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Integrity of Rail Passenger Equipment Glazing Systems

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14. ABSTRACT
Failures of glazing retention mechanisms on passenger trains have led to multiple injuries and fatalities in rollover-type accidents over the last several decades. This research effort reviewed global standards for glazing system design and performance, as well as modes of retention failures under accident conditions, and proposed design concepts to improve retention performance and test methods to evaluate the same. Two of the design concepts were prototyped and evaluated using three test methods. The results were used to propose additional performance requirements that address glazing retention capacity.

15. SUBJECT TERMS
Window, glazing, gasket, zip-strip, derailment, passenger containment, emergency egress, emergency access, fire resistance, fire protection, simulations, finite element model, impact test

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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 ft. (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

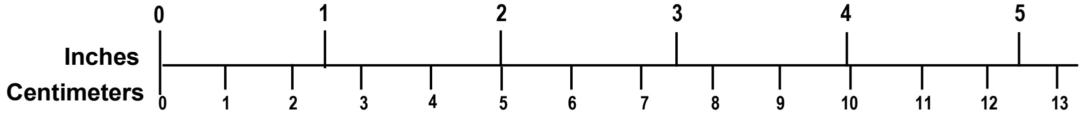
VOLUME (APPROXIMATE)

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 ft. (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°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°

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Executive Summary

In addition to serving the primary function of outward visibility to passengers, glazing systems on passenger railcars also perform the following safety-critical functions:

- Provide impact resistance (both ballistic and large object).
- Allow for emergency egress (car occupants being able to get out of the car).
- Permit rescue access (for emergency personnel trying to enter the car).
- Provide fire resistance.
- Provide occupant containment.

Current standards and regulations establish performance requirements for the first four items, while requirements for the last (occupant containment), are not explicitly addressed. Passenger rollover derailments in the last few decades have resulted in passenger ejections, injuries, and fatalities due to the occupant containment performance of glazing systems. A review of these accidents has underscored the key failure mode that contributed to passenger injuries and fatalities: the failure of the outer gaskets during rollover derailments after the cars have been dragged along the ground. Once the gasket has failed, the window is pushed into the car, leaving an opening through which occupants may be ejected.

This suggests that improving glazing retention could also improve occupant protection. However, improving retention performance has the potential to make emergency access and egress performance more complex; therefore, additional requirements for improving glazing retention need to be carefully considered.

FRA and the Sharma & Associates research team held a brainstorming session to identify and rank design elements that could improve glazing retention performance and test methods by which glazing retention performance could be quantified. Two of the proposed concepts that were qualitatively rated to have a high likelihood of success as well as a high potential for retrofit to existing systems were then prototyped for testing. The concepts, as well as a base case (reflecting the current Amtrak design) were evaluated through three pilot tests:

- A push-through test that quantified the normal/inward force needed to separate the glazing from the frame.
- A pry test that quantified the ability of the system to resist prying loads, such as those that may be imparted by ballast, tree debris, or other wayside features.
- A ballast drag test that reasonably represented the conditions that might be experienced by the sidewall and window section of a passenger rail car during a rollover derailment incident.

The test results demonstrated that the three tests reasonably captured the glazing failure modes observed in accidents and quantified the glazing retention performance of existing or proposed glazing system designs. The tests also showed:

- The base case design tested was highly susceptible to retention failure, as seen in all three tests.

- The two concepts tested significantly improved retention performance under the prying mode, as seen from both the ballast drag and prying tests. These concepts did not offer a significant benefit for the push-through mode of failure. This was not an unexpected result, as these mitigations were designed explicitly to protect the outer gasket only and provided limited additional resistance under this loading scenario.

The research team has proposed an updated set of performance requirements for glazing systems, adding requirements for glazing retention, in addition to the existing safety and functionality requirements. The team suggests that the push-through and pry tests be developed into a test specification/standard with appropriate pass/fail criteria, in collaboration with industry. Load magnitudes and pass/fail criteria have not been established yet, and will likely need additional research and testing. The ballast drag test remains an excellent research tool, but may also be developed into an alternate standard, if desired.

Recommendations for future work include:

- Testing additional commuter car glazing system designs to better quantify the expected glazing retention performance of commonly used designs.
- Additional testing to quantify the push-through load capacity that would be required to resist the corresponding mode of failure during the ballast drag test under heavier loads.
- Investigation of alternative glazing securement methods which do not rely on the traditional gasket methodology and accommodate emergency access/egress requirements.
- Analyses to better estimate the expected loads on the glazing surface, considering the stiffness of key carbody elements (which are not well-represented in the ballast drag test due to physical constraints).
- Calibrating/validating the simulation models using the test data, so that these models can be used for more predictive analyses.
- Working with industry to consider development of the draft performance requirements into a set of specifications, considering the variety of glazing system configurations in use.

1. Introduction

This report describes the work performed by the research team in reviewing glazing system designs and design standards globally, identifying the performance and shortcomings of glazing systems under accident conditions, proposing design elements and test methods to improve and quantify performance, and the results of a pilot prototyping and test effort.

Rail passenger car glazing systems must perform satisfactorily under competing expectations. They must be strong enough to withstand potential train derailments without major deformation. They must allow passengers to escape in an emergency scenario. They also must allow emergency personnel to enter the car if necessary. However, trying to boost performance for one aspect often reduces the effectiveness in another, making this a difficult engineering problem to solve.

1.1 Background

Glazing systems on passenger railcars serve a number of critical functions beyond offering passengers a view outside the car. They also serve certain safety functions: impact resistance, emergency egress, emergency access, fire resistance, and occupant containment.

The design aspects of most of these functions are covered by standards and regulations from various organizations such as the Federal Railroad Administration (FRA) through the Code of Federal Regulations (CFR), the Association of American Railroads (AAR), American National Standards Institute (ANSI), and others [1] [2] [3] [4] [5]. Functionality requirements such as luminous transmittance, abrasion resistance, weather resistance, installation ease, and maintenance needs are also prescribed by these documents in conjunction with vehicle procurement specifications.

Current regulations on glazing strength focus on ballistic and large object impact performance, rather than on occupant retention under accident conditions. Over the last 44 years, at least 25 fatalities have been attributed to passenger ejection through window openings during passenger train accidents [6]. Many of these fatalities have been attributed to the inability of the glazing systems to provide the needed level of resistance to passenger ejection. Reviews of rollover accidents have shown that, more often than not, occupant retention performance (or the lack thereof) has been defined by the capacity of glazing retention gaskets, rather than the strength of the glazing panes. In particular, it appears that these failures are more attributable to the mounting method of the glazing panes, rather than failures of the panes themselves.

1.2 Objectives

Considering the above, there is a distinct need to address the ability of the "glazing system" (including gaskets/mounting) to resist separation under accident conditions in which the system might be subject to different loading conditions, including forces from secondary impact by passengers and abrasive forces resulting from the carbody dragging on its side against the ground or other obstacles. Ideally, this would be addressed through a combination of enhanced requirements, alternative designs, and updated evaluation methods.

Naturally, any endeavor to address/improve glazing system performance should acknowledge that these systems are expected to perform several potentially conflicting, safety-critical functions, including:

- Providing a clear and unobstructed view
- Withstanding a variety of loading conditions due to normal railroad operations, including the aerodynamic effects of fast trains passing each other
- Providing impact protection from potential projectiles
- Containing occupants and crew in the event of an accident
- Allowing for rapid egress and rescue operations, etc.

As an example, the system needs to be strong enough to provide protection from large object impact and aerodynamic forces, while at the same time be easy to remove by potentially injured passengers in an accident. In addition, there are other practical considerations such as manufacturing, installation, weight, and cost. Given the competing expectations for glazing system performance, any efforts to improve/revise the requirements, the design, or the evaluation procedures need to be grounded on a solid technical basis.

1.3 Overall Approach

The intent of this effort was to propose a set of draft engineering requirements for glazing systems, with a focus on safety considerations such as occupant protection and emergency access/egress, but with due consideration to other functionality, including optical performance, manufacturing, service, and maintenance. This was approached through a review of standards/specifications, review of accident performance, review of industry practices, concept development, modeling and simulations, and physical testing.

1.4 Scope

To address the project objectives, the following methodology was adopted:

a. A survey of existing design strategies and an assessment of the effectiveness of these strategies in meeting key requirements
b. A survey of accidents and accident performance
c. Proposed design strategies or design elements that might help address deficiencies.
d. Proposed test methods to evaluate performance of current designs and proposed alternatives.
e. A pilot effort to implement and test proposed design changes and test methods.

Ultimately, the project sought to provide a set of recommendations for potentially improved design strategies and test methods, based on the survey, accident performance review, the analyses, and the assessments.

1.5 Organization of the Report

Section 2 presents an overview of existing designs and design practices from a global perspective. Section 3 presents a review of accidents where glazing performance was a concern, and discusses the modes of failure. Section 4 presents an overview of the modeling and simulations. Section 5 outlines the design concepts that were developed to potentially address some of the challenges observed in the accident review. Section 6 discusses the prototyping effort, test effort, and results. Section 7 presents an overview of engineering requirements proposed, and Section 8 summarizes the effort and recommendations for future work.

2. Current Design Approaches and Details

Glazing systems for passenger railcars have to meet functional requirements such as transparency, optical quality, and maintainability, as well as safety requirements such as emergency egress, rescue access, fire tolerance, and occupant containment. By and large, the globally adopted glazing design approach has been to:

- Meet functional requirements through a glazing quality standard, such as ANSI Z26.1[5] or similar; European agencies use internal specifications such as BN (Bundesbahn Norm) 918 511 (Germany), NFF 01 492:2013 (France), or similar International Standards Organization (ISO) standards.
- Meet safety requirements outlined in regulations (such as 49 CFR Part 223) by additional tests and design features (dimensions, locations, mounting details to meet needs for emergency egress, rescue access, etc.). In some international specifications, milder levels of ballistic or impact resistance are built into the functional glazing standard.

The U.S. rail industry currently uses FRA regulations (49 CFR Part 223 – Railway Glass Testing) to certify glazing materials installed in locomotives, passenger cars, and cabooses. In addition, the systems must meet NFPA 130 requirements for Flame, Smoke and Toxicity. Currently, front windows (windshields) must be FRA Type I and side windows must be FRA Type II, with both standards intended to prevent penetration of particles into the occupied volume. FRA Type I and Type II general requirements include two impact tests, one for ballistic impact and one for large-object impact.

In general, requirements for occupant containment or overall strength of the glazing system are not considered in the design effort, beyond considerations for ballistic requirements and air pressure loads from high-speed operations. In some cases, reduced exposure to derailment loads has been achieved by either recessing the glazing system within the carbody, or by recessing the window area. One exception to this global approach are the current requirements from the U.K., GM/RT 2100, which consist of a series of sequential physical tests with pass/fail criteria to evaluate the strength of the glazing system to withstand external and internal forces that might be experienced under derailment conditions [7]. Another key element of this U.K. approach is that it trades the global approach for emergency egress provisions with the requirement for passenger containment.

While the approach used for glazing system design follows the general outline above, there are differences in the design details. These design details may be broadly classified as:

1. Glazing Materials
2. Glazing Assembly
3. Glazing Framing/Mounting Method
4. Exposure/Aspect
5. Mechanisms for Emergency Egress
6. Mechanisms for Rescue Access

2.1 Glazing Materials (Sheets)

The two most prevalent glazing element materials (individual sheets) used in bodyside passenger railcar windows are:

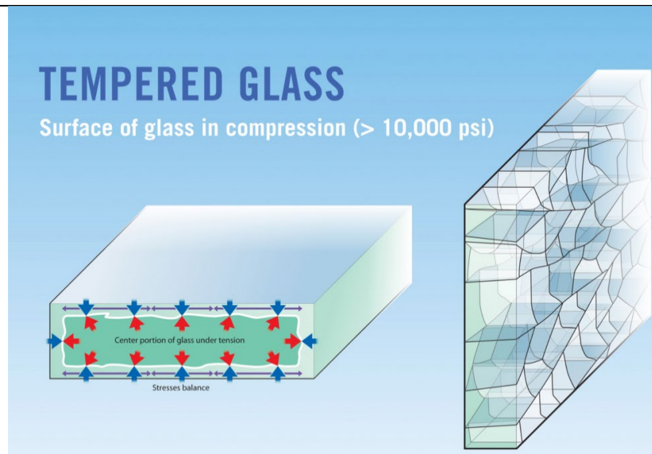
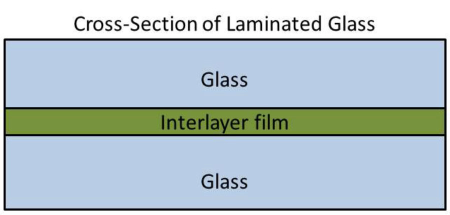
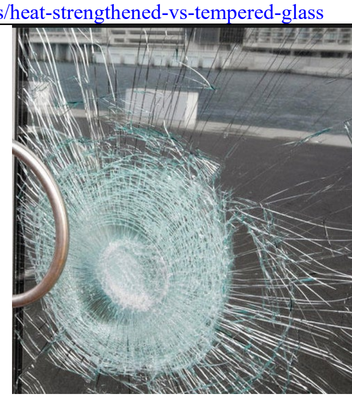
a. Polycarbonate

b. Treated glass

Polycarbonate materials offer better impact performance than untreated glass, plus a weight advantage; these materials are often sold under brand names such as Lexan or Makrolon.

Treated glass is usually heat-treated (tempered or toughened) to improve strength and failure properties. Individual sheets of glass might be bonded together with an intermediate polymer layer, such as polyvinyl butyrate (PVB) or ethyl vinyl acetate (EVA) to form sheets of laminated glass that offer improved strength, insulation, and ultraviolet (UV) reduction properties. Table 1 presents images of the glazing materials.

Table 1. Treated glass materials

Tempered Glass	 Courtesy of: https://glassed.vitroglazings.com/topics/heat-strengthened-vs-tempered-glass	
Laminated Glass		 Courtesy of: https://allspecglass.com/toughened-laminated-glass/

In some applications, these glazing sheets might additionally be coated to improve performance. Acrylic glazing materials are generally not approved for railroad use, as they tend to shatter easily and not meet ballistic impact requirements; plus, they also burn easily and need additional coatings to improve fire performance.

2.2 Glazing Assemblies

Most modern railroad glazing designs have shifted from using a single sheet of glazing toward composite construction with multiple layers. It is common to see windows that have two separate panes of glass with an air interlayer; often one of the glass layers will be tempered or laminated, or both. Some commuter and transit agencies, however, continue to use single layers.

These composite assemblies come in many variants and are usually the result of the experiences and expectations of individual railroads, in terms of functionality. Some of the common arrangements used in passenger carbody side windows include:

a. On its Superliner cars, Amtrak uses windows that are composed of dual-pane, 0.25”-thick, transparent, monolithic polycarbonate glazing sheets with a 0.25” gap, held together by an aluminum perimeter frame.

b. Metro-North Railroad and NJ Transit use a single pane of polycarbonate glazing. 0.46” thick.

c. Specifications developed under the Passenger Rail Investment and Improvement Act (PRIIA) program require a 0.25” tempered glass outer panel with a 0.375” laminated glass inner panel, and a 0.375” air gap.

d. Some Japanese railways utilize a 0.32”-thick polycarbonate outer layer and a 0.16”-thick inner glass layer separated by an air gap of 0.4”.

e. Some commuter railcars in Germany use insulating glass, which is 0.9” thick, with a laminated outer layer. Metro railcars in Germany use tempered glass, which is 0.2” thick.

f. Commuter railcars in France use insulated glass, 1.12” thick, with a tempered glass outer layer.

g. Commuter railcars in the U.K. use insulated glass, 0.73” thick, with a tempered glass outer layer.

2.3 Glazing Framing and Mounting

Most glazing assemblies are first installed in a floating perimeter frame, which is then mounted to the carbody. Common methods of attachment of the glazing to the car frame include:

a. **Gaskets and Seals:** The glazing assembly is held in place on the car shell using either single or multiple elastomeric seals; there are no adhesives, bonding agents, or mechanical fasteners used. This is common on several U.S. railroads, including Amtrak. Zip-strips are used to allow for easy installation and for emergency egress/access reasons. Generally, when the zip-strip is removed from the inside, the windowpane is easily removed to the inside of the car. When the zip-strip is removed from the outside the car, the gasket can be pushed into the car with the use of a pry bar or similar tool. An overview of this mounting application is described in Appendix A.

