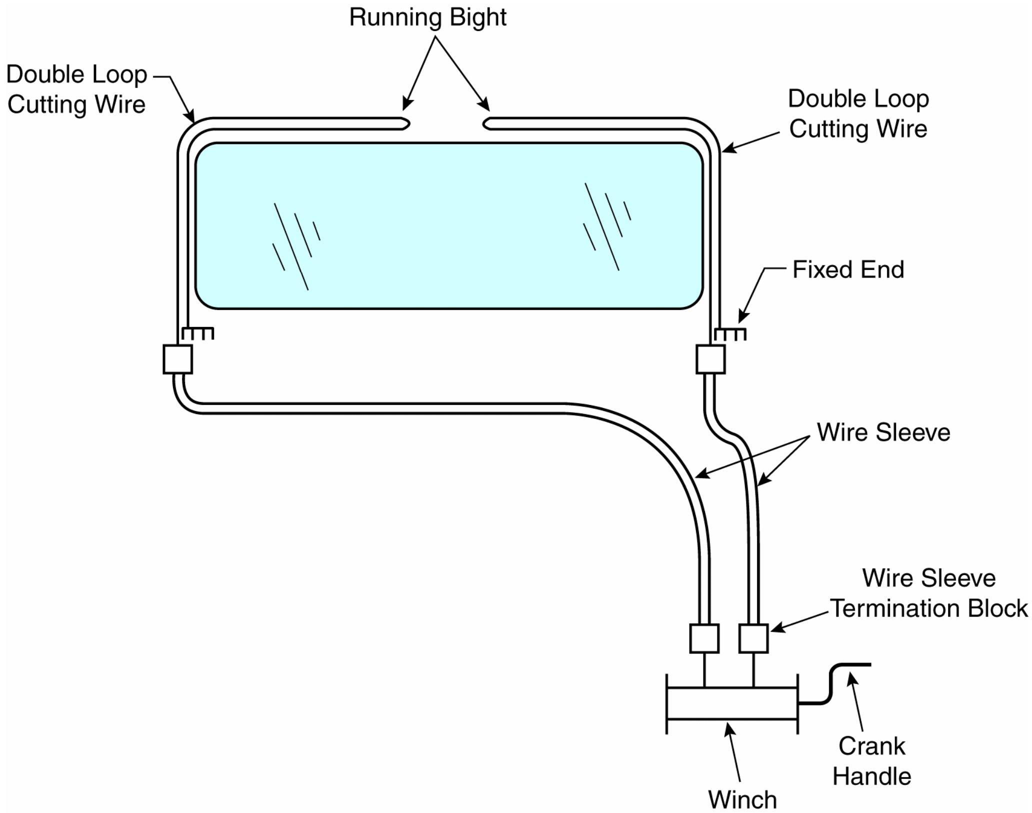

Figure 50. Sketch of wire retrieval actuator system

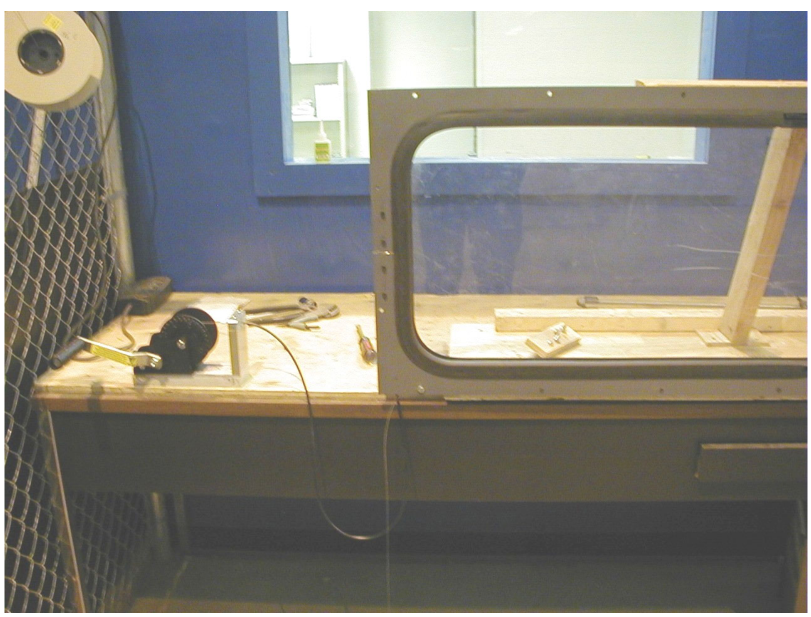

Figure 51. Wire sleeve from windshield frame to winch

Figure 52. Wire sleeve for cutting wire

The wire sleeves add a great advantage to the emergency egress system by allowing the retrieval of two wires from two separate locations. In addition, the sleeves allow the freedom to install a manual or electric winch anywhere in the locomotive rather than being restricted to keeping the winch close to the windshield frame. A termination block allows the wires to be pulled through the sleeves and onto the winch. Figure 53 shows a manual winch attached to the custom built termination block. The two arrows in the figure point to holes in the front of the termination block that will receive the cutting wires and sleeves. Each hole has a large diameter on the front of the termination block. The hole decreases in diameter on the back side of the block. Changing the diameter of the hole allows both the wire and sleeve to enter the block but allows only the wire to exit the block and spool onto the winch.

The manual winch used to retrieve the cutting wire for usability testing and shown in the figures above is a one speed, spur gear hand winch. The winch has a capacity of approximately 600 lb. The gear ratio of the winch is 3.1:1, the spool diameter is 2 in; and the handle length is 6 in. The accumulated mechanical advantage is 6 in/2 in x (3.1) or about 9.3:1. Figure 54 shows the assembled wire retrieval system. The wires covered with the protective sleeves enter the termination block at one side. The winch pulls the wires from the sleeves at the other side of the termination block.

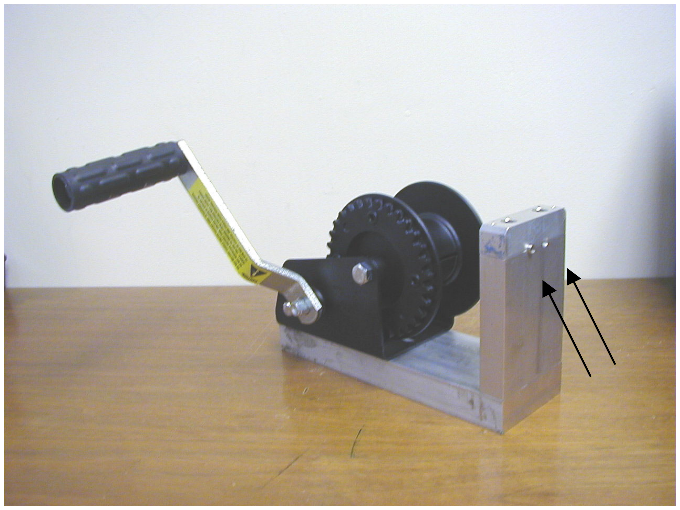

Figure 53. Termination block and winch

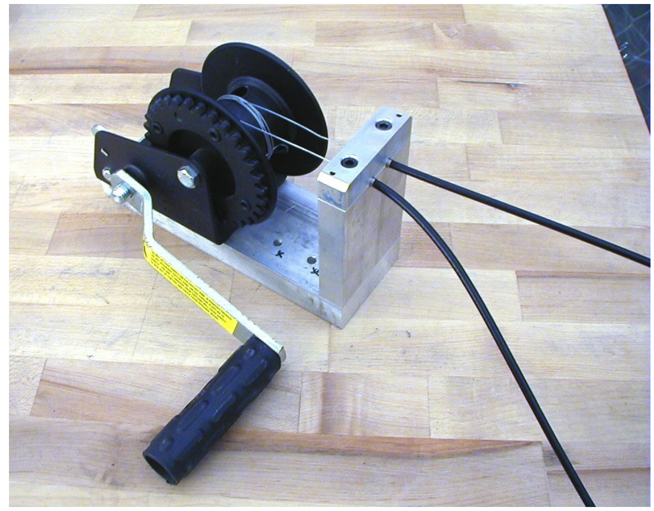

Figure 54. Winch pulling wires from sleeves through termination block

4.4 Usability Assessment

Usability testing employed a prototype windshield installed in the cab mockup. A mockup locomotive windshield frame was fabricated based on the dimensions of the GM EMD locomotive test article located at the Foster-Miller Locomotive Testing Facility in Fitchburg, MA. The prototype system consists of the steel windshield frame, 0.5-in thick polycarbonate cut to match the size of the glazing used in the locomotive, and the modified gasket with cutting wire. Figure 55 shows a photograph of the mockup windshield frame. The wooden mockup locomotive is in the background of the picture. Figures 56 and 57 show the steel mockup windshield frame mounted into the wooden locomotive from the exterior and interior, respectively.