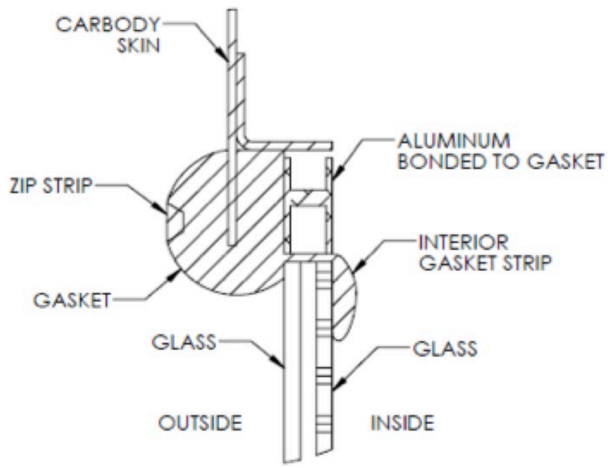
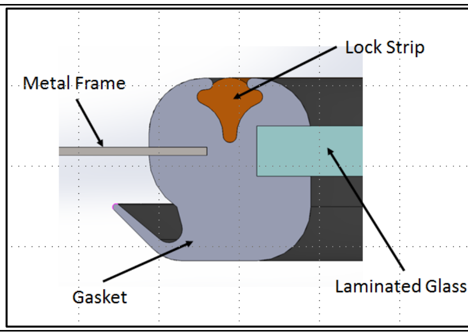
b. **Bonded Applications:** Involve the use of adhesives to bond the glazing assemblies to the carbody. These applications usually have the glazing assemblies connect to either framing elements or gasket elements, which are then adhesively bonded to the car structure.

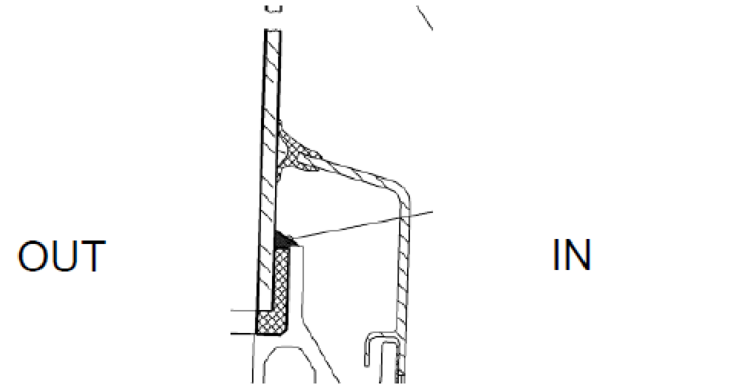
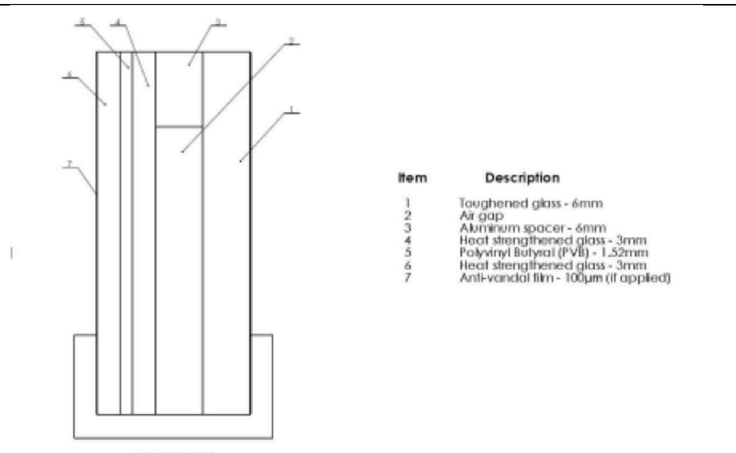
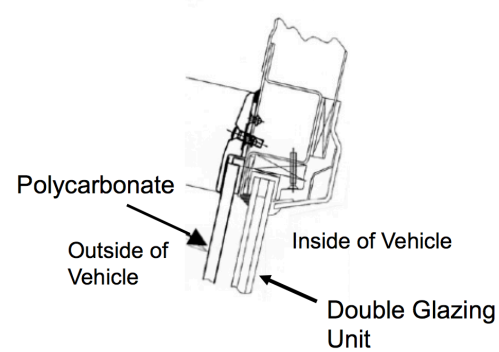
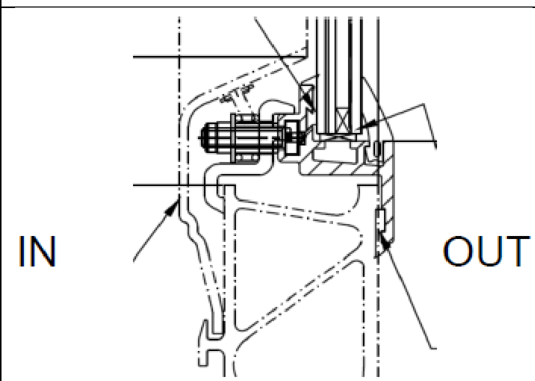
c. **Fastened Applications:** Use mechanical fasteners (screws, bolts/nuts) to attach the glazing frame to the carbody. These are uncommon in the U.S. due to rescue access regulations, but New York City Transit Authority subway cars use a similar approach to address its anti-vandalism needs.

d. **Clamped Systems:** Use a mechanical clamping system to attach the window framing to the car structure. These are relatively rare in railroad applications. While these systems offer the potential for alternate forms of window removal under emergency conditions, in reality, the clamping mechanisms are likely too complex for use by regular individuals under emergency conditions.

Table 2 highlights some sample layouts for each of the framing and mounting methods.

Table 2. Glazing framing and mounting methods

Type	Example	Applications
Gaskets & Seals		Amtrak
Gaskets & Seals		U.S., Single-pane France (Metro)

Type	Example	Applications
Bonded (with frame)		Germany (Metro) [8]
Bonded (with frame)		U.K. – RSSB Study (adhesive – Dow Betamate)[7]
Fastened		Japan [9]
Clamped		U.K. (commuter) France (commuter) Germany (commuter) [8]

2.4 Exposure/Aspect

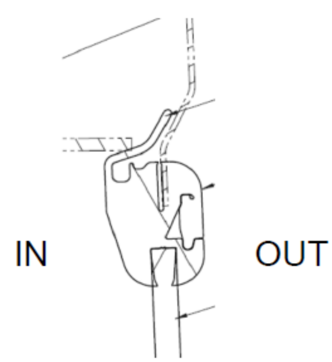
Section 2.3 discussed the specific methods of mounting the glazing system to the carbody. Another consideration is whether the mounting results in a protruding aspect or a flush/recessed aspect.

Several U.S. designs, as well as a few European metro car designs, have adopted a protruding aspect, where a portion of the gasket/seal and the exterior window surface are outside of the carbody envelope. Under this protruding aspect, the glazing systems likely have a higher exposure to prying and normal forces under derailment conditions, and thus are more likely to separate. This was true of the Amtrak bi-level cars in the Crescent City, FL, and Cimarron, KS, accidents as well as the Metro-North cars in Spuyten Duyvil.

Other designs present a recessed or “flush” aspect, wherein the sealing method and glazing are less exposed to derailment forces. This aspect may be achieved either by moving the window mounting inwards, or by having elements/ribs that protrude out of the plane of the carbody/glazing (as in the older SEPTA cars). Most modern high-speed rail equipment has recessed/flush windows.

Images in Table 3 highlight these aspect variations.

Table 3. Exposure/aspect – window glazing

Type		
Protruding Left – Amtrak Right – NJT		
Recessed Left – SEPTA (window area is recessed) Right – CTA (glazing is recessed) [8]		

Interior Zip Strip (The image on the right shows the strip being removed.)		
Breakable Window Left - (tool) Right – (Red dot is tool impact point.) Below (instructions)		
		
"Openable" Cab Window		

2.5 Emergency Passenger Egress

In general, two primary approaches are used for emergency egress:

a. For most U.S. applications, egress is provided through the use of a zip-strip installed with a pull handle (usually red with a conspicuous handle) on the interior side of the window.

b. Another option is to provide a tool/implement in the car, which can be used to break the glass. In the U.K., the MK III vehicles are fitted with tools and double-glazed units of toughened – yet breakable – glass, to create a means of escape. Chinese passenger railcars similarly employ the model of having passengers use an instrument to break specifically designated windows in case of emergency. No zip-strips are used.

Openable windows are not generally used in modern rail passenger cars; however, they may be used on cab windows accessible to train crews only. Under emergency conditions these openable windows may be accessible to passengers under the direction of a train crew. Table 4 provides some sample images of the emergency egress options.

Table 4. Emergency egress options

Type		
Interior Zip Strip (Right image shows strip being removed.)		
Breakable Window Left - (tool) Right – (Red dot is tool impact		

Type		
point.) Below (Instructions)		
"Openable" Cab Window		

2.6 Emergency Rescue Access

Similar to emergency egress options, the two most common methods of rescue access are zip-strips and breakable glass.

a. In the U.S., zip-strips are the prevailing means of emergency access from the exterior of a passenger car. Once the zip-strip is removed, the window can be pushed in to allow access by emergency responders.

b. In the U.K. and in some other applications, emergency responders breaking the glazing from the outside can provide rescue access. Rescue workers have access to tools such as sledgehammers, glass cutters, and implements that make breaking the glass fairly quick. Tempered glass and laminated glass are designed to shatter in a manner that reduces the possibility of injury to trapped passengers. Even in the U.S., if removing the zip-strip is not possible for any number of reasons, breaking the glass using available tools is an easy option for emergency personnel.

3. Accident History

There have been multiple recent accidents in the U.S. in which the poor safety/retention performance of glazing systems has led to passenger injuries or fatalities. While there are some data on performance of glazing systems in accidents that occurred outside the U.S., these are not directly relevant to this effort, as methods for glazing installation in the passenger cars in those incidents differ from common U.S. practice.

3.1 Relevant Accidents in the U.S.

The accident performance of glazing systems has been the subject of critical review by multiple agencies including the FRA and the National Transportation Safety Board (NTSB). A few notable examples from the last two decades are presented below.

3.1.1 Silver Spring, Maryland – February 16, 1996

A collision between a Maryland Area Rail Commuter train and an Amtrak train just north of Washington, DC, caused a derailment [10] that resulted in 11 fatalities and 26 injuries in the accident and subsequent fire (see Figure 1) in 1996. Surviving passengers escaped primarily through misaligned cars as a result of the collision. This was out of sheer necessity – passengers reported experiencing difficulty removing emergency exit windows, and the door exits were rendered unusable by the force of the collision.

Figure 1. Result of collision and fire in Silver Spring accident [10]

3.1.2 Crescent City, Florida – April 18, 2002

This 2002 accident, caused by a track buckle, derailed an Amtrak passenger train in Florida[11]. The train subsequently slid across the ground on its side, resulting in four fatalities and two serious injuries. These six passengers were found either partially or fully outside of the train after the derailment, leading to the conclusion that inadequate passenger containment by the glazing systems (see Figure 2) was to blame.

Figure 2. Result of derailment and rollover accident in Crescent City, FL

Compounding matters, the Superliner railcars involved in this accident have no readily available means of emergency egress when resting on their sides.

Superliner windows are composed of dual-pane, 0.25”-thick, transparent, monolithic polycarbonate glazing sheets with a 0.25” gap, held together by an aluminum perimeter frame. The window frame is kept in place by a rubber gasket fitted around the window perimeter, which protrudes about 0.5” beyond the plane of the railcar carbody sidewall surface.

3.1.3 Flora, Mississippi – April 6, 2004

In 2004, an Amtrak passenger train in Mississippi derailed due to a faulty rail plug [12]. The railcars were dragged on their sides – resulting in 1 fatality, 3 serious injuries, and 43 minor injuries.

It was noted that in at least one instance, the emergency window handle had partially pulled free from the rubber grommet (zip-strip) as a result of accident forces, making emergency egress virtually impossible (see Figure 3).

Figure 3. Example of malfunctioning emergency egress features from accident in Flora, MS

3.1.4 Bronx, New York – December 1, 2013 (Spuyten Duyvil)

A 2013 accident in the Bronx involved a Metro-North passenger train that derailed due to excessive speed through a curve [13]. This happened as a result of improper train handling by the engineer. Four fatalities were reported as well as 61 injuries.

On these cars, the glazing systems are composed of a single, 0.46”-thick pane of polycarbonate material, with a neoprene gasket on the perimeter. The pane and gasket are retained in the window opening (frame) on the car sidewall. These gaskets are further equipped with removable zip-strips to allow emergency egress and/or rescue access.

During the accident, many of the train cars slid on their sides in the direction of travel, and the window glazing detached from the cars (see Figure 4). Due to the extent of dirt and plant matter in the car interior and the locations where the four fatally injured passengers were found, investigators concluded that all four were completely or partially ejected from the train through window openings. Two of the seriously injured passengers also sustained injuries consistent with contacting the ground as the cars slid along the ballast.

Figure 4. Result of derailment accident in Spuyten Duyvil, NY

3.1.5 Cimarron, Kansas – March 14, 2016

In 2016, Amtrak’s Southwest Chief derailed in rural Kansas [14]. Four cars derailed, flipped on their side, and slid along the ground. NTSB determined the cause was misaligned track, created by a highway vehicle colliding with the track. There were 28 injuries reported, but no fatalities and no passengers were ejected.

The research team visited the Amtrak repair facility to inspect four of the derailed cars. The following figures show the extent of the damage to the cars’ glazing systems. All the railcar windows had the same design, with removable zip-strips inside and outside the windows.

Results of this inspection indicated the window failures were caused by exterior gasket failures, mostly when the exterior zip-strip was damaged or removed during the derailment, though some failures were also noted with the zip-strip still in place. In most cases, the windows were pushed to the inside of the car. The interior zip-strips and gaskets did not fail and were still attached to the windows.

Figure 5. Configuration of cars after accident, Cimarron, KS

Figure 6. Zip-strip and gasket condition after accident, Cimarron, KS

Figure 7. Debris collected from sliding along the ground, Cimarron, KS

Figure 8. Condition of car after accident, Cimarron, KS

3.2 Accident Review Summary

In all the accidents examined, the main factor that contributed to passenger injuries and fatalities seemed to be the outer gaskets failing during rollover derailments after being dragged along the ground. Once a gasket has failed, the window is pushed into the car and leaves an open space and the potential for occupants to be ejected.

4. Modeling and Simulations

The modeling conducted as part of this project was designed primarily to estimate the forces that might be imparted to the glazing system under a variety of conditions, including occupant impact on the glazing systems. These simulations attempted to replicate internal and external forces likely to be experienced in an accident. A secondary motivation was to simulate potential test methods.

The research team simulated several scenarios to:

- Estimate the forces on the glazing from occupants impacting the glazing from the inside.
- Estimate externally applied forces from rollover derailments.
- Estimate forces/performance from some test methods used internationally, including steel ball impact and pendulum impact tests.
- Consider new test methods, such as the rolling tire abrasion test.

The modeling work was conducted using LS-Dyna [15], a software package designed for dynamic, large-deflection, non-linear simulations. The models included detailed representations of the framing, glazing, and gasket elements. Non-linear properties for the glazing and gasket materials were extracted from limited available literature, usually for similar, but not identical, materials.

However, as the research team worked on these simulations while simultaneously working on other elements of the project, including the accident review and concept/test development, it became clear that applying the results of the simulations in a quantifiable manner over the course of the project would be impractical, largely due to two issues:

- The observed behavior of the glazing and gasket systems in the simulations was highly dependent on the associated material property assumptions. There were significant uncertainties in modeling the highly non-linear material properties associated with glass, elastomer, and plastic elements, thus making the force estimates uncertain.
- Key modes of failure, including the mode of the gasket being pried open by ballast, could not effectively be modeled, given large model complexities and the uncertainties associated with gasket/glazing separation.

Therefore, the results of the simulation effort were not directly used to drive the project, even though some of the model results showed nominally expected performance. In the interest of report flow, more details of the modeling effort are presented in Appendix B, rather than in the main body of the report.

Since the physical testing has been completed, the models developed may be fine-tuned, calibrated, and/or validated, so that future predictive work can be conducted. These activities may be considered for future or continuing research.

5. Potential Design Concepts

The research team's review of global standards, passenger side window glazing designs and knowledge gained from outcomes of several accidents led them to consider glazing systems that offer improved passenger containment performance – while continuing to meet the current set of safety and functionality requirements.

Research by the Rail Safety and Standards Board (RSSB, U.K.) and a related safety regulation (GM/RT 2100), have moved U.K. standards toward designs that secure the windows against separation during derailment loads, and forego emergency egress requirements. Trading window securement for emergency egress capabilities is not compatible with current FRA regulations which require that passenger railcars have a minimum number of emergency exit windows designed to be rapidly and easily removed by passengers without special tools (49 CFR 238.113).

Rail passenger car glazing systems must perform satisfactorily under competing expectations. They must be strong enough to withstand potential train derailments without major deformation. They must allow passengers to escape in an emergency scenario. They also must allow emergency personnel to enter the car if necessary. However, trying to boost performance for one aspect often reduces the effectiveness in another, making this a difficult engineering problem to solve.

The research team focused on proposing designs and design elements that could improve passenger retention without compromising other elements. To develop more potential concepts, a brainstorming session was held with representatives from FRA and the research team. Over 20 concepts were discussed and were rated based on a variety of parameters. Based on studying previous accidents in the U.S. and the U.K., the team was obligated to nominate passenger containment as the most important aspect of window glazing design – due to the high number of fatalities recorded when passenger containment has failed. Emergency egress and emergency access were deemed second and third most important, with egress being rated higher as a means to allow passengers to exit even before the first responders arrive or can assist. This ranking is also consistent with emergency personnel having tools and equipment to break through typical railcar materials very quickly, whereas passengers do not. Fire protection was rated next only because with emergency egress capabilities preserved, the threat of fire poses less risk of fatalities; in any case, it is unlikely that improving containment performance would lead to a reduction in fire safety.