Figure 55. Steel mockup windshield frame installed in mockup

Figure 56. Exterior view of windshield frame mounted in mockup locomotive

Figure 57. Interior view of windshield frame mounted in mockup locomotive

The wire sleeves are utilized in the mockup locomotive. As the running end of the wire exits the gasket and passes through the frame, the sleeve protects the wire from chafing against the steel frame. The fixed end of the wire exits the frame without a sleeve (Figure 58). In addition, by using the wire sleeves, the winch has the flexibility to be located anywhere within the cab. To demonstrate usability, the prototype emergency windshield was installed into the overturned wooden mockup. A small section of the roof panel was added to the mockup locomotive to provide a mounting location for the winch. Figure 59 shows the winch mounted in the overhead console of the mockup locomotive. The prototype windshield with a steel frame is on the left as shown in the picture. The photograph is rotated 90° to show the orientation of the cab during normal operations, without a rollover. Figure 60 shows the winch installed overhead in the rollover orientation, as is the current condition of the wooden mockup locomotive. The view in Figure 60 shows the wires exiting the termination block as they are spooled onto the winch. In addition, this figure shows the wire sleeves exiting the other side of the termination block, curving around toward the overhead roof panel, and running to the openings in the windshield frame. The paths of the wire sleeves are present in the wider view in Figure 57.

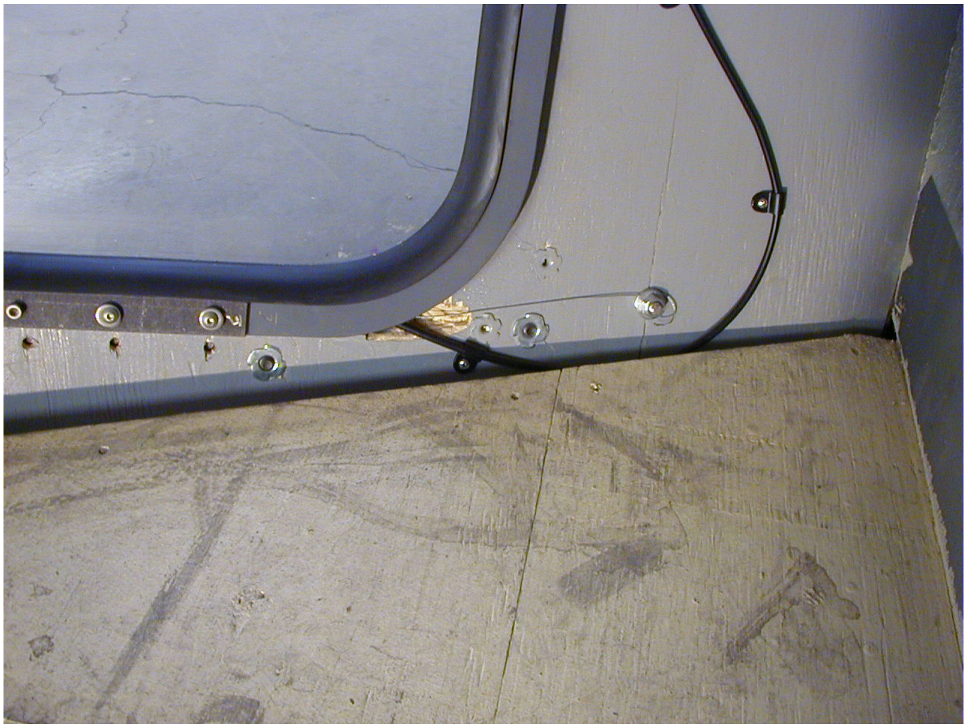

Figure 58. Fixed wire and running wire within sleeve exiting windshield frame

Figure 59. Winch located in overhead console of mockup locomotive

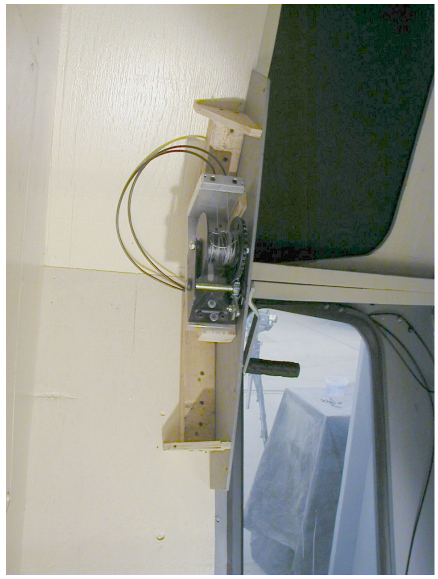

Figure 60. Winch installed overhead, oriented in rollover position

Turning the winch handle actuates the emergency windshield egress system. As the handle turns, wire travels through the wire sleeve and spools onto the winch. The twin double loops close onto each other as designed to cut the gasket (Figure 49). The loops simultaneously cut the gasket on each side of the windshield (Figure 49). The cutting rate of the two loops is identical as they are both retrieved onto the same winch. Once the wire is retrieved to the winch, the gasket on both short sides and one long side of the windshield is cut. The only part of the gasket that remains intact is along one of the long sides of the windshield. Figure 61 shows a gasket severed by the wire. With one intact gasket edge acting as a hinge, a crewmember can push the glazing from the windshield frame. Figure 62 shows a series of pictures that illustrate emergency egress from the mockup locomotive windshield.