Further, proposed concepts were rated based on feasibility, acceptability, implementation time, likelihood of success, and contribution to overall success. Another key element was the ability for the concept to be implemented as a retrofit design.

Shown below are six highly rated concepts that would improve occupant containment during derailments, compared to currently used designs. The concepts allow for egress, and emergency access from outside is also practical, given that emergency personnel have reasonable access to hand tools such as hammers and crowbars, which will allow for the additional protective elements proposed to be pried loose.

[Figure 9](#) presents the current design, which uses outer and inner zip-strips. As can be seen, the outer gasket – especially the zip-strip – is exposed and susceptible to being torn off during an accident.

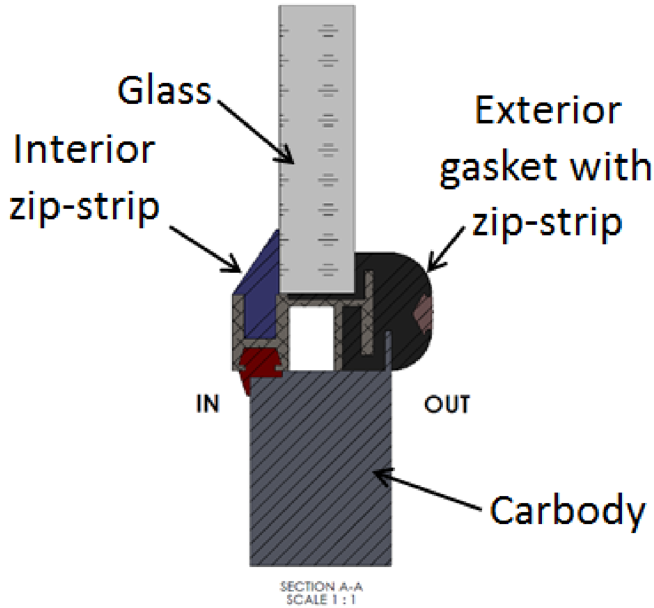


Figure 9. Existing glazing design

Concept 1 (Figure 10) uses a metal cap welded to the carbody to protect the gasket and zip-strip during a rollover. It may be possible to choose the material for the cap in such a way that it crumples around the zip-strip during an accident and further increases safety performance.

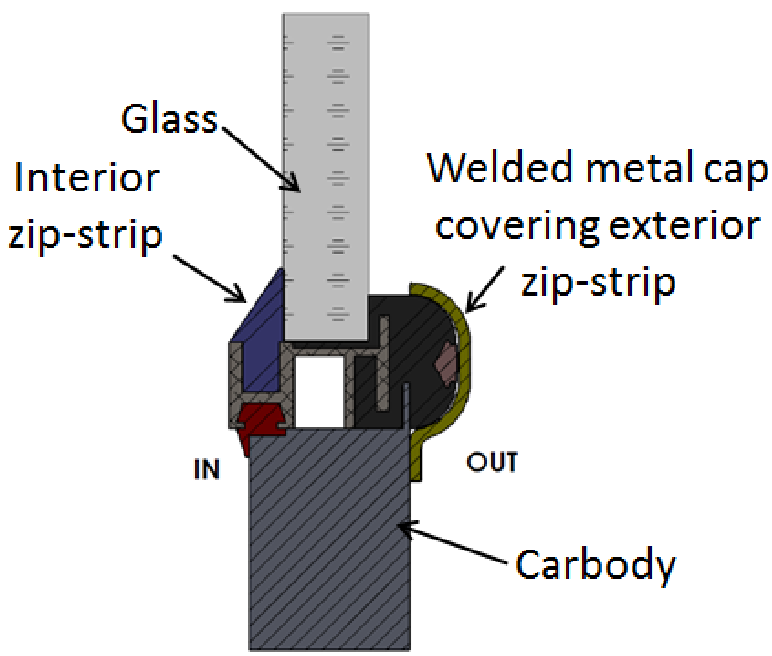


Figure 10. Concept 1 – welded zip-strip cap

Concept 2 involves the use of a clip similar to what is used on car hubcaps (seen in green in Figure 11). The clip is made of metal and would protect the outer gasket during an accident. Emergency personnel can easily pry it loose, when needed.

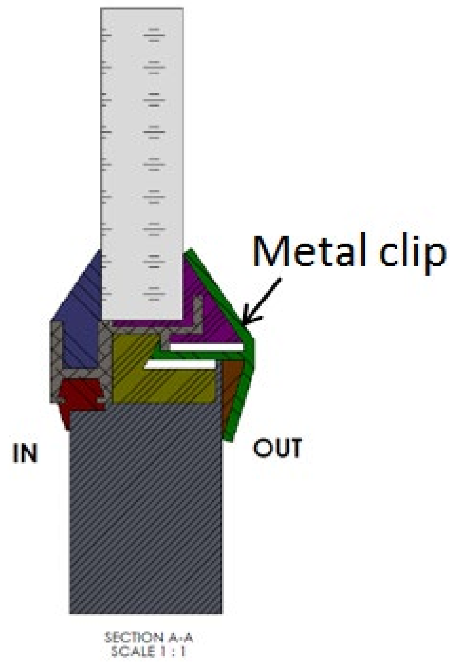


Figure 11. Concept 2 – hubcap-style clip

Concept 3 uses the existing design but relocates the outer zip-strip to a more favorable position. In this configuration, the zip-strip is subjected – in theory – to lower shearing forces during an accident. See Figure 12; the zip-strip sits on the top part of the gasket.

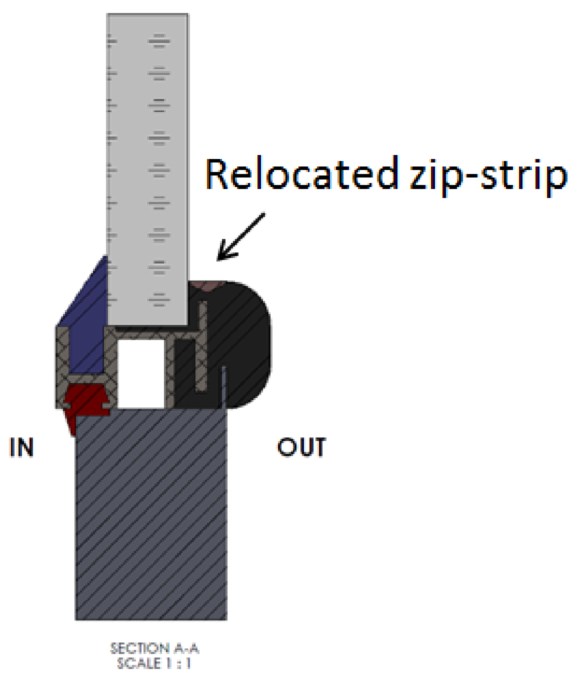


Figure 12. Concept 3 – revised zip-strip location

Concept 4 involves mechanically fastening a metal piece over the outer gasket and zip-strip. This way, there is less chance of the zip-strip ripping out during an accident. One of the main benefits of this design is the ease of retrofitting existing railcars. See Figure 13.

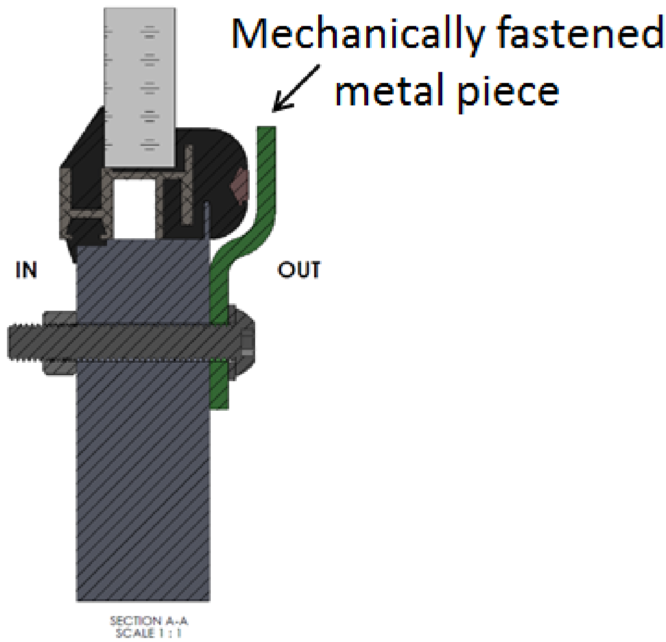


Figure 13. Concept 4 – mechanically fastened

Concept 5, as seen in Figure 14, is to effectively recess the glazing system within the carbody slightly by installing a metal sheet surrounding the glazing system. During a rollover accident, the gasket and zip-strip are likely to experience lower forces and are more likely to remain in place.

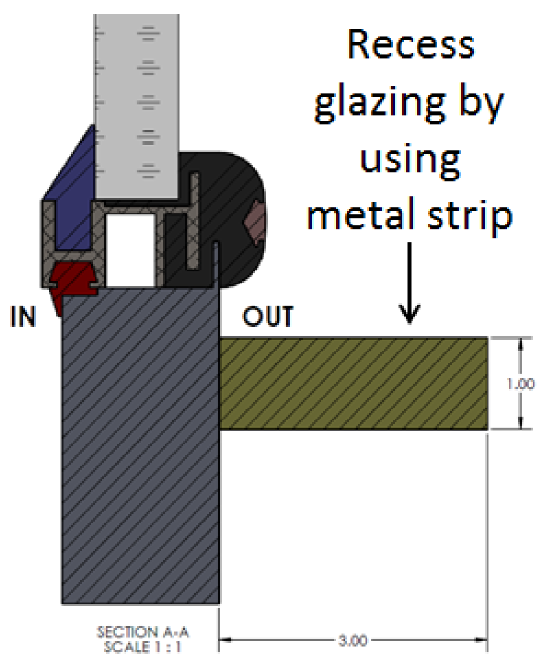


Figure 14. Concept 5 – recessed glazing system

Concept 6 utilizes an inner zip-strip with an outer gasket protected by a mechanically fastened metal sheet. Emergency personnel can pry the gasket open. The inner zip-strip can be removed by passengers. See Figure 15.

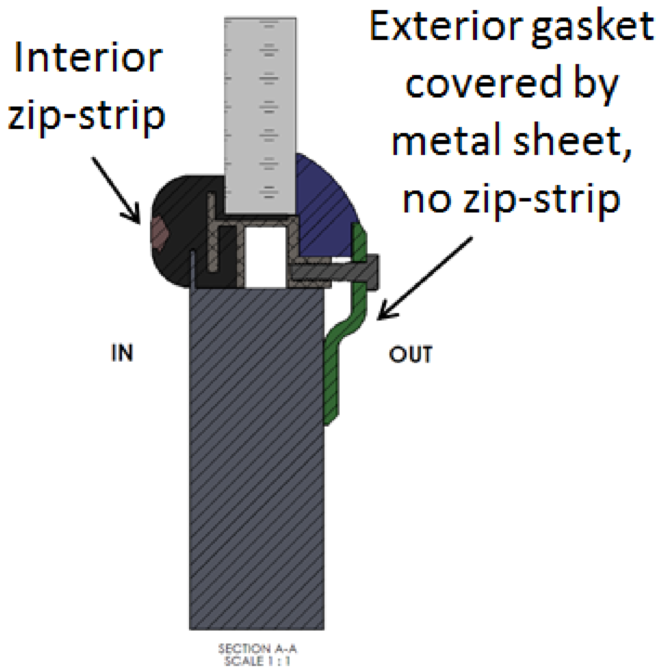


Figure 15. Concept 6 – inner zip-strip with protected outer gasket

The research team and FRA also proposed separating FRA requirements for emergency egress and emergency access. Four windows per car must have emergency egress capabilities. Similarly, the requirement for emergency access from the outside is two windows per car. Instead of having all windows use the same retention design, a safer option may be to optimize which windows have certain capabilities. This will ensure that most of the windows have the maximum occupant containment capacity.

6. Prototype and Test Effort

In addition to developing concepts for improving the performance of glazing systems, the research team also developed concepts for effectively testing glazing performance. These concepts focus on testing glazing performance as a system, rather than its individual elements:

- Conduct quasi-static testing of the glazing system under inward loads, distributed and/or local.
- An abrasive rolling wheel test of the installed gasket to evaluate the potential for gasket separation.
- A prying test of the gasket to evaluate its capacity to retain the glazing in an accident.
- A ballast drag test, attempting to replicate a rollover-type derailment.

As discussed below, three of the above concepts (inward push, pry test, and ballast drag) were developed further and implemented for this test effort. The abrasive wheel test (see Figure 16) was not pursued; the ballast drag test was deemed more realistic, but could be reconsidered in the future.

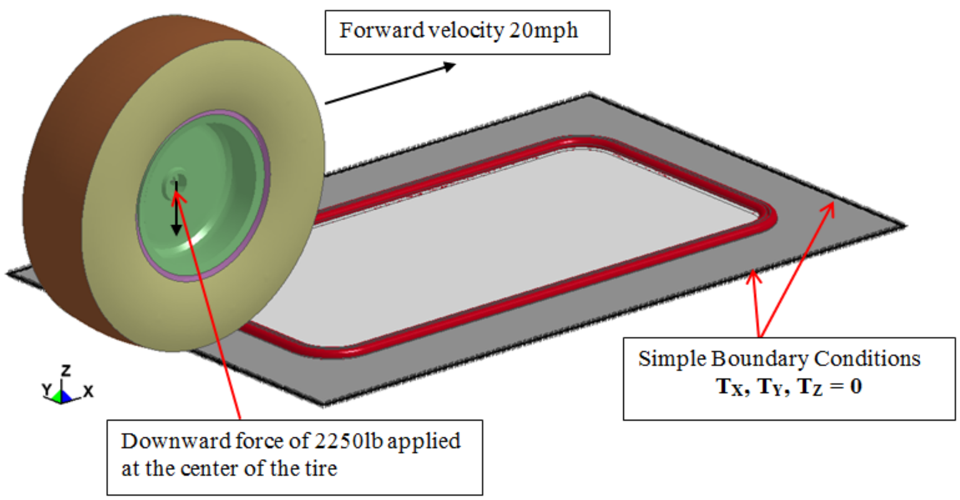


Figure 16. Abrasive rolling wheel concept – not currently implemented

Based on these design and test concepts, the research team implemented a test program to evaluate the effectiveness of glazing retention for a base case and two of the design concepts. This effort also served as a method to evaluate the effectiveness of the test concepts.

6.1 Test Specimen

The initial intent called for the test specimen to be cut out from an Amtrak Superliner passenger railcar (Figure 17). However, this proved challenging for a variety of reasons, and instead, a specimen frame was fabricated using carbon steel plates and angles to best represent the skin and supporting elements used on the Amtrak car. The frame is designed to accommodate the glazing and gasket elements used on the Amtrak cars. In other words, the window opening dimensions and the skin thickness were kept the same as the Superliner car to ensure correct fitment. In addition, the bracing elements (z-sections and perforated angles), with dimensions and thicknesses approximating measurements on the Amtrak car, were added to ensure the structure of the test frame was not a factor in glazing performance. Multiple glazing and gasket samples in new condition were acquired from Amtrak for testing. Figure 18 and Figure 19 present images of the outside and inside of the test specimen.

Figure 17. Superliner window

Figure 18. Test specimen – outside view

Figure 19. Test specimen – inside view

6.2 Concepts Evaluated

Two of the highest-rated concepts presented in Section 5 were selected for prototyping and physical testing. Notated here as Concept A (derived from Concept 1 in Figure 10), the first is a thin sheet metal cover over the gasket that is welded/fastened to the carbody intended to help protect the external gasket and zip-strip from abrasive ballast as shown in Figure 20. Two versions of Concept A, one with a 20-gage sheet (0.0359" thick) and another with a 24-gage sheet (0.0239" thick) were evaluated. The objective is to apply sheet metal covers that are thin enough to be easily pried open by emergency responders, while also providing sufficient protection against abrasion.

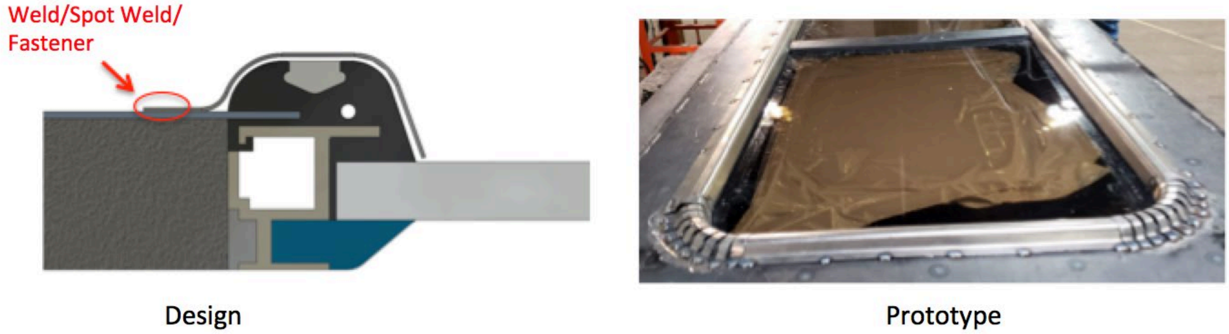


Figure 20. Concept A

Concept B is a clip-in style cover over the gasket, wherein the cover replaces the external zip-strip. This design is a derivative of the hubcap-style Concept 2 shown in Figure 11. It is not mechanically fastened to the car and is simply held in place by the zip-strip groove. Again, the intent is to provide abrasion resistance to the gasket, while also being easy to pry open by emergency responders. As shown in Figure 21, achieving the design intent requires specialized tooling to create profiles with sharp radii and specific shapes, which was not practical for a low volume prototype. Hence, Concept B? was prototyped as a two-piece design as shown in Figure 21, with the solid metallic zip-strip being spot welded to the outer cover.