Figure 61. Gasket after being severed by wire

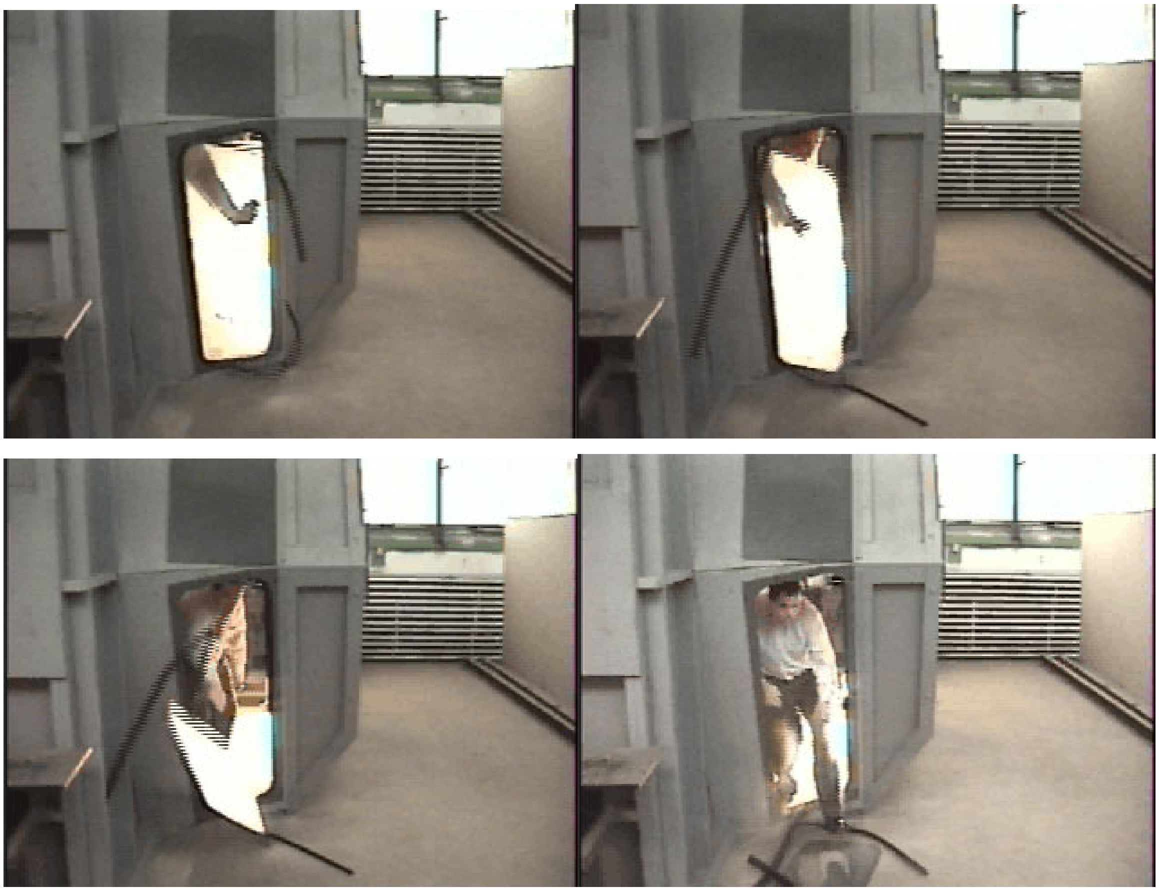

Figure 62. Removal of glazing after cutting the windshield gasket

4.5 Prototype Evaluation

The prototype emergency windshield system was successfully demonstrated in the laboratory. In addition to usability, the researchers reviewed the design for installation and manufacturing cost.

4.5.1 Force Requirements

Prototype testing indicates that peak wire force occurs when initiating the cut. Once the wire begins to cut through the gasket, continued retrieval of the wire requires a much lower force. During prototype testing, a torque wrench measured the force required to initiate the gasket cutting and the force required after the initial cut. The torque required to initiate cutting was 10 ft-lb. The torque required to maintain cutting drops to 4 ft-lb after the initial peak. The handle of the winch is 6-in long; therefore, the force required at the winch handle to initiate and maintain the gasket cutting is approximately 20 lb and 8 lb, respectively.

4.5.2 Egress Time

The time required to exit the locomotive cab is relevant to crew safety during an emergency. Prototype testing indicates that the time required to cut the gasket and push out the windshield was approximately 50 s. This is an acceptable emergency egress time.

4.5.3 Costs

Cost estimates for implementation of the removable windshield system are based on component and labor costs. Costs for the prototype system provide a basis for the estimates. The cost to retrofit an existing locomotive would likely be greater than that to install the system during new construction. Therefore, to be conservative, the authors assumed retrofitting costs for the estimates. The material and labor costs required to retrofit an existing locomotive total less than $1000 per windshield, as itemized in Table 7.

Table 7. Costs to retrofit a locomotive with removable windshield

Description (Parts/Tasks)	Labor	Material	Total
Gasket	n/a	$45	$45
Cutting wire	n/a	$10	$10
Wire sleeve	n/a	$30	$30
Termination block	$180 (3 h @ $60)	$35	$215
Winch	n/a	$40	$40
Installation:	$600 (12 labor-h @ $50)	n/a	$600
Remove windshield glazing and gasket, drill access holes through windshield frame, embed wire into gasket, install glazing and wired gasket into frame, feed wires through wire sleeves, mount winch and termination block in locomotive, connect ends of wire sleeve to windshield frame and termination block, fasten wires to winch			
Total estimated cost per windshield			$940

5. Removable Door Hinge

This section describes the removable door hinge for the locomotive rear door, one of the two secondary egress methods. The design of this innovative door hinge attachment facilitates removal of the cab rear door when deformation of the cab and the door frame prevent normal operation of the door. The design requirements were that (1) the mechanism should be simple and easy for the crew to engage from inside the cab, (2) all the components should be sturdy to last the life of locomotive, and (3) emergency rescue personnel should be able to easily remove the hinge pins from the exterior of the cab. Construction of a prototype door assembly for the GE AC4400 locomotive with the hinge design described below allowed for proof-of-concept evaluation.

5.1 Existing Rear Door Hinge Attachment

The current design practice for the modern locomotive rear door employs either two-hinge or three-hinge construction. Generally the rear door opens outward, for both narrow nose and wide nose freight locomotives. Figure 63 shows the interior view of a cab rear door of a GE AC4400 locomotive in the open position. This figure shows that the hinge line is outside the cab and one leaf of each hinge is welded to the cab structure. The other leaf of each hinge attaches to the rear door with two fasteners, which are spot-welded from inside the cab. Some free space is available on the inner side of the door and could incorporate this secondary egress mechanism.

Figure 63. Interior view of the existing locomotive rear door at a test facility

5.2 Design Concept

Figure 64 schematically shows the conceptual design for the emergency door hinge release mechanism. A single fastener bolt holds the door side leaf of each hinge firmly in place inside a machined slot in the hinge mounting block. The machined block is welded to the edge of the door panel, and the leaf of the hinge is assembled under spring loaded condition with the help of four compression springs held in blind holes of the block. The fastener-nut is tightened from inside the door over the sliding bar with machined key-hole slots. The emergency hinge release handle attaches to the sliding bar with a pin joint for simultaneous release of both fastener nuts, which in turn release the hinge leaves. The detachable hinge system is installed into position with the door as a subassembly. While carrying out this subassembly, care should be taken to ensure proper alignment between the centerlines of the acorn fastener nuts and the key-hole slots on the sliding bar. Some locomotives, like the GE AC4400, have three hinges, while other locomotives, like the GM EMD SD70MAC, have two hinges to support the weight of the rear door, as well as to maintain proper seal compression on the hinge side of the rear door. Addressing this issue effectively requires two stronger and sturdier hinges than those presently used in either type of locomotives.

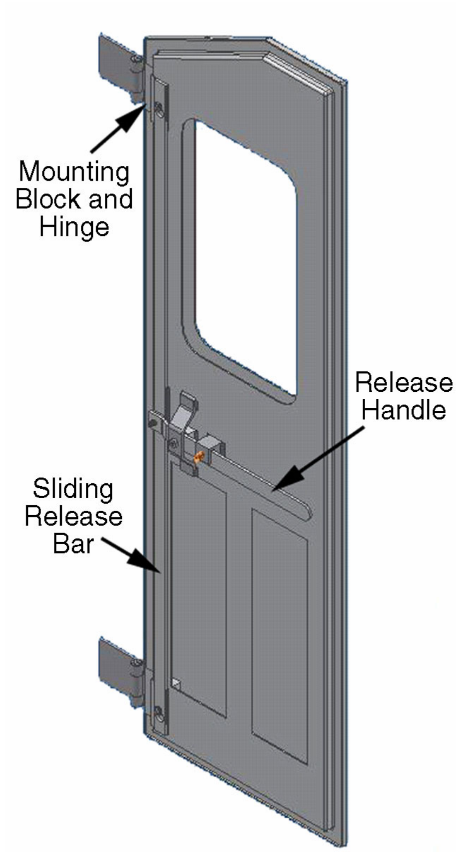

Figure 64. Conceptual design for locomotive rear door hinge release mechanism

Under emergency egress conditions, the crew inside the cab could activate the door hinge release mechanism by removing the locking pin from the handle keeper and pushing down the release handle located at the inner side of the door. The actuation of this handle would make the sliding bar move upward. When the fastener nut positions coincide with the large diameter key-hole slots, the tension on the bolts releases, and the hinge leaves outside of the door swing outward, thereby disengaging the fastener bolts. The crew could then push the hinge side of the door out of the way and escape.

If the crew is injured or for some other reason is unable to exit on its own, the emergency rescue team may approach the cab from outside. With the knowledge of the specially designed removable hinge-pins (see 5.3.4), the team can easily remove the pins, separate the two leaves of the hinges, and remove the door to evacuate the crew to safety.

5.3 Design of Rear Door Hinge Release Mechanism

The hinge release mechanism consists of two hinge mounting blocks, two hinges, a sliding bar with two slotted key-holes, and a hinge release handle along with associated attachment brackets, fasteners, and compression springs. In addition, providing easily detachable hinge pins facilitates access by the emergency rescue team from outside the cab.

5.3.1 Hinge Mounting Block

The main component of the hinge release mechanism is the hinge mounting block. This block must be designed and fabricated with steel so that its thickness dimension properly matches the hinge side thickness variation of the rear door panel construction of both GE AC4400 and GM EMD locomotives. Based on this consideration, the mounting block has two distinct thickness zones, as shown in Figure 65. Each rear door in the locomotive requires two blocks. Each block has one through-the-thickness hole for a steel fastener bolt and four blind holes for holding in position four stiff compression springs. These springs will throw back the hinge leaf once the fastener nut is released from inside the door panel. The hinge leaves support the weight of the door. These hinge leaves sit in the matched groove made on the mounting blocks. The fastener bolt simply holds the hinge leaf tightly in position until it is released from inside. The fastener bolt therefore experiences only tensile force due to tightening of the acorn nut and does not carry any bending load due to the weight of the door. To prevent corrosion due to long exposure to the elements, all the steel components of the door hinge release mechanism should have an anticorrosive treatment before subassembly of the rear door.

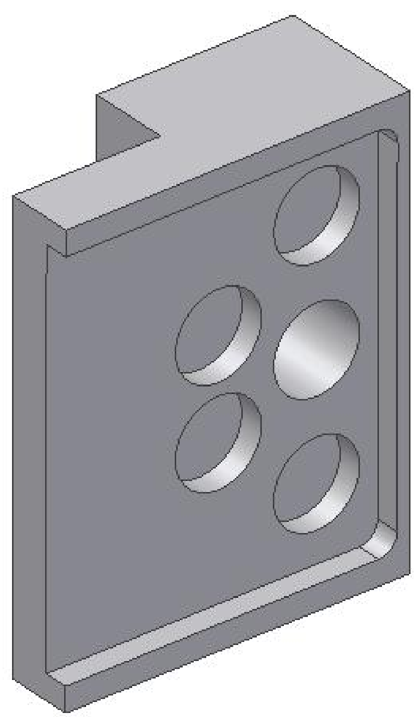

Figure 65. Hinge mounting block

5.3.2 Sliding Bar with Slotted Key-Holes

One ¼-in thick flat steel bar at the inner side of the door facilitates simultaneous release of the fastener nuts of the hinges on operation of the emergency hinge release mechanism. This bar has large size key-hole shaped cutouts at precise positions that match the relative position of the hinges on the rear door of the locomotive. The bar is guided to move only in the vertical (up or down) direction and not sideways. Figure 66 shows the sliding bar.

A pin joint connects this sliding bar to a lever or release handle. When engaged, the release handle makes the sliding bar move up vertically so that the fastener nuts, which are normally tightened on the narrow slot of the key-hole, slide into the large circular hole (oversized for the diameter of the fastener nut). The spring action of the four compression springs, located inside blind holes under the hinge leaf, pushes outward on the hinge leaf.

Figure 66. Details of the sliding bar used in hinge release mechanism

5.3.3 Hinge Release Handle

A handle made of flat steel bar, which is located at the inside of the locomotive rear door, activates the emergency hinge release mechanism. This handle is attached at one end to the sliding bar with a slotted key-hole with the help of a pin joint. A pivot arrangement, about which it can rotate in order to move the sliding bar up for the release of hinges, strongly supports the lever. The handle design offers a large mechanical advantage, which means that the crew would have to exert a small force at the free end of this lever to activate the hinge release mechanism. The force to be applied to this lever depends on the torque with which the fastener nuts located on the sliding bar are tightened to ensure rigidity of the door support. In order to prevent any accidental or inadvertent movement of the release handle during normal operation of the locomotive, a handle keeper block, along with associated hardened and spring-loaded locking pin, is part of the design. Figure 67 depicts the exterior view of a door hinge in the assembled position and attached to the release mechanism inside with a single sturdy fastener bolt. Figure 68 provides a closeup view of the release handle attachment to the sliding bar.

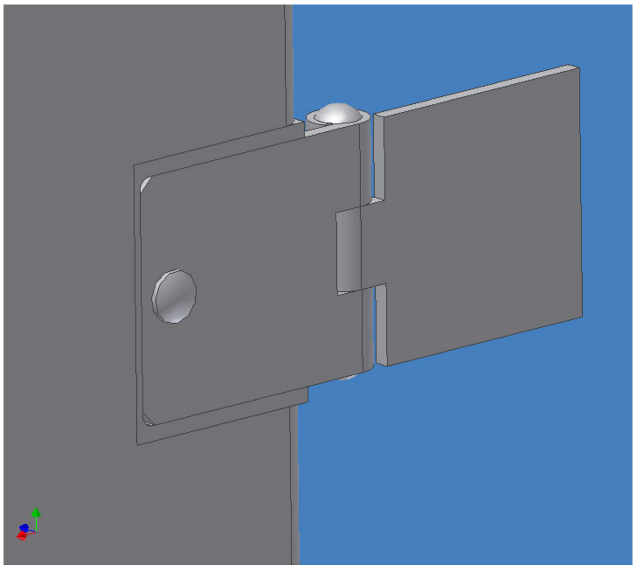

Figure 67. Exterior view of a hinge subassembly attached to the release mechanism with one sturdy fastener bolt

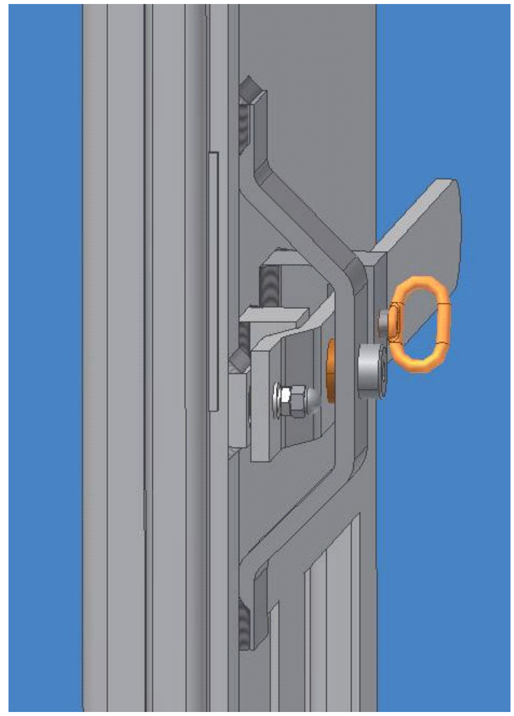

Figure 68. Closeup view of the release handle attachment to the sliding bar

5.3.4 Door Hinge with Detachable Pin

The locomotive rear door hinges, presently employed in different types of locomotives, have small size leaves of relatively low thickness (about 0.125 in). These hinges appear strong enough to support the weight of the door over the cab's lifetime, despite rough usage. The precise alignment required for simultaneous disengagement of the hinge leaves necessitates the use of two sturdier steel hinges of relatively larger size and higher leaf thickness.