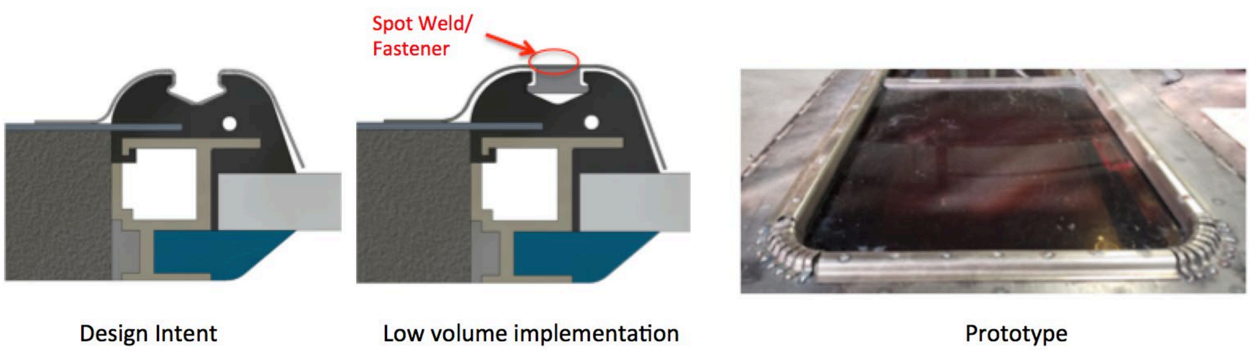


Figure 21. Concept B

Both the above concepts were evaluated with 20-gage and 24-gage configurations, in addition to the base case (current design). To maximize the number of tests and resulting data that could be used for decision-making, some tests were conducted using glazing samples that had been subject to a prior test. The results are annotated appropriately.

6.3 Tests Conducted

Of the brainstormed test ideas, three were chosen for implementation in this phase:

a. Test 1 was a push-through test, where an increasing load was applied perpendicular to the glazing pane, in an inward direction, until the glazing separated from the frame, with both the applied load and displacement being monitored.

b. Test 2 was a pry test, intended to simulate a sharp raking load, similar to what might be experienced by the glazing structure sliding along the ground (post-derailment) and interacting with debris such as a tree branch. Again, the applied load and displacement were monitored.

c. Test 3 was a ballast drag test, where a window test specimen was dragged along the ballast with a static vertical load applied on the window frame. The distance the specimen could be dragged prior to separation of the glazing from the frame was a measure of the effectiveness of the retention scheme.

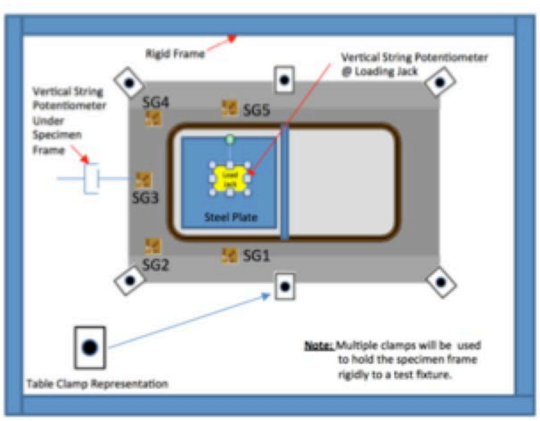
The sections below offer additional detail on the test setups and describe the results.

6.3.1 Push-Through Test

The intent of this test was to quantify the normal force required to detach the glazing from the gasket/frame. A test setup schematic and a picture showing the implementation are presented in Figure 22. For this test series, a complete glazing test specimen was mounted to a rigid fixture, and a steel plate of similar dimensions to the half-window was used for the loading area. A jack/cylinder was used to apply the loads to the instrumented glazing assembly, and the load was slowly increased until the window detached from the steel frame.

Test setup parameters:

- Peak load on jack for the push-through test: 5,000 lbs (Keep increasing until failure, anticipated failure load is less than 5,000 lbs.)
- Loading rate: Manual
- Loading steel plate dimensions: Approximately 20” x 22” x 0.5”
- Vertical location of loading: Centered on the half-window pane



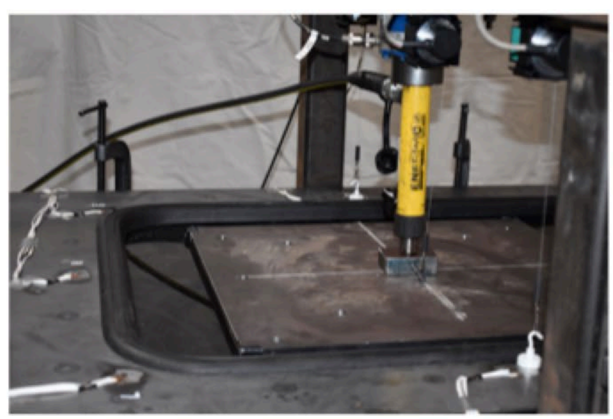


Figure 22. Push-through test – schematic and implementation

The results of the five push-through tests are presented in Table 5. As seen from the results for specimens 1 and 4, the ones in new condition, the glazing pushed through with about 1,180 to 1,270 lbs of force. While the research team did not have any previous expectations for the magnitude of this force, the range of load needed to force window separation was lower than anticipated.

Table 5. Push-through tests – overview of results

Specimen #	Specimen Condition	Peak Load (lbs)	Peak Deflection (mm)	Notes
1	New – base case	1,180	28	Stroke limited
4	New – base case	1,270	46	
3	Reused	750	36	
5	New, w/ minor damage	1,480	48	With 2 shims (0.048”)
5	Reused	970	38	With 2 shims (0.048”), other side of sample 5

Representative force and deflection data from Specimen 4 is shown in Figure 24, and the corresponding post-test image can be seen in Figure 25.

When a reused specimen, i.e., one that had detached in a prior test and had been reinstalled, was tested, the load needed to separate the glazing was even lower, at only 750 lbs. To improve retention capacity, the research team increased the effective thickness of the carbody sheetmetal that the gasket connects to, by adding shims that brought up the thickness of the plate from 0.25” to 0.3” for New Specimen 5 (see Figure 23). This improved the retention capacity by about 200–300 lbs, or about 17–25 percent. Shimming also increased the capacity of Reused Specimen 5 by a similar percentage.

Neither of the proposed design concepts was expected to add capacity in the direction of the push-through test load (inward), and therefore neither of the concepts was evaluated under this test.

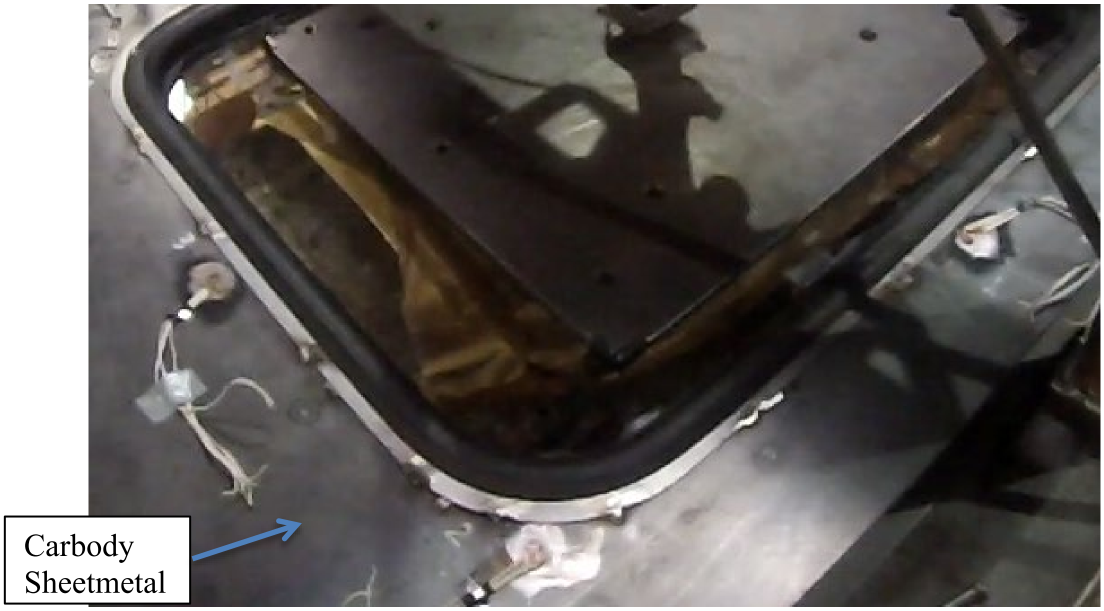


Figure 23. Close-up of shims added to specimen

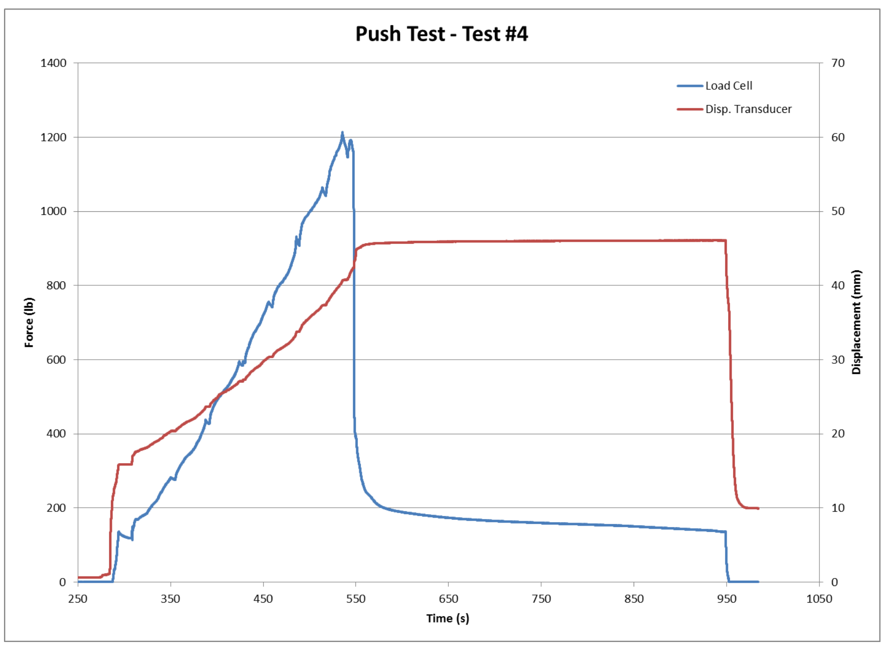


Figure 24. Push-through test – Specimen 4 – force and displacement

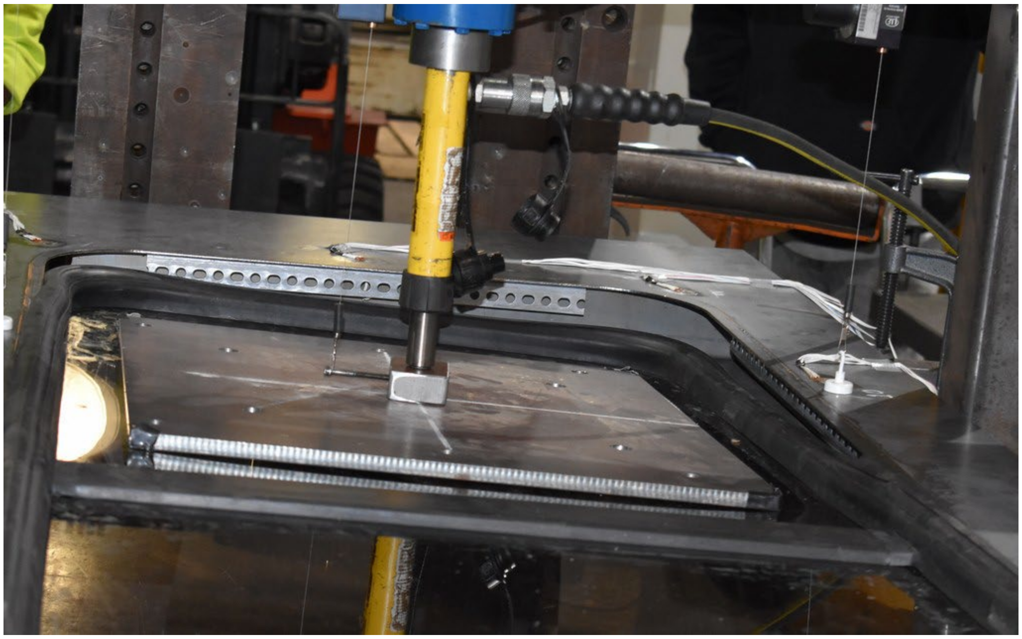


Figure 25. Push-through test – Specimen 4 – showing post-test separation

6.3.2 Pry Test

The pry test quantified the prying force required to detach the glazing from the gasket/frame. A schematic of the test setup and a picture showing the implementation are presented in Figure 26. For this test series, a complete glazing test specimen was mounted to a rigid fixture, and a load parallel to the glazing pane was applied through a wedge, to generate a prying force until either the gasket or the glazing pane separated from the frame. The load was increased until separation was observed.

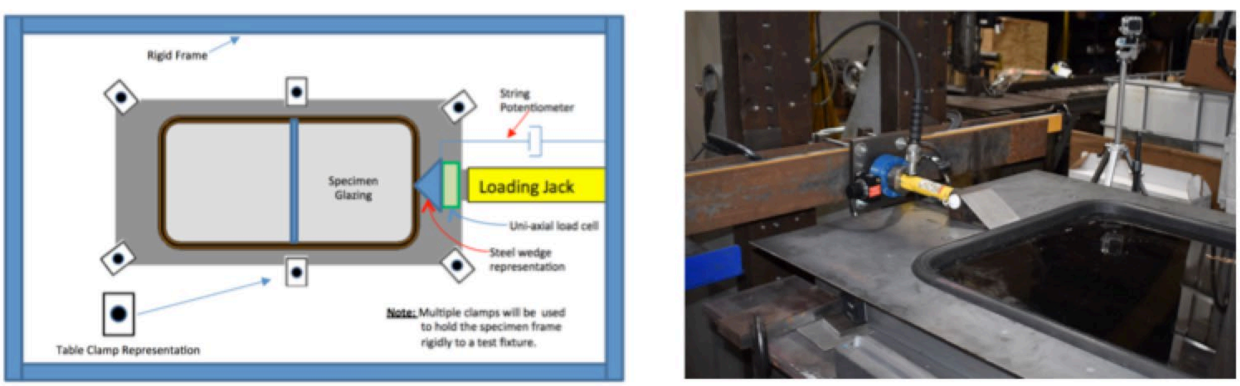


Figure 26. Pry test – schematic and implementation

The test results are presented in Table 6. As seen in the table, for the base case (no protection of the gasket), only a small load (less than 200 lbs) was needed to separate the gasket from the frame (see Figure 27); given the low magnitude of the prying load for the base case, no additional restraint in the vertical direction was needed to keep the wedge movement (stroke) aligned with the longitudinal axis of the test specimen. For both concepts, the wedge rode over the sheet metal cover, and there was no damage to the gasket; this was in spite of an additional vertical restraint being applied to the hydraulically loaded wedge to restrict vertical (override) motion, further proving the effectiveness of the concepts in protecting against this mode.

Table 6. Pry tests – overview of test results

Specimen #	Specimen Condition	Peak Load (lbs)	Peak Deflection (mm)	Notes
2	New – base case	195	48	
3	New – base case	170	47	Initial loading peak
7	New – Concept B– 24 gage	378	N/A	With vertical restraint; wedge rode up sheet metal cover; no damage to gasket
7	Other end – Concept A– 24 gage	720	N/A	With vertical restraint; wedge rode up sheet metal cover; no damage to gasket

These results suggest that even the thin sheet metal style elements could provide reasonable protection against prying objects and corresponding failure modes.