In view of the requirement of this innovative design that the leaves of the two hinges must support the weight of the door, the selected hinges must be relatively large and sturdy. For this reason, the design uses 0.25-in thick, 4.0-in height, and 4.0-in wide (each leaf) steel hinges. The hinge pin diameter is 0.5 in. One leaf of each hinge attaches to the door with one sturdy steel fastener bolt of 0.375-in diameter. During the door subassembly, the fastener bolt in the assembled state compresses four compression springs by 0.25 in inside the blind holes 0.5-in deep, located on the exterior part of the hinge block. Welding of the other leaf of each hinge to the body of the cab occurs at the time of final door assembly as is currently done.

Hinge pins that are easily removable from the cab exterior will facilitate access by emergency responders. These hinge pins are made of round cylindrical steel bars with a machined cap at one end. The other end of each hinge pin has a 0.3125-in diameter reamed hole. A pin-insert of 0.313-in diameter and 0.5-in length with a built-in cap of 1.25-in diameter fits into the reamed hole in the hinge pin with interference. An additional step has been provided in this pin-insert just underneath the cap with a diameter of 0.625 in and a length of 0.25 in. Using a crow bar or any other narrow-tipped tool, the emergency response team can easily remove the hinge pins. The other end of the hinge pin has a built-in cap of 1.125-in diameter. The small pin-insert fits into the top end of each hinge pin with interference-fit after assembly of the two leaves of the hinge. Dipping the small pin-inserts in liquid nitrogen (available in small portable bottles or cylinders) for about 15 min before insertion into the reamed holes of the hinge pin eases the insertion. Under normal ambient temperature conditions, the hinge pins will expand to attain press-fit condition and will function as if the hinge pin is fitted with rigid end caps. Figure 69 shows a photograph of two sample hinge pins, one in partially assembled position and the other with its small pin-insert in detached condition.

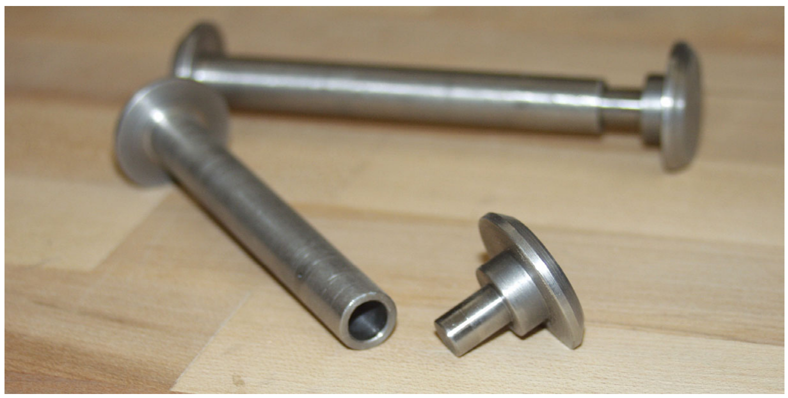

Figure 69. Hinge pins and the interference fit small pin-inserts with cap

In emergency conditions, the rescue team would need only a small crow bar or a similar narrow-tipped tool to forcibly dislodge the pin-insert from the hinge pin and then hammer down the hinge pin with the same tool, so as to separate the leaves of the door hinges to enter inside the cab.

5.4 Considerations for the Modification to Locomotive Rear Door

Incorporating removable door hinges will require minor modifications to the existing rear door design and fabrication process. Building the new doors with the proposed emergency egress features uses the smallest number of modifications possible. Most of the standard parts, like compression springs, nuts, and bolts, are commercially available.

The rigidly fixed steel hinges of the rear door in the present design require modification to be mechanically detachable for emergency egress. One alteration to the rear door fitting is to make provision for two relatively larger and sturdier hinges in place of three small hinges presently employed in GE-AC4400 locomotives. In GM EMD locomotives, the two relatively smaller hinges must be replaced with two sturdier ones, as proposed here. Installing the two new hinges near the top and bottom parts of the rear door requires two cutouts to accommodate the hinge mounting blocks (shown in Figure 65). The steel blocks are welded to the door panel at the cutouts, and a sturdy fastener bolt clamps one leaf of each hinge to the block.

5.5 Proof of Concept

A fabricated rear door with the hinge release mechanisms provided the means to evaluate the functionality of the hinge system. The door specifications are those of a GE AC4400 locomotive. The researchers installed the door and hinge release mechanism on a simple test rig that simulated a rear door frame. Figure 70 shows the exterior view of the door and hinge system in the test rig. The proof-of-concept evaluation involved verifying the functionality of the removable hinges from the simulated cab interior and exterior. Additional figures illustrate the results of this evaluation.

Figure 70. Exterior view of an assembled rear door on the test rig

Figure 71 shows a closeup view of one assembled door hinge, as seen from outside the cab. Figure 72 shows the interior view of the door with most of the components of the hinge release mechanism in assembled condition. Installation of the handle keeper occurred after the photograph was taken.

Figure 71. A closeup view of one hinge in assembled condition

Figure 72. Interior view of the rear door with hinge release handle in assembled condition

As described earlier, the two sturdy leaves of two hinges support the weight of the door. The fastener bolts clamp the hinge leaves into the machined groove of the hinge mounting blocks. The fastening acorn nuts sit on the narrow slot of the keyhole in the sliding bar. During installation, use of a torque wrench assures that this nut is properly tightened, as shown in Figure 73.

Figure 73. Closeup view of an acorn nut assembled on the narrow slot of the key-hole in the sliding bar

Figure 74 shows an interior view of the door and the initial actuation of the hinge release mechanism. Figure 75 illustrates the final position of the hinge release lever on completion of the actuation. Figure 76 shows a closeup view of the disengaged fastener nut inside the circular key-hole, and Figure 77 shows an exterior view of the popped out fastener and the hinge leaf.

Figure 74. Interior view of the door showing the actuation of hinge release handle

Figure 75. Final position of the hinge release handle after actuation

Figure 76. Interior closeup view of the released fastener nut

Figure 77. Exterior view of the fastener bolt and hinge leaf released from the hinge support block

Figure 78 shows the exterior view of the hinge support block after detachment of the hinge leaf. Under accident conditions, on release of both the fastener bolts and the hinge leafs, the crewmembers can easily separate the cab rear door from the two hinges and then leave the cab through the rear door opening.

Figure 78. Closeup exterior view of a hinge support block after detachment of the hinge leaf

Figures 79 and 80 illustrate the procedure for external removal of the door. Figure 79 shows the method to be followed for removal of the interference fit insert to the hinge pin. The rescue team needs to use only a small crow bar or any other tool with a narrow tip to disengage the insert atop the hinge pin as shown in Figure 79. Finally, Figure 80 shows the hinge pin removal from the door hinge. With both the hinge pins removed, the rescue team can move the hinge side of the door out of the way, enter the cab, and carry the crew to safety.

Figure 79. Removal of the pin-insert from the hinge pin

Figure 80. Removal of the hinge pin before separation of the rear door

5.6 Long-Term Functionality and Maintenance Considerations

In principle, the emergency egress mechanisms incorporated into a locomotive cab are for use only in the event of an emergency arising out of an accident or crash that leads to normal cab entry and exit routes being blocked or disabled. Since railroad locomotives are in service for 20 to 30 yr, long-term functionality and routine maintenance are concerns. Therefore, the components of the rear door hinge release mechanism are rugged and heavy duty.

Exterior components exposed to the elements require anticorrosive treatment consistent with current practice for locomotive construction. This together with periodic preventive mechanical maintenance should ensure long-term functionality of the rear door hinge release mechanism. Installing a prototype system into an operational locomotive is the appropriate way to evaluate the system's performance under normal operating conditions. This may be a part of a future program.