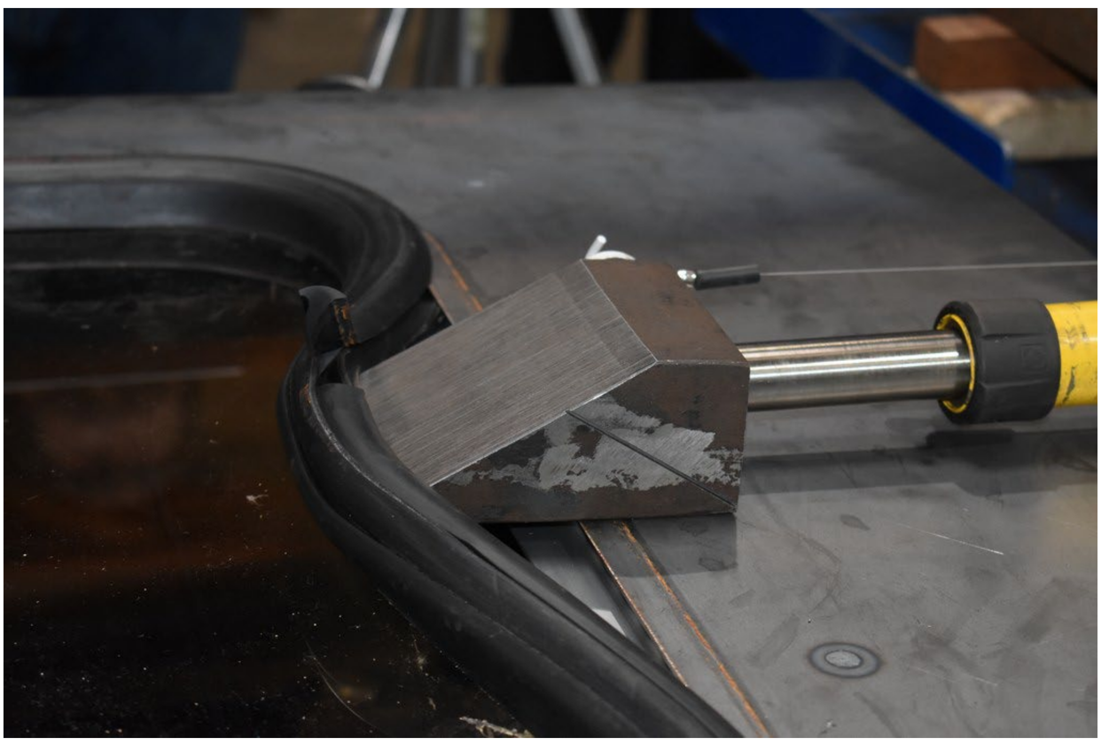


Figure 27. Pry test – Specimen 3 – separated gasket

6.3.3 Ballast Test

This test simulated a passenger car, post-rollover derailment, being dragged through ballast. For this test, a large “sandbox” was constructed and filled with railroad ballast. The dimensions of the box are 6’ wide x 40’ long with a ballast depth of 12” (see Figure 28 and Figure 29). The test specimen representing a window section (see Figure 30) was dragged across the ballast box, using a winch, and the travel distance required to achieve gasket separation was noted as a measure of the retention capacity of the system.

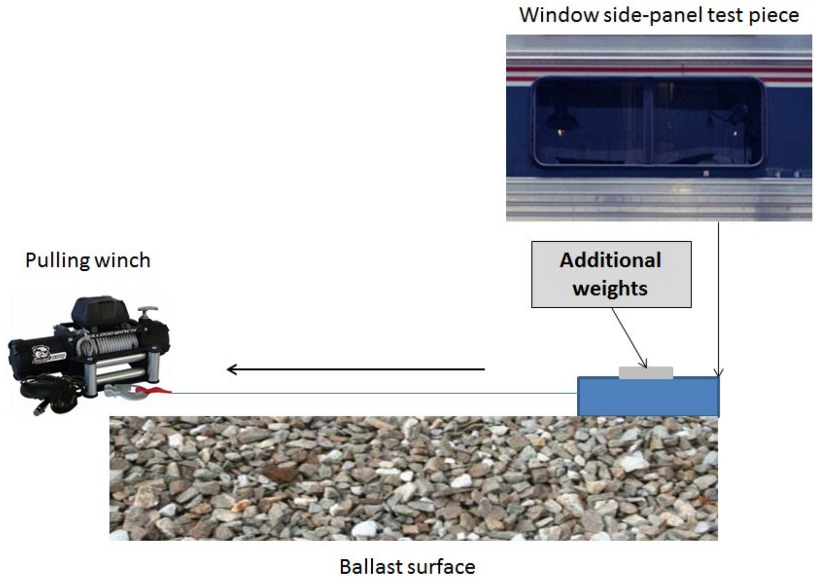


Figure 28. Schematic of ballast drag test

Figure 29. Ballast test setup

Figure 30. Test specimen and prototype of Concept 1

To simulate the force (normal to the glazing) that the car would experience when derailed onto its side, additional weight was added to the specimen. If an estimated AW3 load (with trucks) of a modern bi-level style car is about 180,000 lbs, and the surface area of the side of a car is roughly 16’ x 85’ (1,360 sq. ft.), a car on its side will experience a pressure of 132 lbs per sq. ft. (assuming uniform static distribution). This means that for a test panel of glazing that has a surface area of about 23 sq. ft., an additional weight of about 3,050 lbs (in addition to the weight of the specimen itself, 350 lbs) will simulate the normal load. The structural elements of the car, including the side sills, end frames, roof rails, mid-level floor, etc., would likely pick up a little more of the load than the skin, but the derived load was a reasonably conservative estimate.

Initial tests using this weight indicated the base case gasket would tear and separate from the structure in less than 1 ft. When the frame and glazing structure was used without any additional weight (a base weight of 350 lbs), the gasket survived for 6–8 ft., but the specimen was skittish and slightly unstable. Based on trial-and-error tests, the research team used a weight of 950 lbs (350-lbs base weight plus 600 lbs added weight), for most of the tests, with a few additional tests at the heavier (3,050 lbs) load.

Lights and cameras were added to the test specimen (see Figure 30) to allow both the leading and trailing edges of the specimen to be observed and recorded while being dragged, permitting an estimate of the distance dragged before failure. Key test results are presented in Table 7 below. As before, specific specimens were reused to maximize what could be learned; the number of specimens was limited.

Table 7. Ballast drag tests – overview of test results

Specimen #	Specimen Condition	Static Load (lbs)	Estimated Drag Distance to Separation	Notes
6	New – base case	950	14" – 24"	Failure started @ 14", corner-to-corner separation in 24"; trailing edge undamaged.
6	Concept B – 24 gage; reused	950	123" – 134"	Undamaged trailing edge from prior test now leading; failure started @ 123", corner-to-corner separation in 134".
9	Concept B – 20 gage; new	950	87' without retention failure	Glazing and gaskets still in place; test continued as shown below.
9	Concept B – 20 gage; continuation of above test	3,050	42" – 60"	Glazing and gasket did not fail. Ballast built up under the frame and pushed the window through.
8	Concept A – 24 gage; new	950	86' without retention failure	Glazing and gaskets still in place; continued below.
8	Concept A – 24 gage; continuation of above test	3,050	40" – 66"	Glazing and gasket did not fail. Ballast built up under the frame and pushed the window through.
10	Concept A – 20 gage; new	3,050	36" – 46"	Glazing and gasket did not fail. Ballast built up under the frame and pushed the window through.

As seen above, the base case specimen did not fare well even when the static vertical load was reduced to 950 lbs. As noted earlier, during preliminary tests with a 3,050-lb load (not listed in the table above), base case specimens separated within less than 1 ft. of drag.

Concept A, with the sheet metal cover spot welded to the skin, performed well even with the thinner (24-gage) cover, surviving for about 86' (which is about three rounds of drag on the ballast pan and approximately one car length) under the 950-lb applied load (Specimen 8), at which point the test was stopped, and the load increased to 3,050 lbs. Under the increased load, the design lasted only for about 3 to 5 additional ft., with the gasket separating on the trailing end due to ballast buildup.

Concept B, with the clipped-in cover, had similar results, particularly with the thicker gage (20 gage) material, lasting for three rounds of dragging under the 950-lb load (Specimen 9), before the load was increased to 3,050 lbs, after which it failed in 3 to 5 additional ft. of drag, with a similar mode of failure to Concept A. Concept B, with the thinner sheet metal, performed better than the base case, lasting about 10 to 11 ft. under the 950-lb load, but not as well as Concept A or Concept B with the thicker gage material.

Figure 31 below outlines the observed failure modes. When the normal loading on the frame was lighter (950 lbs), the gasket covers on both the leading and trailing edges performed well in keeping the ballast from pulling out the gasket and the zip-strip, and the ballast was allowed to escape the trailing edge. When the loading on the frame was high (3,050 lbs), the gasket covers still protected the gasket from tearing, but the ballast pile-up at the trailing end pushed the glazing inward, increasing the load normal to the glazing, causing separation.

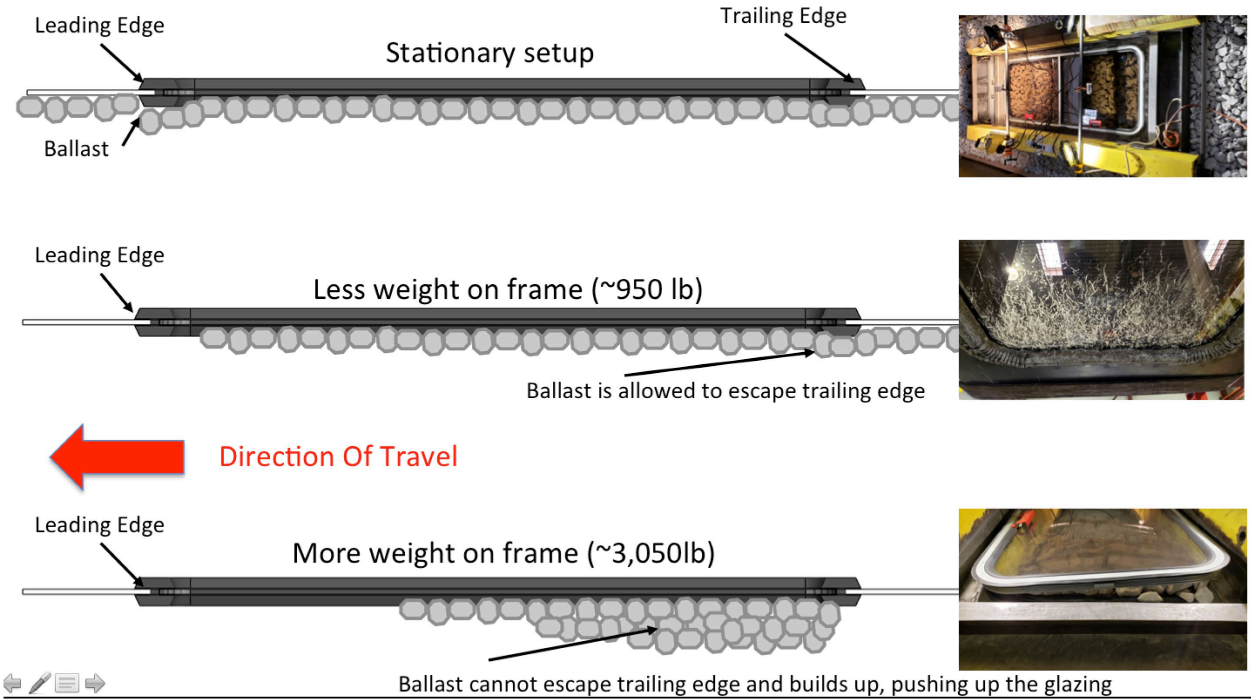


Figure 31. Failure modes during ballast drag test

Figure 32, Figure 33, and Figure 34 present additional images highlighting some of the test results.

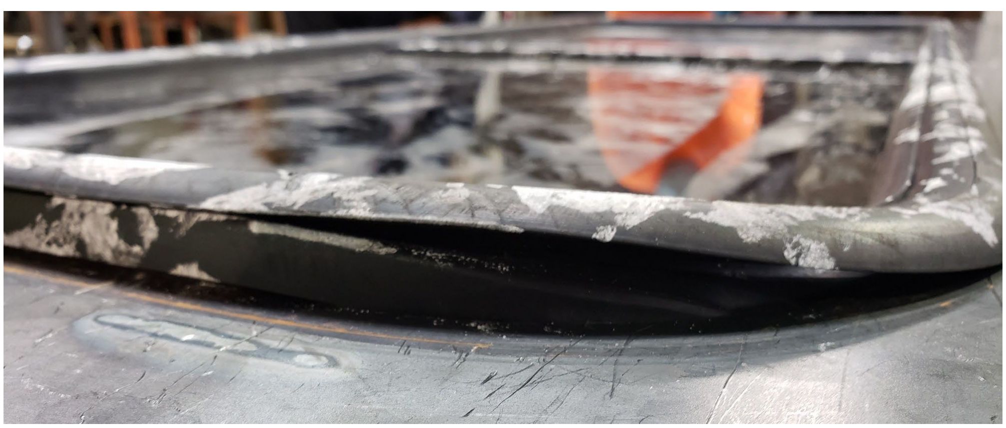


Figure 32. Drag test Specimen 6 – base case – gasket separation at leading edge

Figure 33. Drag test Specimen 8 – glazing intact after 86' of drag @ 950-lb load

Figure 34. Drag test Specimen 10 – push-through failure at trailing edge

6.4 Summary of Test Effort

The ballast drag test performed reasonably well in representing the conditions that might be experienced by the sidewall and window section of a passenger railcar during a rollover derailment incident. It also represented the modes of failure that may be expected, i.e., the prying out of the gasket (usually on the leading edge), or a push-through (usually on the trailing edge).

The team concluded that the push-through tests and the pry tests evaluated system performance under the same two modes of failure, but under more controlled conditions than could be realized for the ballast drag test. In other words, the pry test provided a reasonable measure of the failure mode when the loads on the framing were light; the push-through test provided a measure of the failure mode when the loads were heavy.

The two concepts tested made a significant improvement to retention performance under the prying mode, as seen from both the ballast drag and prying tests. The concepts were not expected to and did not offer a significant benefit for the push-through mode of failure. As seen from the push-through tests, tightening the frame-to-gasket connection by adding shims made a modest improvement to the push-through capacity of the system.

The ballast drag test method is an excellent research tool that can be used to evaluate retention performance for a variety of designs and conditions, but it may be difficult to standardize as a specification with clear pass/fail criteria. However, it remains a viable testing alterative. Alternatively, the push-through and pry tests allow for the two failure modes to be evaluated in a manner that is more suitable for inclusion in a specification with explicit pass/fail criteria since the test conditions are fully controlled.

7. Discussion of Engineering/Performance Requirements

As discussed earlier, glazing systems on passenger railcar side windows serve a variety of safety-critical functions beyond providing the obvious function of outward visibility to cab/car occupants:

- Impact resistance (both ballistic and large object)
- Emergency egress (car occupants being able to get out of the car)
- Rescue access (for emergency personnel trying to enter the car)
- Fire resistance
- Occupant containment

The performance requirements for glazing systems can be broadly classified under:

a. Safety requirements (encompassing the list above)
b. Functionality requirements (including visibility, maintenance, etc.)

The project team compiled a list of existing requirements for glazing systems from both regulations and industry practices; plus, it proposed a draft set of additional requirements to improve glazing system performance under accident/derailment conditions. Table 8 provides an overview of the proposed safety requirements. Existing requirements are listed in black, and the proposed additional requirements are highlighted in red. Further discussion of these requirements is presented in Appendix C. Please note that the table is limited to engineering requirements and that documentary requirements such as marking, certification, etc., are not listed.

Table 9 presents generalized functionality requirements. In general, most agencies, based on their experience, have specific requirements from a functionality perspective, and their procurement specifications outline the type of glazing and securement as well as agency-specific coating, durability, and testing needs.

Glazing systems commonly used in North American passenger service are currently being designed and built to meet the requirements laid out in the tables, except for the newly proposed occupant containment requirements. Any conflicts between current requirements have already been resolved by existing designs. Anticipated conflicts between the proposed requirements and current requirements are primarily related to how additional requirements for occupant containment would align with the needs for emergency egress or rescue access. A potential secondary (and less important) source of conflict might be whether tighter requirements for passenger containment could influence ease of maintenance or replacement. In general, attempts to improve the passenger containment performance are likely to enhance the anti-vandalism features of glazing systems rather than detract from them.

Table 8. Overview of glazing system safety requirements

No.	Category	Regulation/Industry Practice (IP)	Component/System	Comment
1	Impact Resistance – Ballistic	Regulation	Component – Glazing	49 CFR Part 223: Defines the test conditions and pass/fail criteria.
2	Impact Resistance – Large Object	Regulation	Component – Glazing	
3	Emergency Egress	Regulation/IP	System	49 CFR 238.113: Defines the number, dimensions, conspicuity, and location of emergency windows. Specifics of construction (zip-strips, etc.) are defined by procurement specifications.
4	Rescue Access	Regulation/IP	System	49 CFR 238.114: Defines the number, dimensions, conspicuity, and locations of rescue windows. Specifics of construction (zip-strips, etc.) are defined by procurement specifications.
5	Fire Resistance	Regulation	All components	49 CFR 238 defines smoke and flame requirements, with specifics being defined in further ASTM Standards, such as ASTM C 1166-00 (Gaskets).
6	Strength	Regulation	System	49 CFR 238.221 requires glazing systems to resist/survive air pressure differences due to passing trains. Most specifications do not clearly define the specific loads/pressures. A pressure load of 35 lbs/ft^2 with a factor of safety of 2.5, or 70 lbs/ft^2 limiting loads are suggested by Transit Cooperative Research Project (TCRP) Report 15 [15], but this is intended for transit vehicles. One option is to specify values that will provide additional strength to survive derailments.
7	Occupant Containment – Inward Load	Proposed	System	Quasi-static testing of glazing system with a weight or other applied load in an inward direction. Load magnitude will need to be quantified in discussion with industry and validated with potential additional testing.

No.	Category	Regulation/Industry Practice (IP)	Component/System	Comment
8	Occupant Containment – Glazing Retention	Proposed	System	Gasket prying test. A lateral load (with vertical restraint) is applied through an appropriately shaped loading block to the gasket system with the intent of prying open the gasket. The specifics of the loads are TBD.
9	Occupant Containment – Glazing Retention	Proposed - Alternate	System	Ballast drag test, with the glazing system dragged through a simulated ballast field, with a constant vertical load on the system. Pass/fail criteria to be defined as distance dragged prior to separation.
10	Emergency Access/Egress	Proposed Additional	System	If measures are implemented to improve occupant protection, additional human performance testing may be desired to ensure the additional retention elements do not unduly hamper emergency access/egress. This may be accomplished through a design review, demonstration, testing, training, or a combination thereof.

Table 9. Overview of glazing system functionality requirements

S. No.	Category	Regulation/Industry Practice (IP)	Component/System	Comment
11	Optical Quality	IP	Component – Glazing	ANSI Z26.1 is the base standard used by most specifications. Several ASTM specifications outline specific elements of optical quality such as transparency, haze, light stability, deviation, etc. However, ANSI Z26.1 serves as a "master" specification that covers all these requirements.
12	Physical Characteristics	IP	Components – Glazing and Seals	Dimensional stability and flexibility characteristics for glazing materials are outlined in ANSI Z26.1. Durometer and strength requirements for gaskets and other seals are outlined in ASTM C542, with test methods outlined in related ASTM specifications.
13	Weather Resistance	IP	Components – Glazing & Seals	These are outlined in ANSI Z26.1 for glazing materials and other ASTM standards for seal and gasket materials.
14	Durability	IP	Components – Gaskets and Seals	ASTM C 542 identifies durability characteristics for gasket material.
15	Durability	IP	Components – Glazing	ANSI Z26.1 covers the abrasion resistance and chemical resistance requirements for glazing materials.
16	Corrosion Resistance	IP	System	These are rarely specified explicitly. ASTM B 117 specifies the test methods, if warranted for specific applications.
17	Ease of Maintenance	IP (soft)	System	These are generally "soft" requirements, such as a change-out time of 15 minutes or less, with 5 minutes or less being "desirable."
18	Anti-Vandalism	IP (soft)	System	These are generally very system-specific and are more elaborate for urban "light rail" transit systems rather than for heavy-rail passenger and commuter systems.

8. Summary and Recommendations

This report describes research on evaluating and improving the performance of passenger railcar glazing systems under accident conditions. As part of the effort, the research team reviewed the accident performance of glazing systems, and global standards and designs for glazing systems.

The accident review underscored the key failure mode that contributed to passenger injuries and fatalities: the outer gaskets failing during rollover derailments after being dragged along the ground. Once a gasket has failed, the window is pushed into the car, leaving an open space and the potential for occupants to be ejected.

Improving retention performance has the potential to make emergency access and egress performance more complex, and therefore, additional requirements for improving glazing retention must be carefully considered.

The team proposed design elements that could improve glazing retention performance and the testing methods that could quantify it. Two of the proposed concepts, qualitatively rated to have a high likelihood of success and a high potential for retrofit on existing systems, were then prototyped for testing.

- Concept A is a thin sheet metal cover over the gasket that is welded/fastened to the carbody – to protect the external gasket and zip-strip from abrasive ballast
- Concept B is a clip-in style sheet metal cover, inserted in place of the external zip-strip – also anticipated to protect the external gasket from abrasion.

The two concepts, as well as a base case (current Amtrak design) were evaluated through three tests:

- A push-through test that quantified the normal/inward force needed to separate the glazing from the frame.
- A pry test that quantified the ability of the system to resist prying loads, such as those that may be imparted by ballast, tree debris, or other wayside features.
- A ballast drag test that reasonably represented the conditions that might be experienced by the sidewall and window section of a passenger railcar during a rollover derailment.

The test results showed the three tests captured the failure modes observed in rollover accidents and quantified the glazing retention performance of existing and proposed glazing system designs. The tests also showed:

- The base case design tested was highly susceptible to glazing retention failure, as seen in all three tests.
- The two concepts tested made a significant improvement to glazing retention performance under the prying mode, as seen from both the ballast drag and prying tests. The concepts did not offer a significant benefit for the push-through mode of failure. This was not an unexpected result, as these mitigations were designed explicitly to protect the outer gasket only and provided limited additional resistance under this loading scenario.

The research team has proposed an updated set of performance requirements for glazing systems, adding requirements for glazing retention performance in addition to existing safety and functionality requirements. The team suggests the push-through and pry tests be developed into a test specification/standard with appropriate pass/fail criteria (in collaboration with industry). Load magnitudes and pass/fail criteria have not yet been established, and will likely need additional research and testing. The ballast drag test remains an excellent research tool, but may also be developed into an alternate standard.

Recommendations for future work include:

- Testing additional commuter car glazing system designs to better quantify the expected glazing retention performance of commonly used designs.
- Additional testing to quantify the push-through load capacity required to resist the corresponding mode of failure during the ballast drag test under heavier loads.
- An investigation of alternative glazing securement methods which do not rely on the traditional gasket methodology and which accommodate emergency access/egress requirements.
- Analyses to better estimate the expected loads on the glazing surface, considering the stiffness of key carbody elements (which are not well-represented in the ballast drag test due to physical constraints).
- Calibrating/validating the simulation models using the test data, so that these models can be used for more predictive analyses.
- Working with industry to consider development of the draft performance requirements into a set of specifications, considering the variety of glazing system configurations in use.

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Appendix A – Zip-Strip Functionality

This section outlines the functionality of the zip-strips on the inside and outside of the car, documented during a visit to Amtrak's shops in Beech Grove, Indiana. During the team's visit, a new car was inspected before the windows were installed. They were installed from the outside; the exterior rubber gasket was folded up without the exterior zip-strip. After the window was in place, the zip-strip was installed to secure the window.

When the zip-strip was removed from the inside, the window pane was easily removed to inside the car. When the zip-strip was removed from the outside the window, the gasket could be pushed into the car with the use of a pry bar or some other tool. The following pictures document the different steps.

Figure 35. Example of the interior zip-strip being removed

Figure 36. Window pane pulled into the car after the interior zip-strip was removed

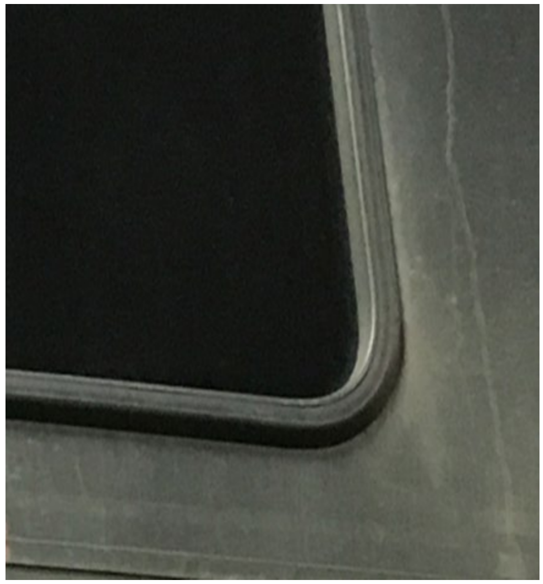

Figure 37. Exterior window with zip-strip in place

Figure 38. Exterior window with zip-strip removed

Figure 39. With the exterior zip-strip removed, the gasket can be pried up into the car

Figure 40. A demonstration of window and gasket system being pulled into the car

Appendix B – Finite Element Modeling Details

The finite element (FE) models were developed using HyperMesh [16], an FE pre-processor that generates the geometry and the mesh representations. Simulations were performed using LS-DYNA, a multi-purpose explicit and implicit FE program used to analyze the nonlinear response of structures. It has a long history of application for various problems in crashworthiness, blast and impact response, occupant and pedestrian safety analysis, and other related problems.

The developed FE model components include (see Figure 41):

- Metal frame representing the outside sheet of the passenger car
- Rubber gasket
- Lock strip (zip-strip)
- Laminated glass

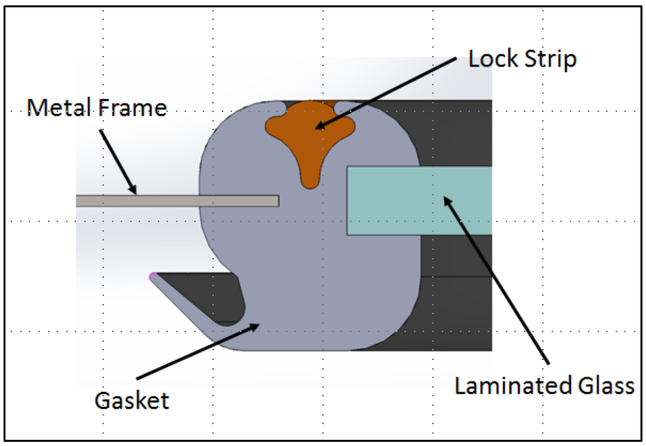

Figure 41. Components of the FE model

Representative dimensions of a laminated glass pane 27.6" wide by 53.55" long and 0.46" thick were used. The laminated glazing was based on CAD geometry presented in Figure 42.

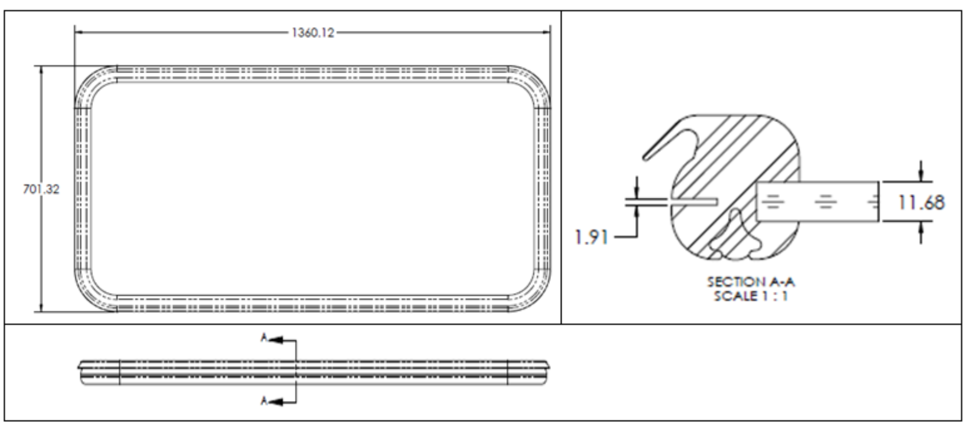

Figure 42. CAD geometry of window glazing

LS-DYNA Model Characteristics

Typical LS-DYNA element types were used to construct the glazing models. The metal frame was modeled with Belytschko-Tsay (BT) shell elements. These are four-node shell elements with a single integration point in the plane of the shell element, but multiple through-thickness integration points could be used to calculate stress variations. Typically, four integration points are specified through the thickness of the shell for each element to accurately capture the bending response. The shell elements of the metal frame are shown in Figure 43.

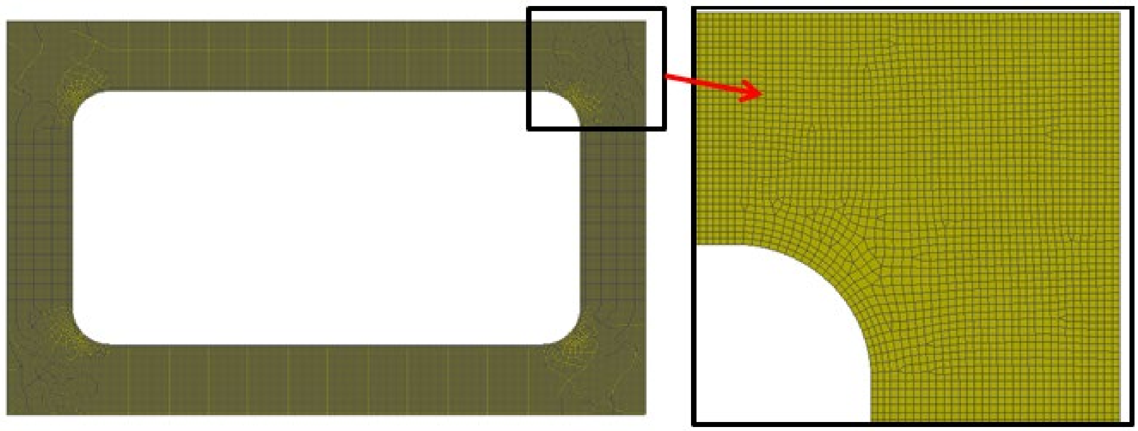

Figure 43. Metal frame shell elements mesh

For the lock strip (zip-strip) and the rubber gasket, and 8-node, solid hexahedron elements with single-point integration were used. This is a commonly used solid-element type in LS-DYNA due to its balance of computational efficiency and accuracy. The solid-element components are shown in Figure 44, laminated glass elements in Figure 45, and the integrated model in Figure 46.

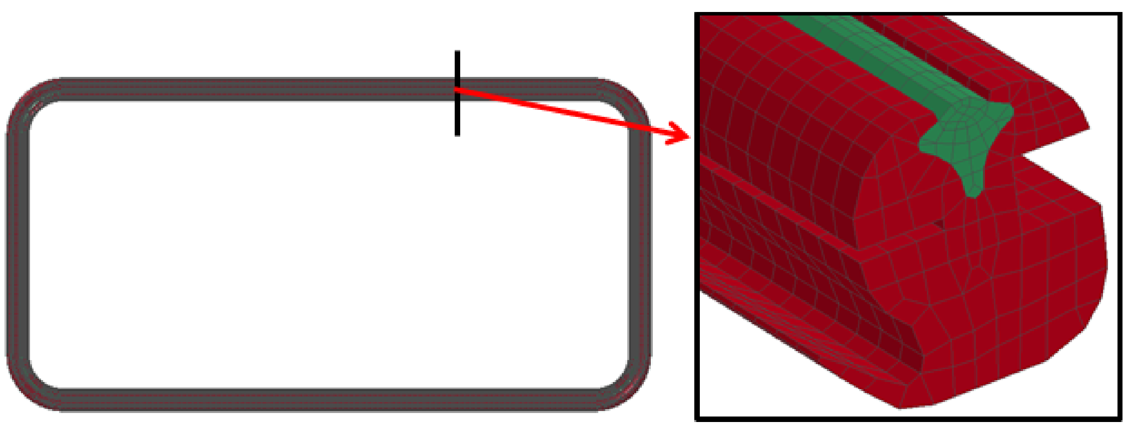

Figure 44. Rubber gasket and lock strip (zip-strip) solid elements mesh

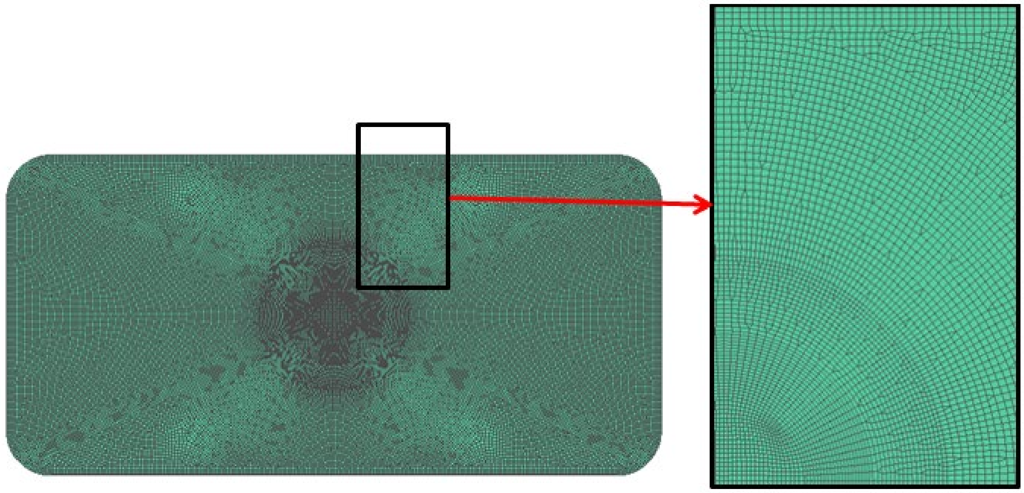

Figure 45. Laminated glass shell elements mesh

Figure 46 shows the FE mesh details of the glazing structure used first to characterize the strength of the glass, and then to analyze the mounting method.