Regarding the frequency and cost of required maintenance, the existing routine maintenance schedule for the mechanical components of the locomotive should suffice. The extra effort necessary to maintain these components would include using a torque wrench to check the tightness of the two acorn nuts assembled with a lock washer. These nuts may need resetting to the prescribed torque value, followed by light lubrication of the hinges in metallic components assembled inside the door. The estimated time to accomplish the above maintenance should not be more than an hour during scheduled routine maintenance of the locomotive. As a fail safe approach, however, it is recommended that once a year, the hinge release mechanism be activated during the mechanical maintenance and all the components be reassembled after a thorough cleaning of all parts. This process would involve two technicians and no more than 2 h.

6. Key Findings and Recommendations

Construction of the prototype hatch egress system and subsequent usability testing demonstrated the feasibility of this approach as a viable means of emergency egress from a locomotive cab. Similarly, the design and construction of proof-of-concept prototypes for the removable windshield and removable rear door hinges illustrated the engineering feasibility of these concepts. This section presents the key findings of the developmental work and suggests how future research can further these concepts toward incorporation in road freight locomotives.

6.1 Key Findings

Since the focus of this work was on three separate egress options, the following describes the findings separately with respect to each option.

- *Hatch system*–The hatch system, including the hand/footholds and complementary photoluminescent lighting, is usable by both crewmembers and emergency responders as designed. The system provides a viable means of exit for crewmembers following a crash. Similarly, emergency responders demonstrated that they could successfully remove an injured crew member via the hatch. Based on the usability tests, an exterior foothold would be a beneficial addition as it would aid emergency responders in entering through the hatch. Before installing the hatch system in a working locomotive, however, several engineering design issues merit exploration. The hatch requires testing to establish resistance of its seal to air and water leaks. In addition, the hatch requires a separate test to evaluate the effect of vibration on the latching mechanism.
- *Removable windshield*–The double cutting loop method for removing the windshield from the cab interior appears feasible. The proof-of-concept test found that, using this method, a crewmember can remove the windshield without excessive force in a matter of minutes. The installation process used for the proof-of-concept testing, however, was time consuming. In addition, if the cutting wire was not carefully placed in the gasket groove, the wire would not function properly. This egress option may be relatively inexpensive to install on current locomotives because it requires only substitution of a modified gasket, available at the same cost as current gaskets.
- *Removable door hinges*–The hinge release mechanism, initially intended for all three door hinges, appears to function properly when the door has only two hinges. The design appears suitable for retrofit on existing doors. Additional testing and installation in a working locomotive will determine if the day-to-day use of the door will compromise the functionality of the release mechanism.

6.2 Recommendations for Future Research

The results of the research described in this report suggest areas for further research relative to improved emergency egress for locomotive crews. The following discusses these areas.

Refine hatch system design

The results of the usability tests suggest several potential refinements in the hatch system design. The issues that merit investigation include alternate placement of the exterior grab irons, the size of the opening, exterior hand/footholds to facilitate entry, and exterior markings to aid emergency responders in locating the hatch. The photo luminescent lighting might prove to be a distraction to the train crew during nighttime operation. Testing in a road locomotive would determine whether or not this will be problematic.

Several engineering design issues also remain to be explored. Testing of the hatch seal for its ability to prevent either air or water leaks has not yet occurred. Noise insulation must also be added so that the noise level in the cab does not increase. Over time the vibration of the locomotive may compromise the performance of the latching mechanism. This potential problem requires investigation.

Test hatch system and secondary egress equipment under partial rollover condition

To date, tests of the prototype egress equipment have involved either an upright locomotive or a 90° rollover. Since a locomotive may become partially toppled, perhaps at 45°, following a crash, it is desirable to assess the functionality of the hatch system and the secondary egress equipment in this configuration. These tests will require a special test fixture that rotates the mockup.

Conduct usability tests for removable windshield and door hinges

Usability testing to date has focused on the hatch system. Both the removable windshield and the door hinge system require the same type of assessment. As was done with the hatch system, both locomotive crewmembers and emergency responders should be participants in these usability tests of the door hinges. Since the removable windshield is designed for use by crewmembers, only these individuals will participate in the usability test.

Conduct usability tests under partial rollover condition

Once the hatch system and the secondary egress equipment have performed satisfactorily in a partial rollover configuration, additional usability tests will be possible for this scenario.

Obtain and incorporate industry feedback

Locomotive builders, the railroad industry, railroad labor, and FRA all have an interest in emergency egress. Deployment of any of the three emergency egress concepts requires review and acceptance from all four groups. At this point in the development of the three concepts, it is important to get feedback from each group and refine the designs to address their concerns. Meetings with each stakeholder group can provide a forum to discuss a range of issues, such as operability in critical or hazardous situations, the cost impacts to install and maintain the equipment, structural considerations, and necessary changes to installation and maintenance procedures.

Validate functionality of windshield and hinges under accident conditions

The intended use of the removable windshield and removable door hinges is under accident conditions. Testing can validate the functionality of these devices under these conditions. A crash test will validate that the modified gasket does not cause the window to release as the result of a crash and that the window can be released from the cab interior following a crash. Similarly a crash test that involves structural damage to the rear door frame will validate the utility and functionality of the hinges.

Examine retrofit to existing equipment

The hatch system was designed for installation in a new locomotive. Installation in existing equipment may also be feasible, but this possibility remains to be examined. The primary issue appears to be relocation of wiring harnesses currently in the roof and any equipment, such as global positioning systems, installed on the roof. In terms of the removable windshield and the removable door hinge, these are likely to be less problematic when installed on existing locomotives. Assessing the feasibility of retrofitting each of the three innovative egress devices requires consideration of both structural and cost issues. Consideration of cost includes material and installation expense, as well as periodic maintenance over the life of the equipment.

Investigate smart technologies to enhance egress options

Advances in Intelligent Transportation Systems and sensors offer the technology to create systems that automatically detect and self-actuate in the event of a crash. By drawing on available components and systems, application of these smart technologies to the locomotive environment should require minimal development. Concepts that merit exploration include:

- Communication system that automatically notifies the dispatcher and emergency rescue personnel of the crash.
- Exterior warning lights to assist rescue personnel in locating the locomotive at the crash site.
- Automatic dislodging of the side window for egress in the presence of smoke.
- Automatic release of masks with fresh air flow for crew survivability in the event of smoke in the cab.

7. References

Carter, J., Gertler, J., Acton, S. & Kokkins, S. (2003). *Evaluation of Concepts for Locomotive Crew Egress.* (DOT/FRA/ORD-03/07). Washington, DC: Federal Railroad Administration.

Federal Railroad Administration Office of Safety. (1996). *Locomotive Crashworthiness and Cab Working Conditions, Report to Congress.* Washington, DC: Federal Railroad Administration.

Kokkins, S.J. (2002). *Locomotive Crashworthiness Research: Locomotive Crew Egress Evaluation*. (DOT/FRA/ORD-02/03). Washington, DC: Federal Railroad Administration.

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Appendix A.
Informed Consent

- INFORMED CONSENT -

PARTICIPATION IN A RESEARCH STUDY

You have been asked to participate in a research study. In this document we explain the nature of your participation, describe your rights, specify how your experimental data will be treated, and obtain your consent for participation.

1. Overview of the Study

Title: Usability of a roof-mounted escape hatch system as means of egress from a toppled locomotive.

Sponsor: Federal Railroad Administration (FRA), Office of Research and Development, 1120 Vermont Ave. NW, Washington, DC 20590.

Organization Performing the Research: Foster-Miller, Inc., 350 Second Avenue, Waltham, MA 02451.