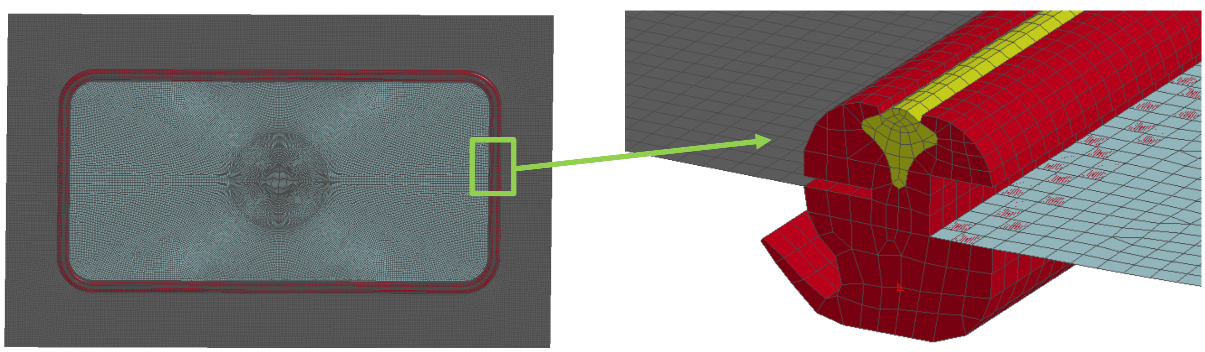

Figure 46. Details of integrated FE model

LS-DYNA Model – Material Properties

Researchers performed a literature survey to select the material models that could be used for the window and rubber components. A common type of glass used in transportation applications is called laminated glass. This type of glass is characterized by two heat-strengthened glass panels sandwiched with a polymer interlayer, polyvinyl butyral (PVB), because of its high adhesive and optical characteristics. The interlayer (PVB) serves numerous functions when subjected to dynamic loading such as impact resistance and the prevention of spalling.

The team found that there are different ways to model laminated glass in LS-DYNA. Research findings [15] demonstrated the 3D laminated glass model provides more accurate results and enables the user to investigate the influence of controlling parameters and support conditions. The 2D laminated glass model (material model 32) gives results with reasonable accuracy using less computational time, and hence can be used to investigate the global behavior of laminated glass panels. Since the scope of this project is related more with the mounting method of the current glazing systems and not necessarily with the glass itself, the use of the 2D laminated glass model was deemed an acceptable approach (see Figure 47).

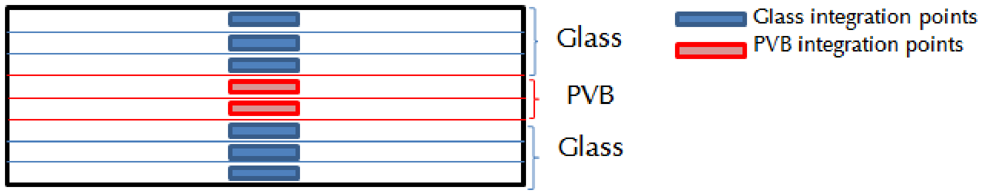

Figure 47. Cross-section of the laminated glass model

In this material model, several integration points can be defined through the thickness of a shell element such that each integration point represents either glass or a PVB interlayer. Material properties such as Young's modulus, Poisson's ratio, and density are defined for both glass and interlayer in Table 10. Material model 32 allows defining failure criteria for the glass based on the failure strain where integration points are deleted if they exceed the failure strain. One of the limitations of this material model is the inability to define failure criteria for PVB, as it is allowed to deform indefinitely without any failure strain.

Table 10. Material properties of glass, PVB, and rubber used in the model

Material Property	Glass	PVB	Rubber/Elastomer
Density	2,483 kg/m^3	1,100 kg/m^3	1,100 kg/m^3
Young's modulus	72.4 GPa	985 MPa	-
Poisson's ratio	0.23	0.492	0.499

Regarding the rubber/elastomer components, there are multiple material models that LS-DYNA has implemented. The choice of material model depends on the availability of material properties and experimental data. Ogden_Rubber material model (MAT77) was chosen to model rubber sealant joints. This material can be fit to uniaxial or biaxial data. Data need to be provided in both the compression and tension regimes to ensure proper fit. The stress vs. strain curve for the rubber material used in this model is presented in Figure 48, and the material properties are presented in Table 10.

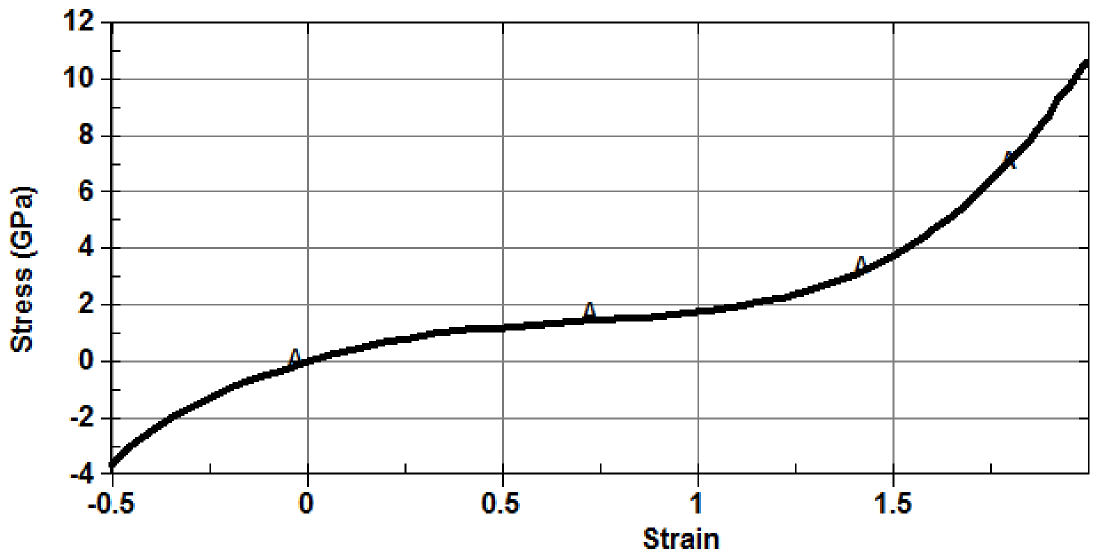

Figure 48. Stress vs. strain curve for rubber/elastomer material

Analyses and Results

GMRT2100 Analyses

The first step of the FE analysis was to make sure the material model used for the laminated glass gave reasonable results based on known/documented loading/impact conditions. The tests and results listed in the RSSB report [7] were used for this effort. The following two simulations were performed:

1. The external impact of a solid steel ball weighing 5 kg travelling at 34 km/h
2. A 50-kg pendulum, internal impact, from height of 1,200 mm

For both simulations, simple boundary conditions around the steel frame were used. Contact was defined between the rubber gasket and zip-strip, rubber gasket and laminated glass, and rubber gasket and steel frame.

Since failure criteria for the PVB interlayer cannot be defined for MAT32, the failure is defined qualitatively by observing the area of the damaged zone and the effective plastic strain from the simulations. The deformation patterns and general behavior observed from these simulations gave the team confidence the material model behaved as intended.

The results are shown in Figure 49 and Figure 50.

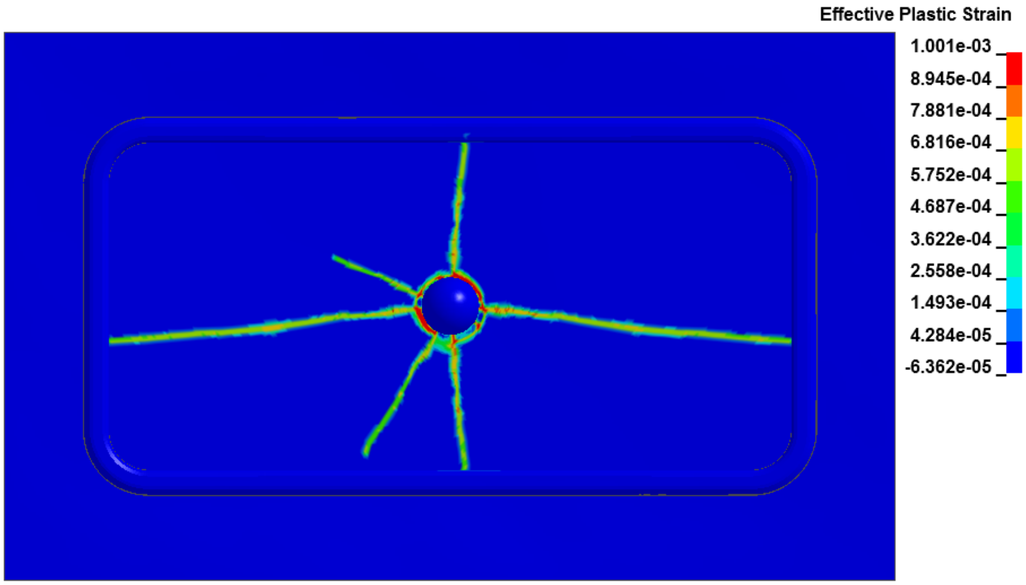

Figure 49. Result of steel ball impact test

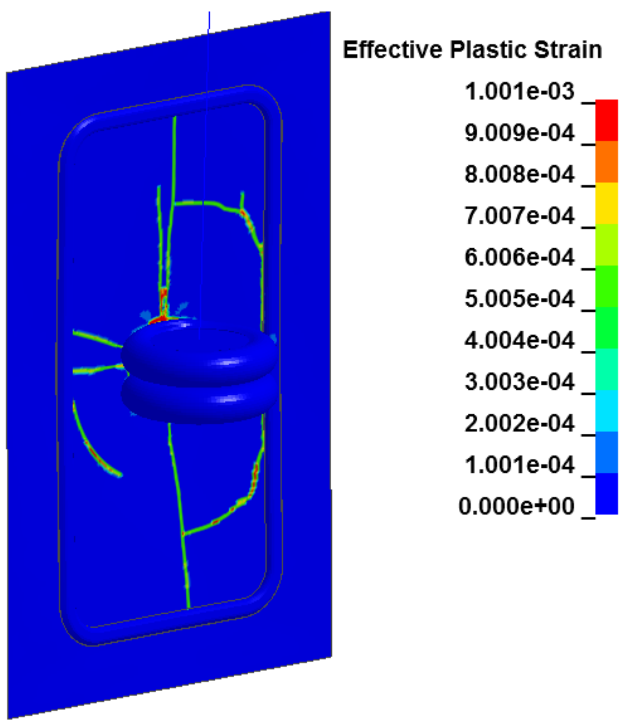

Figure 50. Result of pendulum test

Modeling of Internal Impact

A model was developed to estimate the forces which could be generated from passengers striking the window glazing during an accident. A Hybrid III 95th percentile male anthropomorphic test device (ATD) was simulated falling and accelerating through a distance equal to the width of the railcar onto the window glazing. At the time of impact, the 100-kg ATD was traveling at 6.67 m/s. The peak force experienced by the window from the impact with the ATD was 21.7 kN. This was a very short duration pulse with a duration of about 50 ms; for comparison, the standard triangular pulse used for vehicle interior fixture strength evaluations has a duration of 250 ms. The nominal load over the 50 ms duration is about 11 kN. A time-lapse of the simulation is shown in Figure 51.

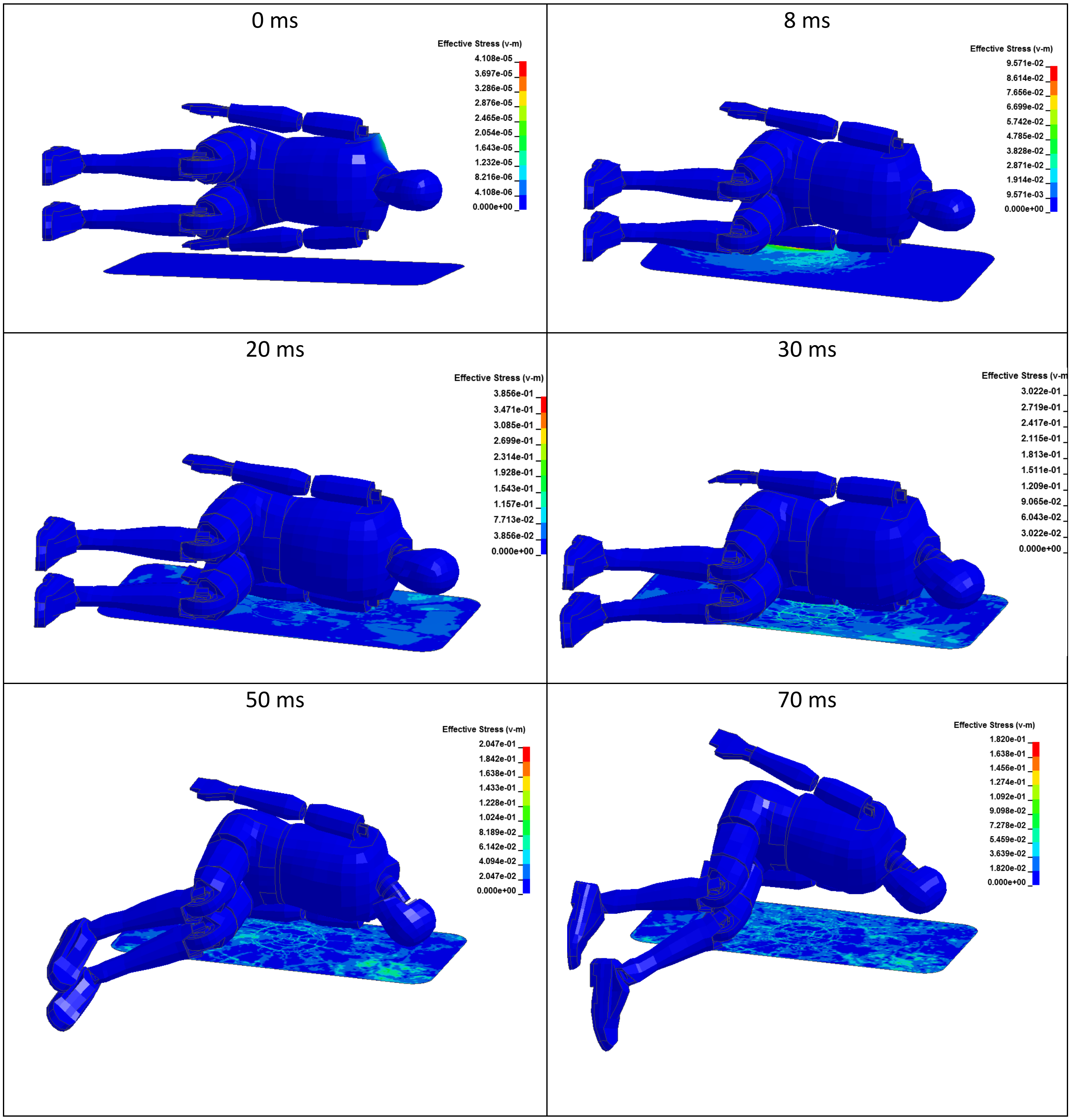

Figure 51. Time-lapse of internal impact test

Rolling Tire Test

A simulation involving rolling a tire with an applied load over the glazing was performed to replicate what might be seen in a rollover-type accident (see Figure 52).

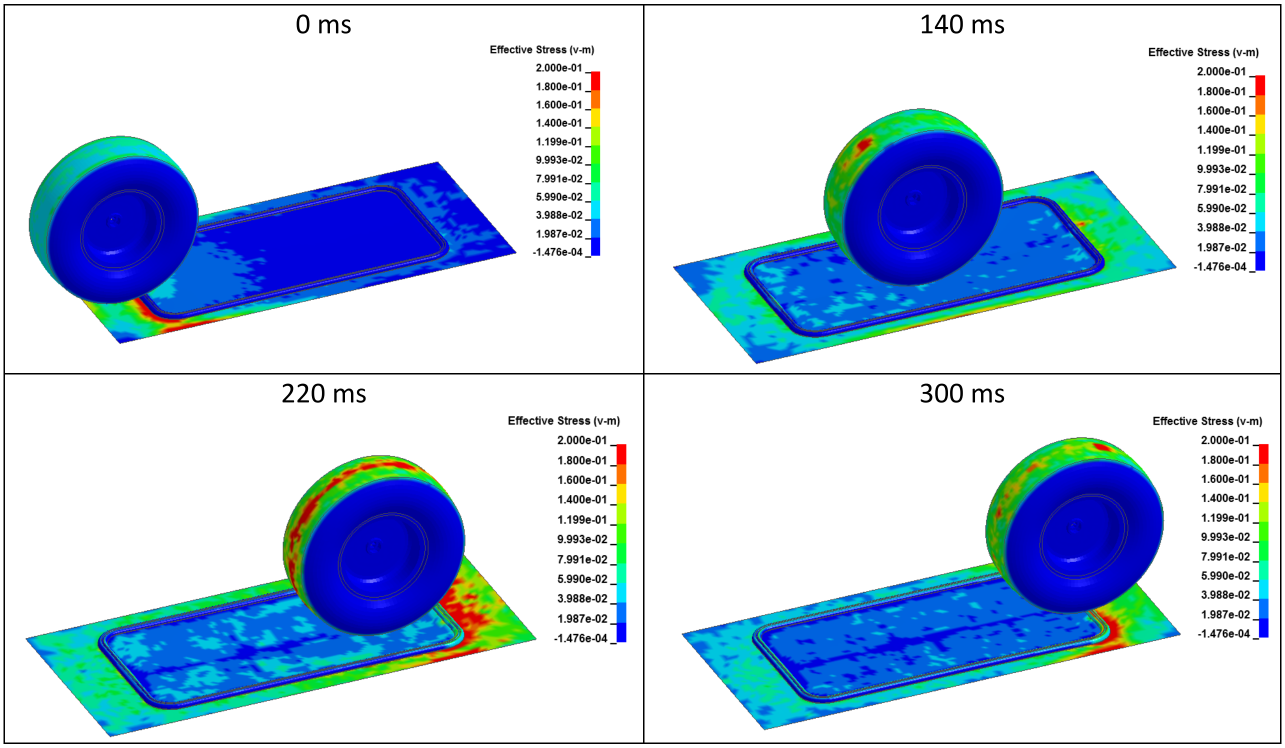

Figure 52. Time-lapse of rolling tire test

The tire weighed 50 kg; a plot of the applied load is shown in Figure 53. Preliminary runs were made with the load held constant at 5 kN until near the end of the simulation, when it was increased linearly to 7 kN (1,100 lbs to 1,500 lbs). The simulated glazing system survived with no signs of detachment or fracture.

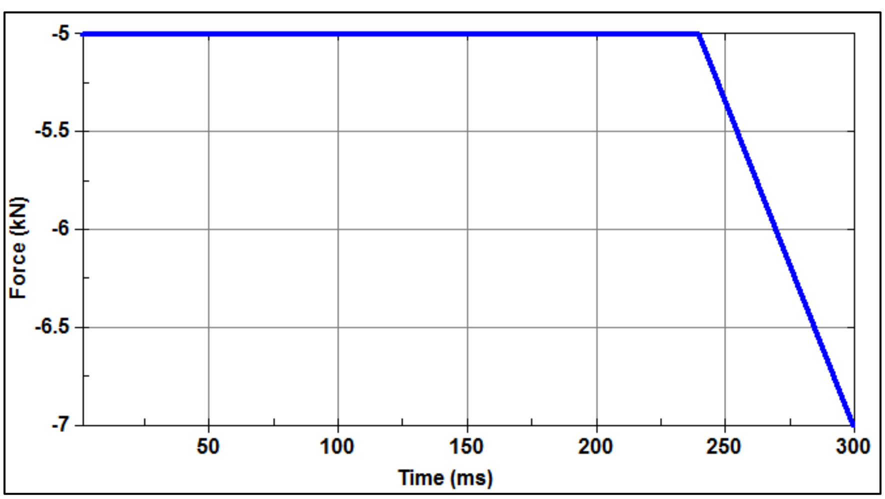

Figure 53. Load applied by the rolling tire

Appendix C – Discussion of Safety and Functionality Requirements

The safety and functionality requirements outlined in the main report are further discussed in this appendix.

Safety Requirements

Certain characteristics of window glazing are directly related to the task of keeping passengers safe. Properties such as glass thickness could make the difference between passengers surviving a crash versus being seriously or fatally injured. The following safety requirements outline criteria window glazing systems must meet in order to maximize passenger safety. These requirements do not specify properties that make the passengers more comfortable or ensure they have a more enjoyable experience, such as having a clear view out of the train.

Items 1, 2. Impact Resistance (excerpts from the CFR)

49 CFR Part 223 Appendix A [1] Certification of Glazing Materials: the Test Specimen for glazing material that is intended for use only in side facing glazing locations shall be subjected to a Type II test regimen consisting of the following tests: Ballistic Impact in which a standard 22 caliber long rifle lead bullet of 40 grains in weight impacts at a minimum of 960 ft per second velocity; Large Object Impact in which a cinder block of 24 lbs. minimum weight with dimensions of 8 inches by 8 inches by 16 inches nominally impacts at the corner of the block at a minimum of 12 ft per second velocity. The cinder block must be of the composition referenced in ***ASTM C33*** [19] or ***ASTM C90*** [20]. Three different test specimens must be subjected to the ballistic impact portion of these tests. Two different test specimens must be subjected to the large object impact portion of these tests. Test specimens must consecutively pass the required number of tests at the required minimum velocities. Individual tests resulting in failures at greater than the required minimum velocities may be repeated but a failure of an individual test at less than the minimum velocity shall result in termination of the total test and failure of the material.

Item 3. Passenger Emergency Egress (Excerpts from the CFR)

49 CFR 238.113 [2] – Emergency window exits lists the requirements for windows with regards to emergency egress. Each single-level passenger car shall have a minimum of four emergency window exits. At least one emergency window exit shall be located in each side of each half of the car, in a staggered configuration where practical.

Each main level in a multi-level passenger car is subject to the same requirements specified for single-level passenger cars.

Except as provided in the paragraphs below, on or after August 1, 2009, any level other than a main level used for passenger seating in a multi-level passenger car, such as an intermediate level, shall have a minimum of two emergency window exits in each seating area. The emergency window exits shall be accessible to passengers in the seating area without requiring movement through an interior door or to another level of the car. At least one emergency window exit shall be located in each side of the seating area. An emergency window exit may be located within an exterior side door in the passenger compartment if it is not practical to place the window exit in the side of the seating area.

Only one emergency window exit is required in a seating area in a passenger compartment if it is not practical to place an emergency window exit in a side of the passenger compartment due to the need to provide accessible accommodations under the Americans with Disabilities Act of 1990, there are no more than four seats in the seating area, and a suitable, alternate arrangement for emergency egress is provided.

Each level of a passenger car with a sleeping compartment or a similar private compartment intended to be occupied by a passenger or train crewmember shall have at least one emergency window exit in each such compartment. For purposes of this paragraph, a bathroom, kitchen, or locomotive cab is not considered a “compartment.”

On or after November 8, 1999, each emergency window exit shall be designed to permit rapid and easy removal from the inside of the car during an emergency situation without requiring the use of a tool or other implement.

Except as provided in paragraphs below, each emergency window exit in a passenger car, including a sleeping car, ordered on or after September 8, 2000, or placed in service for the first time on or after September 9, 2002, shall have an unobstructed opening with minimum dimensions of 26 inches horizontally by 24 inches vertically. A seatback is not an obstruction if it can be moved away from the window opening without using a tool or other implement.

An emergency window exit located within an exterior side door may have an unobstructed opening with minimum dimensions of 24 inches horizontally by 26 inches vertically. Any emergency window exit in addition to the minimum number required need not comply with the minimum dimension requirements but must otherwise comply with all requirements in this part applicable to emergency window exits.

Item 4. Rescue Access (Excerpts from the CFR)

49 CFR 238.114 – Rescue access windows lists the requirements for windows with regards to emergency rescue access:

Each single-level passenger car shall have a minimum of two rescue access windows. At least one rescue access window shall be located in each side of the car entirely within 15 ft of the car's centerline, or entirely within 7 1/2 ft of the centerline if the car does not exceed 45 ft in length. If the seating level is obstructed by an interior door or otherwise partitioned into separate seating areas, each separate seating area shall have a minimum of one rescue access window in each side of the seating area, located as near to the center of the car as practical.

Each main level in a multi-level passenger car is subject to the same requirements specified for single-level passenger cars.

Except as provided in the paragraphs below, any level other than a main level used for passenger seating in a multi-level passenger car, such as an intermediate level, shall have a minimum of two rescue access windows in each seating area. The rescue access windows shall permit emergency responders to gain access to passengers in the seating area without requiring movement through an interior door or to another level of the car. At least one rescue access window shall be located in each side of the seating area. A rescue access window may be located within an exterior side door in the passenger compartment if it is not practical to place the access window in the side of the seating area.

Only one rescue access window is required in a seating area in a passenger compartment if: it is not practical to place a rescue access window in a side of the passenger compartment due to the need to provide accessible accommodations under the Americans with Disabilities Act of 1990, there are no more than four seats in the seating area, and a suitable, alternate arrangement for rescue access is provided.

Each level of a passenger car with a sleeping compartment or a similar private compartment intended to be occupied by a passenger or train crewmember shall have a minimum of one rescue access window in each such compartment. For purposes of this paragraph, a bathroom, kitchen, or locomotive cab is not considered a “compartment.”

Each rescue access window must be capable of being removed without unreasonable delay by an emergency responder using either a provided external mechanism or tools or implements that are commonly available to the responder in a passenger train emergency.

Each rescue access window in a passenger car, including a sleeping car, ordered on or after April 1, 2009, or placed in service for the first time on or after April 1, 2011, shall have an unobstructed opening with minimum dimensions of 26 inches horizontally by 24 inches vertically. A rescue access window located within an exterior side door may have an unobstructed opening with minimum dimensions of 24 inches horizontally by 26 inches vertically. A seatback is not an obstruction if it can be moved away from the window opening without using a tool or other implement.

Item 5. Fire Resistance and Smoke Emission

The following test methods are excerpted from 49 CFR Appendix B to ***Part 238***, Test Methods and Performance Criteria for the Flammability and Smoke Emission Characteristics of Materials Used in Passenger Cars and Locomotive Cabs.

> ***ASTM C 1166-00*** [21], Standard Test Method for Flame Propagation of Dense and Cellular Elastomeric Gaskets and Accessories
>
> ***ASTM E162 – 16*** [22], Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source
>
> ***ASTM E 662-01*** [23], Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials

Item 6. Strength (Pressure and Deflection)

49 CFR 238.221 – Specifies that each exterior window on a locomotive cab and a passenger car shall remain in place when subjected to forces due to air pressure differences caused when two trains pass at the minimum separation for two adjacent tracks, while traveling in opposite directions, each train traveling at the maximum authorized speed.

TCRP Report 15 [17], *Procurement Specification Guidelines for Mass Transit Vehicle Window Glazing*, notes that side windows shall be designed to withstand pressure loadings of 35 lbs/ft^2 (approximately equivalent to a 125 mph wind loading) with a safety factor of 2.5 against failure. Deflections shall be limited to 1/180 of the short span. Both negative and positive pressures shall be considered. Pressure tests shall be performed on the side windows to show conformance with the specified deflection requirement under pressure loads of 35 lbs/ft^2. Under pressure loads of 70 lbs/ft^2, no window glazing shall come free of its retaining frame, no glazing failure shall occur, and the retaining frame shall suffer no permanent deformation. Pressure tests shall be conducted for both positive and negative pressures. The glazing frame and retention devices shall be the same as those used in production transit vehicles or simulated to the satisfaction of the authority.

These specific criteria are generally not explicitly integrated into most specifications.

Another strength element seen in TCRP Report 15 is a requirement for windows, window frames, and mechanisms to withstand, without damage, peak forces of 100–200 lbs applied in any direction. The window shall withstand a specified number of cycles of open-and-close testing with no degradation in performance. Such requirements are more likely to be seen in urban transit systems with ‘openable’ windows, rather than on heavy rail systems where the windows are generally sealed.

Item 7. Occupant Containment – Inward Load

This is envisioned as an inward load, applied to the outside of the window. Researchers attempted to estimate the force magnitudes from simulations and other test results; however, it is not straightforward to convert the results of dynamic tests or simulations into a static or quasi-static load that can be used for a simplified test. It is clear from the test effort described in this report that the load will need to be greater than 1,500 lbs. Additional research/testing is needed to better quantify this.

Item 8. Occupant Containment – Glazing Retention – Pry Test

In this setup, a sharp loading block is pushed into the gasket with an applied force in the transverse direction (with vertical restraint), with the intent of prying the gasket loose. The specific loads are yet to be determined. A passing test may also show that the loading block passes over the gasket with minimal gasket damage.

Item 9. Occupant Containment – Glazing Retention (Alternate) – Ballast Drag Test

The ballast drag test is proposed as another alternate. As seen in this report, this test was an excellent research tool that captured the failure modes seen in the field. It may be a challenge to convert this into a specification, but this remains a reasonable alternative.

Item 10. Confirmation of Emergency Access/Egress Performance

This is intended as a check to confirm that the efforts to improve glazing retention have not made emergency access/egress functionality unduly difficult or complex. This may be achieved in a variety of ways including design review, demonstration, testing, or training.

Functional Requirements

Certain characteristics of window glazing pertain not to the safety of the passengers, but to the overall performance of the system after considering transparency, maintenance, durability, and other properties. The following functional requirements ensure that the glazing systems will provide a reliably comfortable environment for passengers. The requirements are also in place so windows can be replaced quickly and easily.

Item 11. Optical Quality

Optical quality of the window materials includes requirements for haze, distortion, inclusions, scratches, drips, runs, and other defects. The base standard commonly used in the North American rail industry is ***ANSI Z26.1*** [5], which includes requirements for Light Stability, Luminous Transmittance, Optical Deviation and Visibility Distortion, and Haze.

There are several other ASTM standards that offer alternate requirements and test methods for Optical Quality, but specifying these might become over-restrictive for rail vehicle windows and windshields. ***ANSI Z26.1*** [5] appears to provide the requisite set of requirements needed for railroad applications. Other additional requirements (if needed), can include:

- ***ASTM C 1036*** [24] for quality of the window glass, which includes requirements for inclusions; knots, dirt, and stones; scratches and rubs; crush; digs; ream, strings, lines, and other linear distortion; wave; and process surface blemishes.

Item 12. Physical Characteristics

Physical parameters related to glazing materials are specified in ***ANSI Z26.1*** [5], including Dimensional Stability, Flexibility, Fracture, and Impact characteristics. Please note the impact characteristics specified in the ANSI standard are superseded by FRA requirements for railroad applications.

Physical characteristics for gasket elements such as the hardness, maximum deformation under load, tensile strength, and elongation, are outlined in ***ASTM C 542*** [25].

- The gasket durometer hardness specified is 70 ± 5. Filler strip rubber may be specified at a durometer hardness of 80 ± 5 (Test Method: ***ASTM D 2240*** [26])
- The specification allows a maximum of 35 percent permanent deformation under load for the gasket; however, some agencies use a more restrictive maximum of 25 percent (Test Method: ***ASTM D 395*** [27])
- Tensile strength of the rubber gasket should be verified using ***ASTM D 412*** [28].
- ASTM C 542 requires a minimum of 175 percent elongation for the gasket; however, some agencies require a minimum of 300 percent elongation (Test method: ***ASTM D 412*** [28]).

Item 13. Weather and Environmental Resistance

Weather resistance of glazing components is covered by ***ANSI Z26.1*** [5], which identifies tests and requirements for simulated weathering, humidity, and high temperature exposure. These include Test 3 – Humidity Test, Test 4 – Boil Test, Test 5 – Bake Test, and Test 16 – Weathering Test.

ASTM C 542 [25] provides required specifications for zip-strip (lock-strip) glazing rubber gaskets in regards to withstanding weather and environmental conditions.

Requirements for system performance are generally specified in individual vehicle procurement documents. These are usually defined at a high level in terms of environmental characteristics the system needs to survive – in addition to specific water tightness, or other leak tests, under car washing conditions. TCRP Report # 15 provides a sample: "The window system must not leak under specified test conditions. The test shall cover the surface area of the side of the vehicle including the window/frame assemblies. The water spray shall be located so that full overlap between nozzle patterns is obtained on the surfaces of the transit vehicle body. Distances from the nozzles to the transit vehicle surfaces shall be as required to obtain overlap but shall not exceed 5 ft. Each nozzle shall deliver a minimum of 6 gal of water per minute with a nozzle velocity that will simulate 75 mph (or other velocity specified by the transit authority) transit vehicle speed conditions and transit vehicle wash conditions."

Item 14. Durability – Glazing Materials

The durability requirements for glazing materials are also largely covered by ***ANSI Z26.1*** [5], which includes multiple tests and requirements for abrasion resistance and chemical resistance.

Item 15. Durability – Gasket Materials

Various durability characteristics of the rubber gasket are outlined in ***ASTM C 542*** [25]. Test methods for ozone resistance, heat aging resistance, and oil aging resistance are in ***ASTM D 1149*** [29], ***ASTM D 573*** [30], and ***ASTM D 471*** [31], respectively.

Item 16. Corrosion Resistance

Glass and glass-based glazing components are generally resistant to corrosion. Usually, most specifications do not explicitly specify corrosion requirements for glazing systems. If required for a specific agency or order due to corrosion concerns, a salt-fog test and a test duration may be specified. In such cases, a test of the full glazing system, including framing elements, would be required for a nominal test duration, such as 7 days. The test method for the corrosion test is outlined in ***ASTM B 117*** [32].

Item 17. Ease of Maintenance

This is a "soft" requirement and has the potential to cover two areas: ease of cleaning and ease of replacement. Ease of cleaning, if specified, is generally handled through the addition of removable layers (peel-off plies) or coatings, including anti-graffiti coatings (see item 18).

Ease of replacement, if identified, is specified as a change-out time. ***TCRP Report 15*** [17] recommends the requirement for change-out time for the transparent window panel ("glass") be 15 minutes or less; a time of 5 minutes or less is the most desirable. The transit authority should also specify the side from which the window will be changed-out – either the inside or the outside of the vehicle.

Item 18. Anti-Vandalism Requirements

These are not very common in heavy-rail specifications; system-specific elements are usually specified for urban, light rail/metro vehicles, and include:

- Window mounting specifics, including requirements for specific fasteners
- Coatings or additional layers for ease of graffiti removal
- "Non-stick," graffiti-resistant coatings and shields