Investigators: Judith Gertler (Principal Investigator), Alex Viale (Co-Investigator), Sarah Acton (Co-Investigator)

2. Purpose

The purpose of your participation in this study is to help Foster-Miller evaluate a new roof-mounted escape hatch system as a means of egress from a toppled locomotive. You will be asked to exit (enter and exit if you are an emergency response person) the locomotive quickly and safely, and lower yourself to the ground. You will be asked to repeat this task under a number of different conditions. While we are seeking information regarding the amount of time it takes you to exit (enter and exit for emergency response crew) the locomotive, we are mainly concerned with your safety, and the usefulness of the system, as well as any suggestions you may have for improvements.

3. Procedures

1. Timeline: Your participation in this study will last approximately 45 minutes.

2. Requirements for participation: As a participant in the study, you will be asked to do the following after signing the Informed Consent:

(a) First, you will be asked to complete a brief background survey that asks your age, gender, height, weight, job title, and years of work experience. Such information, as it relates to you, will be kept confidential pursuant to the confidentiality section below. Please do not write your name on this document.

(b) Next, you will be briefed on what you can expect from participating in this study.

(c) You will then be escorted to the locomotive mockup. In order to simulate an accident scenario, and possible disorientation, we will ask you to put on a blindfold, and a researcher will assist you with turning around twice and sitting you down on the floor of the cab. Next, you will be asked to remove the blindfold, escape through the roof hatch, and lower yourself to the ground. You will be asked to perform this task under a number of different conditions. **At all times, your performance will be recorded with the use of video taping equipment**. This will in no way jeopardize your confidentiality, and is simply done in order to capture each performance in the event it requires referencing at a later time. Remember, that although we are interested in how efficiently you can exit the locomotive, your first priority should be to perform this task safely.

(d) At the conclusion of each trial, you will be asked to complete a brief survey that contains questions pertaining to your tasks. You will also be asked to complete an exit survey, soliciting your suggestions for improvements to the hatch system.

4. Risks and Procedures for Termination of Participant

Due to the careful planning and ergonomic design of the roof-hatch, tether line safety system, hand/footholds, grab irons, and the use of photoluminescent egress materials, no injuries are anticipated while participating in this study. However, there is always the slightest chance for injury. Possible injuries may relate to: disorientation, bumping into something in the low-visibility (darkness) scenario, bumping one's head upon entrance or exit of the hatch; losing grip of the grab irons and landing on the ground; or turning an ankle when lowering oneself onto the ground. If you sustain any type of injury, or feel any discomfort whatsoever, you may discontinue your participation at any time by simply telling the experimenter you wish to stop. Further, the investigators will monitor your activity throughout each trial, and will be in immediate proximity to you at all times (one researcher inside the locomotive cab, and one just outside the cab). Investigators will look for any signs of injury or discomfort and will stop the trials immediately if any of these signs present themselves. **In the unlikely event you are injured, we will transport you to the nearest hospital emergency room, or call 911 (if necessary), but you are responsible for the treatment and care of said injury and agree to release us from any responsibility related to said injury.**

5. Benefits

You will benefit from the study by taking part in an investigation that may improve the safety of locomotive operations, which ultimately may result in a reduction in fatalities, injuries and associated costs. After the study has been completed and the results are analyzed, a final report will be provided to the Office of Research and Development of the Federal Railroad Administration. You may view the report by contacting any of the Foster-Miller investigators for a copy of the report. Contact information is provided at the bottom of this form.

6. Compensation

There is a $60 compensation for your participation in this research. This will be awarded to you upon completion of all tasks, or in the event you wish to withdraw from the study due to an injury you sustained during your participation.

7. Confidentiality

We will be collecting a variety of data as part of your participation in this study today. These data include paper-based questionnaires and performance data, and a video recording of your performance. As a participant in this study, you will be assigned a unique identification number which is known only to you and the investigators from Foster-Miller, Inc. We will use this unique identification number to match your performance data with the paper-based forms that you fill out and the video recording of your performance. Your name will not be recorded anywhere except on this consent form and a spreadsheet that Foster-Miller will use to manage the study. All of these data will be maintained by Foster-Miller, Inc. and will be kept strictly confidential. In the event of any publications or reports on this study, your identity will not be disclosed. We will *not* provide any information on your participation to the Federal Railroad Administration (FRA), Brotherhood of Locomotive Engineers (BLE), United Transportation Union (UTU), or any other party to the extent permitted by law.

8. Research-Related Injury Coverage

Your participation in this research study should not result in any physical discomfort or injury to you. **Again, in the unlikely event you are injured, we will transport you to the nearest hospital emergency room or call 911 (if necessary), but you are responsible for the treatment and care of said injury and agree to release us from any responsibility related to said injury.**

9. Voluntary Participation

Your participation is voluntary and you may withdraw from participation in the study at any time by simply telling the experimenter you wish to stop. All information collected will still be held strictly confidential.

10. Questions

You may contact the Foster-Miller investigators at any time with questions you have about the study or the conditions of your participation as a research participant. The investigators are:

Judith Gertler	Principal Investigator	781-684-4270
Alex Viale	Co-Investigator	781-684-8444
Sarah Acton	Co-Investigator	781-684-4281

11. Consent and Signature

I have read and understand the requirements of my participation in this study as described in this Informed Consent, as well as my rights to refuse to participate or to stop participating at any time. I am fully aware that my participation will be recorded on video tape and expressly consent to such recording. I understand the possible risks and discomforts I may experience and the possible benefits to me and to others as a result of this research. I also understand that the information collected about me will be kept confidential. Any questions I had have been answered, and I agree to voluntarily cooperate and participate in good faith.

Name (print): ____

Signature: ____ Date: ____________

Signature of witness: __________________________________ Date: ____________

Background Survey

Unique ID: ______________________ Date: _____________________

1. Gender (circle one): Male Female
2. Age: __________________
3. Height: ________________
4. Weight: _______________
5. Job Title: ____
6. Number of years experience at this type of work: _____________

Appendix B.
Post-Scenario Survey

(Emergency Response Personnel)

ID#_______ Date_______

Instructions:

To help us in making future decisions about the design of the hatch system, please take a few minutes to complete the following survey. Some questions will ask you to respond using a five-point scale. **Please select and circle one of the five numbers on the scale that best corresponds to your response.** Descriptions of each number are provided directly underneath the scale. We will use these results to gain additional insight into hatch system design. If you have any questions, please do not hesitate to ask the researcher for assistance. *Thank you!*

1. How difficult or easy was it to **determine how** to open the roof hatch?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

2. How difficult or easy was it **physically** to open the roof hatch?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

3. How difficult or easy was it to **enter** the cab through the roof hatch?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

4. Did you use the **grab irons** (on the outside of the locomotive) to help you **enter** the locomotive?

No ______ Yes ______

If you used any of the **grab irons**, how ineffective or effective was their **placement**?

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

5. How difficult or easy was it to **determine how** to operate the **hand/footholds**?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

6. Please check off which **hand/footholds** you used (if any) during entrance entrance and exit.

Entrance		**Exit**
	Highest hand-foot-hold (above the hatch)	
	Middle hand-foot-hold (just below hatch)	
	Lowest hand-foot-hold (very bottom)	

If you used any of the **hand/footholds**, how ineffective or effective was their **placement**?

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

7. How difficult or easy was it **physically** to maneuver the hand/footholds into a usable position?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

8. How difficult or easy was it to **exit** the cab through the roof hatch (with full gear and an injured person)?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

9. Did you use the **grab irons** (on the outside of the locomotive) to help you **exit** the locomotive, and/or lower yourself to the ground?

No ______ Yes ______

If yes, how ineffective or effective was their **placement**?

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective nor effective	somewhat effective	extremely effective

Please explain your answer:

10. Overall, do you feel that this new system is an effective way of **entering** a toppled locomotive?

No_____ Yes_____

11. Overall, do you feel that this new system is an effective way of **exiting** a toppled locomotive (with full gear and an injured person)?

No_____ Yes_____

Post-Scenario Survey

(Crew Survey – Light 1st, Dark 2nd, Part I)

ID#_______ **Date_______**

Instructions:
To help us in making future decisions about the design of the hatch system, please take a few minutes to complete the following survey. Some questions will ask you to respond using a five-point scale. **Please select and circle one of the five numbers on the scale that best corresponds to your response.** Descriptions of each number are provided directly underneath the scale. We will use these results to gain additional insights into hatch system design. If you have any questions, please do not hesitate to ask the researcher for assistance. *Thank you!*

1. How difficult or easy was it to **determine how** to operate the **hand/footholds**?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

2. Please check off which **hand/footholds** you used (if any) during exit:

Highest hand-foot-hold (above the hatch)
Middle hand-foot-hold (just below hatch)
Lowest hand-foot-hold (very bottom)

If you used any of the **hand/footholds**, how ineffective or effective was their **placement**?

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

3. If you used any of the **hand/footholds**, how difficult or easy was it **physically** to maneuver them into a usable position?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

4. How difficult or easy was it to **determine how** to open the roof hatch?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

5. How difficult or easy was it **physically** to open the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

6. How difficult or easy was it to **exit** the cab through the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

7. Did you use the **grab irons** (on the outside of the locomotive) to help you exit the locomotive, and/or lower yourself to the ground?

No ______ Yes ______

If yes, how ineffective or effective was their **placement**?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

8. **Overall**, do you feel that this new system is an effective method of exiting a toppled locomotive?

No_____ Yes_____

9. Do you feel that the roof hatch, hand/footholds, or grab irons would, in any way, interfere with the **normal everyday operations** of the locomotive?

No______ Yes______

If yes, how so:

Post-Scenario Survey

(Crew Survey cont… – Light 1st, Dark 2nd, Part II)

ID#_______ **Date_______**

1. How **visible** were the **hand/footholds** (during the darkened condition)?

1	2	3	4	5
not visible at all	not very visible	neither invisible or visible	somewhat visible	extremely visible

2. How **visible** was the **roof hatch** (during the darkened condition)?

1	2	3	4	5
not visible at all	not very visible	neither invisible or visible	somewhat visible	extremely visible

3. How **visible** were the **operational instructions** of the roof hatch?

1	2	3	4	5
not visible at all	not very visible	neither invisible or visible	somewhat visible	extremely visible

4. If you attempted different methods of exiting the locomotive (head-first / both feet-first, one leg at a time), which method did you find the **most effective**?

Head First _______ Both Feet First _______ One leg at a time _______

5. **Overall**, do you feel that this new system is an effective method of exiting a toppled locomotive?

No_____ Yes_____

Post-Scenario Survey

(Crew Survey - Dark 1st, Light 2nd, Part I)

ID#_______ Date_______

Instructions:

To help us in making future decisions about the design of the hatch system, please take a few minutes to complete the following survey. Some questions will ask you to respond using a five-point scale. **Please select and circle one of the five numbers on the scale that best corresponds to your response.** Descriptions of each number are provided directly underneath the scale. We will use these results to gain additional insights into hatch system design. If you have any questions, please do not hesitate to ask the researcher for assistance. *Thank you!*

1. How **visible** were the **hand/footholds**?

1	2	3	4	5
not visible at all	not very visible	neither invisible or visible	somewhat visible	extremely visible

2. How difficult or easy was it to **determine how** to operate the **hand/footholds**?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

3. Please check off which **hand/footholds** you used (if any) during exit:

Highest hand-foot-hold (above the hatch)
Middle hand-foot-hold (just below hatch)
Lowest hand-foot-hold (very bottom)

If you used any of the **hand/footholds**, how ineffective or effective were their placement?

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

4. If you used any of the **hand/footholds**, how difficult or easy was it to **physically**, to maneuver them into a usable position?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

5. How **visible** was the **roof hatch**?

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

6. How **visible** were the **operational instructions** of the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

7. How difficult or easy was it to **determine how** to open the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

8. How difficult or easy was it **physically** to open the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

9. How difficult or easy was it to **exit** the cab through the roof hatch?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely difficult	somewhat difficult	neither difficult nor easy	somewhat easy	extremely easy

10. Did you use the **grab irons** (on the outside of the locomotive) to help you exit the locomotive, and/or lower yourself to the ground?

No ______ Yes ______

If yes, how ineffective or effective were their **placement**?

1-------------------------2-------------------------3-------------------------4-------------------------5

1	2	3	4	5
extremely ineffective	somewhat ineffective	neither ineffective or effective	somewhat effective	extremely effective

Please explain your answer:

11. Overall, do you feel that this new system is an effective method of exiting a toppled locomotive?

No_____ Yes_____

12. Do you feel that the roof hatch, hand/footholds, or grab irons would, in any way, interfere with the **normal everyday operations** of the locomotive?

No______ Yes______

If yes, how so:

Post-Scenario Survey

(Crew Survey cont... - Dark 1st, Light 2nd, Part II)

ID#_______ **Date_______**

1. If you attempted different methods of exiting the locomotive (head-first, both feet-first, one leg at a time), which method did you find the **most effective**?

2. **Overall**, do you feel that this new system is an effective method of exiting a toppled locomotive?

   No_____ Yes_____

Appendix C.
Data Sheet

(Emergency Response Personnel)

ID#_______ **Date_______**

1. Time to enter and exit

	Lighted Condition
Time (2 people):	
Time (3 people):	
Time (4 people):	
Time (5 people):	

2. Researcher Comments

Condition 1:

3. Comments or suggestions regarding the grab irons?

4. Comments or suggestions regarding the hatch?

5. Comments or suggestions regarding the hatch markings?

6. Comments or suggestions regarding the hand/footholds?

Data Sheet
(Crew Personnel)

ID#_______ **Date_______**

1. Time to exit

	Condition 1	Condition 2	Condition 3	Condition 4
Time				

2. Researcher Comments

Condition 1:

Condition 2:

Condition 3:

Condition 4:

3. Participant Comments

a. Comments or suggestions regarding the grab irons?

b. Comments or suggestions regarding the hatch?

c. Comments or suggestions regarding the hatch markings?

d. Comments or suggestions regarding the hand/footholds?

Appendix D.
Description of Training Video

Foster-Miller produced a training video designed to prepare emergency responders to respond to a locomotive wreck. The title of this video is “Locomotive Emergency Response Operations.” The video helps emergency responders to:

- Understand the railroad transport system.
- Assess their coverage area for special risks.
- Approach a site and enter a locomotive after an accident.
- Extricate the crew.

The video explains that a railroad is divided into territories, each under the jurisdiction of a dispatcher, who manages that territory from a dispatching center. Signal systems and dark territory are also explained. Emergency responders are encouraged to become familiar with the railroad operations in their coverage area and to identify any special situations such as bridges, tunnels, and track, in difficult to access areas. The various parts of the locomotive—such as the fuel tank, high pressure hoses, traction motors, and emergency shut off switches—are illustrated. The video suggests the steps to take in responding to a crash and how to approach the site and enter the cab. Techniques for extricating the crew are demonstrated in the video. The video concludes with an actual worst-case scenario and how the emergency responders managed the situation.

Three handouts accompany the video: (1) checklist of things to do when approach the site, (2) checklist of things to do when entering the locomotive, and (3) instructions on railroad flagging procedures.

Abbreviations/Acronyms

AC	alternating current
APTA	American Public Transit Association
ASTM	American Society for Testing and Materials
cd/m²	candela per square meter
DC	direct current
DIN	Deutsches Institute für Normung eV (German Institute for Standardization)
EMD	General Motors Electromotive Division
fc	foot-candle
FRA	Federal Railroad Administration
ft	foot (feet)
ft-lb	foot-pound
GE	General Electric
h	hour
IMO	International Maritime Organization
in	inch
IRB	Institutional Review Board
LED	light emitting diode
mcd/m²	millicandella per square meter
min	minute
NFPA	National Fire Protection Association
PVC	polyvinyl chloride
yr	year